Underwater acoustic noise characteristics of the OWEZ wind farm operation (T1)

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Report number: OWEZ_R_251 T1 2014-05-28 IMARES C069/13

IMARES Wageningen UR

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Publication date:	28 May 2014

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Summary

The demand for renewable energy has led to a significant growth of offshore wind farms in European waters. According to the statistics of the European Wind Energy Association of January 2013 the total installed capacity in Europe increased to 4000 MW in December 2012 (Arapogianni et al., 2013) and is expected to increase a factor 37 in 2030. Turbine dimensions increased from 2 MW in 2006 to 5 MW at present.

In the Netherlands the first two offshore wind farms, the "Offshore Wind Farm Egmond aan Zee" (OWEZ) and "Prinses Amalia Wind Park" (PAWK) were built in respectively 2006 and 2007. Beside the main goal of producing electric energy from wind resource the construction of the first wind farm (OWEZ) was also used to demonstrate the impact of such a construction on the environment. The construction was licenced to NoordZeeWind, a consortium of Shell and NUON. The 36 turbines of 3 MW each were completed in August 2006. To demonstrate the environmental impact an extensive Monitoring and Evaluation Program (MEP) was developed. The program was divided 5 sub-projects, carried out by IMARES: (1) Effects of the wind farm on fish, (2) Individual behaviour of fish in the wind farm (3) Underwater acoustic characteristics of the wind farm operation, (4) Habitat preferences of harbour seals in the Dutch coastal area, (5) The effects of the OWEZ wind farm on harbour porpoise.
The results of the third sub-project are presented here and focus on characteristics of wind farm related production noise and the effects of the noise to the hearing of harbour seal *(Phoca vitulina)*, harbour porpoise *(Phocoena phocoena)*, Atlantic cod (*Gadus morhua*) and Atlantic herring (*Clupea harengus*).

Underwater noise was measured in a frequency range of 10 Hz to 20 kHz using two self-contained acoustic recording systems. The hydrophones were positioned 1 m above the seabed, one at a distance of 100 m from a wind turbine (WTG27) and a second position 7.4 km to the north of WTG27. The second position is used as background noise reference not exposed to wind farm noise. The measuring periods involved 83 hours in January and 88 hours in February 2013 and covered conditions of maximum turbine power production.

Turbine noise levels were detected as soon as the turbine power exceeded 100 kW. At a wind speed between 6 to 8 $m.s^{-1}$ the levels increase substantial, further increase above 2000 kW is minor. Broad-band turbine noise levels (10 minute averages) measured at wind speeds of 12-15 $m.s^{-1}$ were 123 dB re 1 $\mu Pa^2/Hz$ for both measuring periods. For the duration of the first measuring period with strong mainly eastern wind the sea state noise contribution was lowest and the difference between turbine and background noise level the highest (8.1 to 8.4 dB). On the second period with northern winds and higher sea state noise contribution the difference between turbine and background noise levels was lower and contained higher uncertainties ranging between 3.5 to 7.5 dB. During these conditions turbine noise will equal the background noise level between 272 to 417 m accordingly, assuming the intermediate of spherical and cylindrical spreading (15 Log distance).
During the condition with lowest sea state noise contribution (8.1 to 8.4 dB difference) turbine noise will equal the background noise level at 449 to 463 m from the turbine. When the overall measurement error (0.3 dB) is taken into account the maximum unmasked distance will be 480 m, while we maximized the unmasked distance at 500 m in this present report.

Turbine noise peaked in the 16, 50, 100 and 200 Hz Third-Octave bands and equalled the background noise level in the bands ≥ 315 Hz. When not masked by shipping, turbine noise had the strongest contribution in the 200 Hz band (115 dB re 1 μPa^2 $^{+}/_{-}$ 1.2 dB). Turbine noise levels in the range of 16 Hz occurred for the duration of 12 hours of low power production on eastern wind and lowest sea state

noise. On similar low power conditions with northern winds and higher sea state noise it was not observed.
Contribution from auxiliary engines related to the wind turbine structure was negligible and were only detected incidentally on activation of the turbine from idle mode.
Wind farm related shipping noise of water taxis, type “WindCat” masked the turbine noise in all recorded conditions up to a distance of 3760 m. The maximum range is 7 times the estimated distance (500 m) where turbine noise is masked by the background noise. Shipping noise was recorded at WTG27 28.6 % of the total measured time, 8.2 % of this is attributed to “WindCat” noise. Noise of other shipping was dominant in some cases over long distance. The noise from a cargo ship sailing along the northwest side of OWEZ towards the main shipping lane was partly simultaneously received in both measured positions, although the distance between the received positions was 7.4 km. The masking threshold was reached when the ship was at 10 km distance from the hydrophone close to the wind turbine. The passing ship masked the turbine noise for a period of 40 minutes and a sailed distance of 20 km.
Temporary Threshold Shift (TTS) is defined as the threshold range (“onset”) where the hearing sensitivity is temporarily reduced and the latest stage before a Permanent Threshold Shift (PTS).

TTS-onset in harbour porpoise (Phocoena phocoena)
For harbour porpoise the audible part of turbine noise level in the received position peaks in the 200 Hz-band with 12 dB above the background noise level. Given the expected growth of wind farm power production by a factor 37 in 2030 the long-term effect of turbine noise was analysed using the most sensitive approach. The TTS-onset reference (Kastelein et al., 2012a) was adapted to the level of turbine noise presently reported. The Sound Pressure Level (SPL), which was used in this TTS range was 124 dB re 1 μPa^2, which is 9 dB lower than the overall average proposed by Verboom et al., 2012. The exposure to the highest turbine noise level will cause TTS-onset in harbour porpoise after 75 days. This result suggests TTS in harbour porpoise could occur on permanent exposure, but it is unlikely that harbour porpoise will remain stationary for such a period in the exposed area. Another condition contributing to TTS is the interval required to recover from TTS and if these animals will meet these conditions given the expected growth of wind farms. Due to the lacking knowledge of TTS in the turbine type of noise the TTS-onset estimate includes extrapolation. One of these is a 30 dB compensation for the frequency mismatch of turbine and TTS reference noise (respectively 0.2 to 4 kHz). This compensation is encouraged by a 40 dB reduction reported in the TTS-study in bottlenose dolphin (Finneran et al., 2010).

TTS-onset in harbour seal (Phoca vitulina)
For harbour seal the audible part of turbine noise in the received position peaks at 200 Hz with 20 dB above the background noise level. The exposure to the highest turbine noise level will cause TTS-onset in harbour seal after 7 days and 12 hours. In this estimate the TTS-onset reference of 163 dB re 1 $\mu Pa^2 s$ (Kastelein et al., 2012b) was applied. As references on TTS in the frequency range of turbine noise are lacking no compensation was applied although the hearing sensitivity of harbour seal between 4 kHz and 0.2 kHz reduces with 8 dB. Given the haul-out period ashore it is unlikely that TTS-onset in harbour seal will be reached. Information on the spatial and temporal use of wind farm areas is lacking.

The effects on two North Sea fish species
The effects of turbine noise on two fish species Atlantic cod (*Gadus morhua*) and Atlantic herring (*Clupea harengus*) showed that weighed turbine noise is 10 dB above the background noise at 160 and 200 Hz and that the bandwidth of the unmasked noise was not reduced after weighing. Under both weighed and unweighted conditions turbine noise leveled the background noise at 400 Hz. There is lack of knowledge at what distance turbine noise can be detected, in particular on the relation between signal and noise in fish. The weighing results showed that Atlantic cod and Atlantic herring have the ability to detect turbine noise over the full unmasked spectrum in particular around 160 and 200 Hz.

Recommendations
Given the lack of knowledge on the effects of low-frequency type of noise, similar to turbine noise, it is recommended to conduct TTS-experiments with turbine type of noise on harbour porpoise and harbour seal following the methods of Kastelein et al., 2012.
TTS-onset in harbour porpoise is not likely to occur, although the reported estimate suggests that TTS can be reached on long term exposure. As TTS-onset also depends on the recovery intervals after exposure additional behavioural research is needed on the spatial and temporal use of harbour porpoise and harbour seal in the unmasked zone of turbine noise.
The results confirm that the positioning of wind farms close to shipping lanes is the best approach to mask this relatively low level noise source by shipping and so minimising the periods that turbine noise rises above the level of the background noise.

1 Introduction

The contribution of renewable energy from offshore wind farms is a common aim for most of the North Sea countries to reduce the negative effects of CO^2 emission and to reduce the exhaust of fossil resources and fossil powered energy production. Offshore wind farms have the advantage over onshore sites that the efficiency is much higher due to the larger size and higher wind speeds. The Horns Rev1 wind farm, constructed in 2002 in Denmark, was the first major construction in Europe and consisted of 80 turbines of 2 MW capacity each. The total installed Dutch offshore wind energy capacity is 249 MW and concerns the two operational wind farms OWEZ and "Prinses Amalia". By August 2010, the total installed capacity of offshore wind farms in European waters had reached 3000 MW (Rock & Parsons, 2010) with the United Kingdom as world leader of offshore wind energy production (1371 MW). According the statistics of EWEA (European Wind Energy Association) of January 2013 (Arapogianni et al., 2013) the current projection of offshore wind farm capacity in European waters is estimated to grow to 150000 MW in 2030 with the aim to reach 13-17 % of the European Union's demand of electricity.

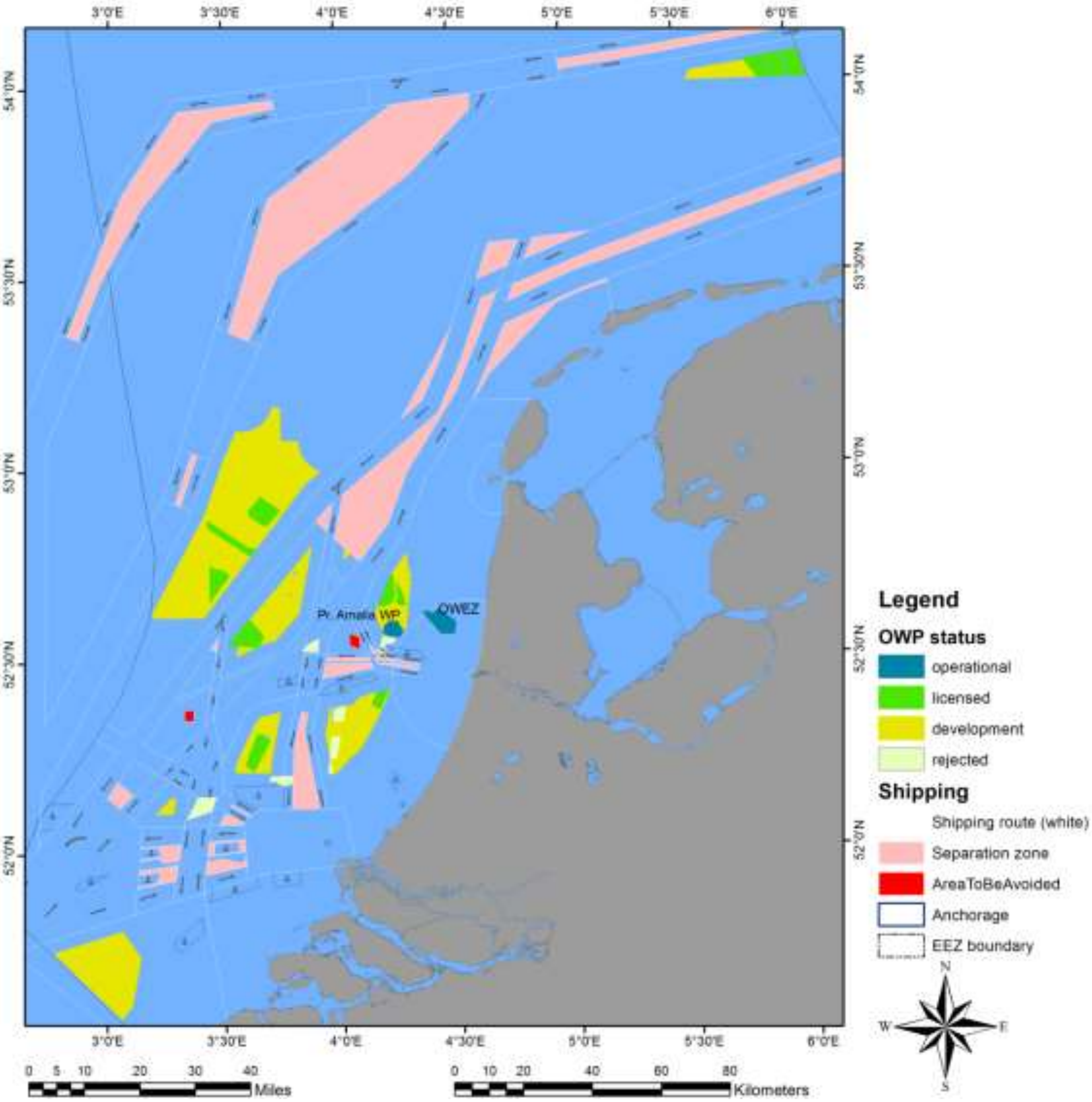

Figure 1 Overview of existing and expected future wind farm location in the Dutch North Sea zone (August 2013)

At the end of 2012, the average water depth of wind farms was 22 m and the average distance to shore 29 km. Given the aimed growth to 150 GW in 2030 the future planned construction of wind turbine power will increase (at present 5 MW) and the turbine arrays are likely to be built in deeper waters at longer distances from shore. Announced projects are up to 200 km from shore and in water depths up to 215 m. With this ambition there is a raising concern on the impact to marine animals, in particular species that depend on sound to communicate forage and orientate. An average service life of a wind farm is estimated to be at least 20 years. The expected growth of wind power production is expressed in the new licenced wind farms (Figure 1) based on the planning of August 2013 with the existing (blue), new licenced (green), developed (yellow) and rejected licences (light green) locations. With respect to the expected growth in 2030 there is a concern of the effects on the marine environment, in particular on the construction of wind turbine and the exposures of high impulsive pressure waves during the hammering of the foundations and the long term exposure to constant emission of production noise.

1.1 Overview of the OWEZ wind farm location and shipping routes

The OWEZ wind farm (Q8), west of Egmond aan Zee was built in 2006 and one of the earliest production plants in Dutch coastal waters and became fully operational in 2007. The OWEZ wind farm consists of 36 Wind Turbine Generators (WTG's, type V90) of 3 MW nominal power capacity each (Figure 2).

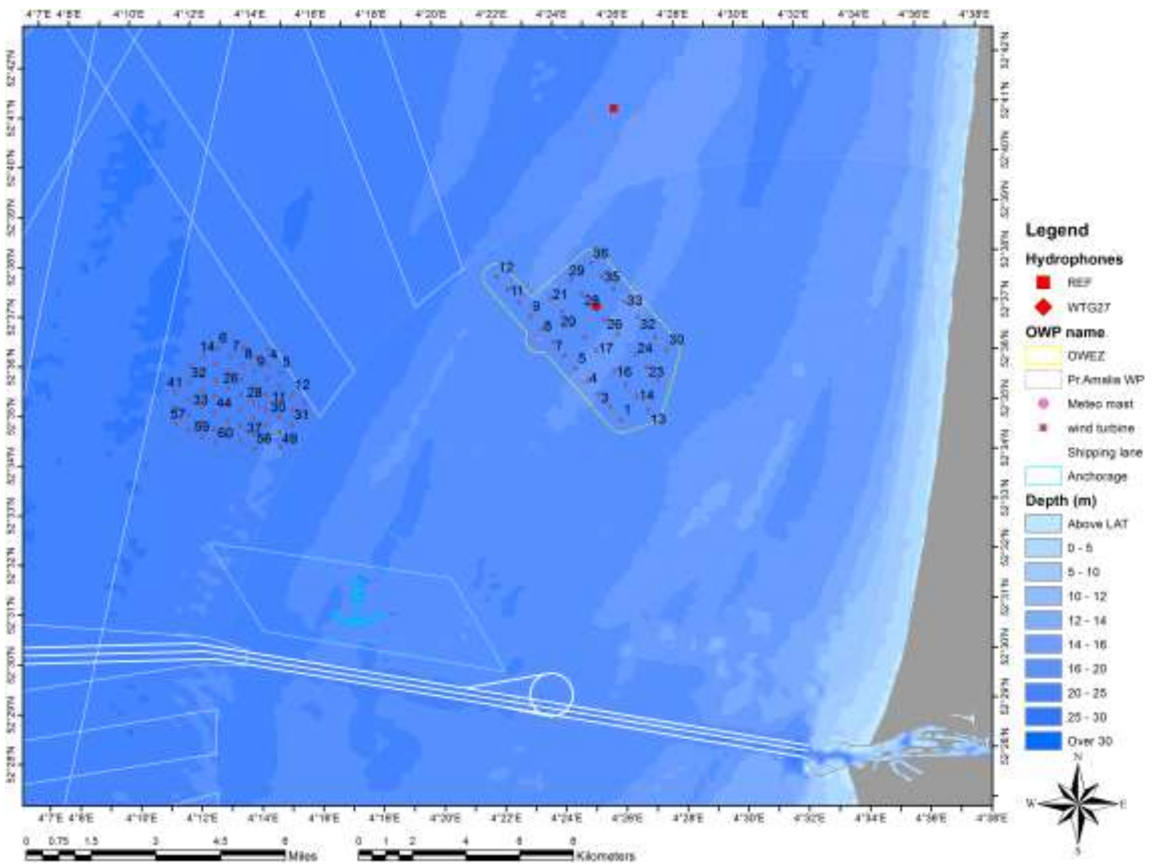

Figure 2 Location of the OWEZ wind farm with at the west "Prinses Amalia Wind Park" and coastal shipping lanes. To the west of the OWEZ site the sub lanes towards the main shipping route. The map marks the measuring position of the hydrophone 100 m east of Wind Turbine Generator 27 (WTG27) (red diamond) and the hydrophone in a reference position 7.4 km to the north (red square).

The overall dimensions of the OWEZ wind farm cover an area of 6934 m (maximum length) and 2896 m (maximum width). The other wind farm of similar scale, "Prinses Amalia Wind Park" (PAWP) was built at a distance of 4 miles west of OWEZ in more or less the same period and consists of 60 turbines (type V80) of 2 MW power each. This wind farm is in operation since June 2008. Both wind farms are in close range of the shipping routes as illustrated in Figure 2. The route along the west side of the OWEZ wind farm connects ships to and from IJmuiden to the main coastal shipping lane. Southwest of both wind farms the anchoring area allocated to ships waiting to enter the sea gate to the harbour of Amsterdam and IJmuiden.

1.2 Aims of the research

The increasing scale of offshore wind farms in the Dutch sector of the North Sea and how this new type of noise source relates to the traditional background noise requires more research on the effects.

The aim of this research is to investigate the noise contribution of wind turbines of the OWEZ wind farm on the environment and the effects on marine animals and is a part of a Monitoring and Evaluation Program (MEP) with six other research fields commissioned to IMARES:

- Effects of the wind farm on fish (OWEZ_R_264_T1_20121215_final_report_fish);
- Effects of the wind farm on macro benthos community (OWEZ_R_261_T1_20121010);
- Local birds in and around the OWEZ wind farm (OWEZ_R_221_T1_20111120);
- Benthic communities on the hard substrates of the wind farm (OWEZ_R_266_T1_20120206);
- Individual behaviour of fish in the wind farm (OWEZ_R_265_T1_20100916);
- The effects of the OWEZ wind farm to harbour porpoise (OWEZ_R_253_T1_20120202).

This MEP covered a baseline programme, which was executed in 2003-2004, followed by work during the construction and in the operational phase. It focussed on the impact of the wind farm on benthic organisms, fish, birds and marine mammals, as well as the underwater noise measurements before and during the construction and the noise emission of the wind farm during the power production.
A summary of the interim results of the IMARES research was published in 2011 (Lindeboom et al. 2011). The research was addressed to gain knowledge and experience for future large scale wind farms at sea.

Within this main frame underwater acoustic noise measurements were executed prior to the construction of the OWEZ wind farm as baseline reference of the condition before the building of the wind farm (de Haan et al., 2007a), the noise emission during the construction of the wind farm (de Haan, et al., 2007b), and this present part, the underwater noise from the wind farm operation (T1).
The description of the methods for measuring the wind farm operational noise (de Haan and van Hal, 2012), procedures and risk assessment was accepted on 22 May 2012 by Rijkswaterstaat.

The overview of published results and reviews on wind farm noise of similar scale indicated that wind turbine noise is mainly developed in low frequency ranges < 500 Hz with sound pressure levels too low to cause hearing loss or impairment (Madsen et al., 2006). The reported turbine noise level can be regarded as a relatively low level type of noise, but when it is not masked by other noise sources its presence is permanent, provided the activation by wind.

A motive to investigate long term exposure is the expected growth of offshore wind production (37 times the present offshore wind power production) and the spreading of wind farms over a wider area of the North Sea. The analysis of the effects will address the question if long-term exposure turbine noise could cause Temporary Threshold Shift (TTS) in harbour porpoise and harbour seal.

The methods of measuring and analysing the results of this research were developed according the guidelines and recommendation summarised in a TNO-report by de Jong et al., 2011.

1.3 Wind turbine noise characteristics

A wind turbine structure consist of a number of different types of sound sources, some directly related to the transmission system of the turbine others indirectly from engines to control and protect the turbine's operation. These noises contain broad-band, tonal sound and impulsive elements. As tonal sounds have different effects on the marine environment than broad-band noise it is important that the contribution of these individual aspects is determined.

1) Tonal sounds consist of pure tones developed in most cases by transmission systems, such as the set of mechanical gears used to transfer the low rotational speed of the rotor to a speed high enough to generate electrical power. These gears produce tonal sounds at some critical speeds and the contribution depends on the design and classification. Small changes (tooth shape, gear ratio and case thickness) could have a significant effect on the development of tonal sounds in terms of frequency and level. There are two auxiliary engines installed to tune the turbine to the optimum wind condition. The first is an electric motor-driven system, which sets or unsets the turbine in the wind direction (the operation is known as "Yawing"). The second is a hydraulic rotor blade pitch engine, which is used to set the blade angles of the rotor to the most efficient wind speed condition and/or protects the rotor/turbine against overload at high wind speed conditions. All engines are directly built on the steel foundation and coupled to seawater.

2) Broad-band noise is characterized by noise in a broad frequency spectrum with no dominant frequencies involved. An example of this type of noise is the aerodynamic noise developed by the interaction of wind and rotor blades, produced by the air flow over the rotor blades;

3) Impulsive noises are developed by the rotor blade control system, which is equipped with pistons to lock/unlock the hydraulically driven rotor blade control mechanism.

All parts of the wind turbine engines are directly mounted on the metal structure of the wind turbine construction and are propagated through the tower wall and transition piece (yellow coloured section) into seawater according the principle propagation model illustrated in Figure 3. The assumption is that the structure-borne noise will propagate in a symmetrical way in all directions. The seismic component coupled into the stratum and the effects are not negotiated in this report.

Figure 3 Basic sound propagation noise model of the structure-borne propagation path of rotational devices, gearbox, turbine and auxiliary engines.

1.4 Main particulars of the OWEZ wind turbine and noise sources

The OWEZ nacelle (Figure 4) is positioned at a height of 70 m above the water surface positioned on a steel tower with a diameter of 4.6 m and 45 mm wall thickness. The rotor blade arrangement has a diameter of 90 m and a swept area of 6362 m^2. The operational rotor speed range is 8.6 to 18.4 RPM (16 RPM nominal). The rotational direction is clockwise in front view and the orientation upwind. The turbine (type Vestas V90) is coupled by use of a gearbox consisting of three stages with a kinematical ratio of 1 to 104.557, which converts the nominal rotor blade rotational speed from 16 RPM to 1673 RPM at the generator level. The wind sensor appellation is acoustic resonance (2 units) with a signal resolution of $^+/_-$ 0.5 $m.s^{-1}$ (< 15 $m.s^{-1}$) and an accuracy of $^+/_-$ 4 % (> 15 $m.s^{-1}$).

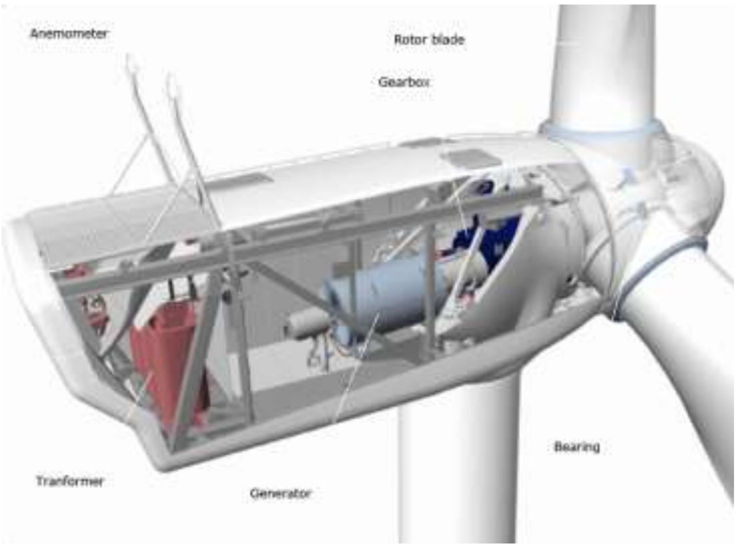

Figure 4 Overview of the Wind turbine construction (nacelle) with main parts of the construction.

The Vestas V90 turbine power curve, as shown in Figure 5 is taken from the General Specification V90-3.0 MW Class 1 item 950011R8, 2005-06-13. The curve shows that the nominal power condition is reached at a wind speed of 15 $m.s^{-1}$, or 29 knots, which is around a wind force 7 Beaufort condition.

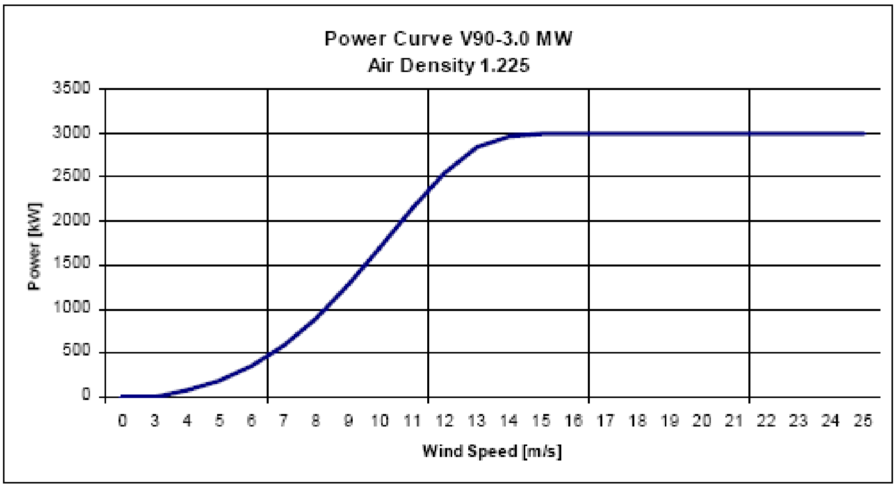

Figure 5 Power curve of the Vestas V90 wind turbine as a function of wind speed

The wind turbine (nacelle, Figure 4) is set and controlled to the wind direction and this operation, identified as “Yawing”, is driven by an electric auxiliary engine. The rotor blade pitch is actively controlled to optimize the efficiency of wind energy production and to limit the maximum produced power at the higher end of wind speed ranges. The rotor blade pitch control system is driven by a hydraulic auxiliary.

An additional factor with influence on the efficiency of production of wind power is the air density. The nominal standard specification of 1.225 kg/m^3 (Figure 5) is referred to an air temperature of 15 °C. Air density is a function of relative humidity, air pressure and air temperature is mostly referred to its constant standard value of 1.225 kg/m^3 at a temperature of 15 °C. The power production (P) is a function of the air density (p), the swept area of the rotor blades (A) and the wind speed (v) according the formula:

$$P = \frac{1}{2}\rho A v^3$$

The air density could vary between 1.1 and 1.4 kg/m^3 and the effects on the power production are not further negotiated in this report. As acoustic turbine noise measurements were executed in the winter period with a strong eastern wind the wind power production on the first mission was in its most efficient range. This means that the turbine reached the maximum power range at slightly lower wind speeds.

1.5 The propagation model for wind turbine noise and related noise sources

The turbine acoustic noise signature is a composition of noise from all rotational devices built in the WTG. All these noises are propagated through the structure-borne path into the sea and illustrated in the overview of Figure 3. The spectrum of the turbine noise will probably involve a range up to 500 Hz and will peak around 100 to 200 Hz as was found in wind turbines of similar physical scale (Madsen et al., 2006). The propagation of this noise and the attenuation over distance is related to a number of factors, like water depth, absorption and reflection losses, the type of substrate. A high share is related to the frequency of the sound. Low frequencies propagate over longer distance. As we measured turbine noise at a single fixed distance, at 100 m from the turbine we estimate the propagation as close as possible based on the theoretical circumstances and available knowledge from similar conditions.

The transmission losses (TL) can be expressed as the spreading losses (SL) + the frequency dependent absorption coefficient (∂r):

TL= SL + ∂r

∂ is frequency dependent and is related to the frequency in the equation:

$\partial = 0.036 f^{1.5}$ dB/km (Richardson et al., 1995)

Based on the theory of Urick, 1983, the transmission losses in the free acoustic field are according the 20 log distance model, which is called a spherical spreading. In shallow water condition, such as around the OWEZ location the propagation approaches cylindrical spreading would be between 10 and 15 log distance model. For a more accurate calculation, a “ray-tracing” model has to be applied. Details on the propagation models are given by Urick (1983). Additional complications are the absorption losses, reflections losses of sound reflected on the seabed and water surface. The losses related to the frequency range of the sound can be ignored as the losses of turbine noise <1 kHz will be 0.1 dB km^{-1}. So, in shallow water the propagation of low frequency sound in the range of 0.1 to 1 kHz, such as turbine noise, can be much higher than sound around 10 kHz.

In Thomsen et al., 2006, an estimate on transmission loss is reported based on a model of Thiele (2002). This model is developed for North Sea & Baltic waters with a water depth up to 100 m, substrate based on sand and wind speeds < 20 knots:

TL = (16.07+0.185 FL) (Log(r/1000m) +3)+(0.174+0.046 FL+0.005 FL^2)* r

(FL = 10log (f/1 kHz; 1 m - 80 km, frequency f in kHz from 0.1 kHz - > 10 kHz)).
The transmission losses are given for the spherical and cylindrical model and the intermediates per frequency (Figure 6).

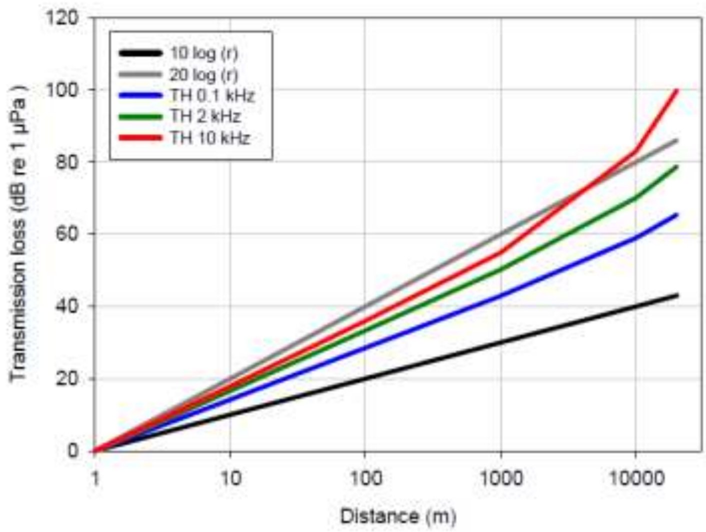

Figure 6 Transmission loss models according spherical (20 log R) and cylindrical spreading (10 log R) and the models for 0.1 and 2 kHz according Thiele (2002) in Thomsen et al., 2006.

According the model of Thiele the transmission loss is intermediate between spherical and cylindrical spreading for 100 Hz. At this frequency the model estimates 4.5 dB losses at double distance with 9 dB at 500 m from the turbine with an approximate attenuation of 15 logR. As this model was used for similar North Sea conditions (Thomsen et al., 2006) we used this prediction to estimate the distance where turbine noise became masked by the ambient noise level.

The water depth in the measured positions of 18 m can be marked as a shallow water condition, which implies that wavelengths of 4 times the water depth will not propagate and are cut-off. The exact cut-off wavelength depends on the sound velocity in water and in the sediment. Sound velocity in the sediment can be ignored on solid sediment conditions, applicable to the OWEZ area. The cut-off frequency is according the formula:

$F_0 = V_w/4D)$

When a sound velocity of 1500 $m.s^{-1}$ is assumed the cut-off frequency will equal 20.8 Hz. The sound energy may still be present as local pressure or particle displacement, but propagation of waves below this threshold is not possible. Frequencies present in the structure-borne path can also be developed outside the predicted turbine spectrum and originate from two auxiliary engines used to tune the nacelle and the rotor blades to the wind. These could also add tonal contribution above the 300 Hz range of turbine noise, which could propagate over longer distance and might have a stronger effect to marine animals. All noise producing engines of the wind turbine structure are directly mounted on the steel foundation without vibration isolators and the noise from these sources is accumulated through the structure-borne path into the sea, assuming an omni-directional propagation. The distances of adjacent wind turbine positions towards the WTG27 measurement location are 581 m to WTG26, 711 m to WTG28, 1074 m to WTG 19 and 825 m to WTG 34. We don’t expect adjacent wind turbines will add to the noise measured 100 m east of WTG27. Other noise sources contributing to the background noise level are of shipping. We monitored the shipping activities in the area around the OWEZ wind farm by use of the Automatic Identification System (AIS). The ship’s identification system is based on a transponder system mounted on the vessel, which transmits data of ship identification, destination, momentary position, sailing speed, all to be received ashore. We positioned a receiver on the IMARES rooftop of the IMARES laboratory (Section 2.4) and logged the AIS-information of shipping activity around the OWEZ area for a period of two years, starting 2011.

A randomly selected daily AIS-record from this database, of 24 August 2011 (Figure 7) shows a mixture of shipping activities of fishing (orange), survey/support (green marker) and a passenger ship (yellow marker) and a hopper dredger (pink marker) as part of yearly returning beach nourishment north and south of the OWEZ area. The AIS-record confirms the registrations made in the T0-phase of the acoustic measurements (de Haan et al., 2007a). In this report the measured noise levels in the area of the planned OWEZ construction site matched the Wenz reference qualification of “heavy ship traffic” (Wenz, 1962). The report showed that the coastal area around OWEZ is intensively used by shipping of different kind with deviations of broad-band background noise varying as much as 10 dB.

At present a new shipping activity, related to wind energy production is added to earlier reported activities. Fast-sailing catamarans, type “WindCat” are daily used to transfer personnel to wind turbines for maintenance and repair (Figure 8).

The contribution of these shipping noise sources will be identified when possible and weighed against the noise characteristics of wind turbine noise.

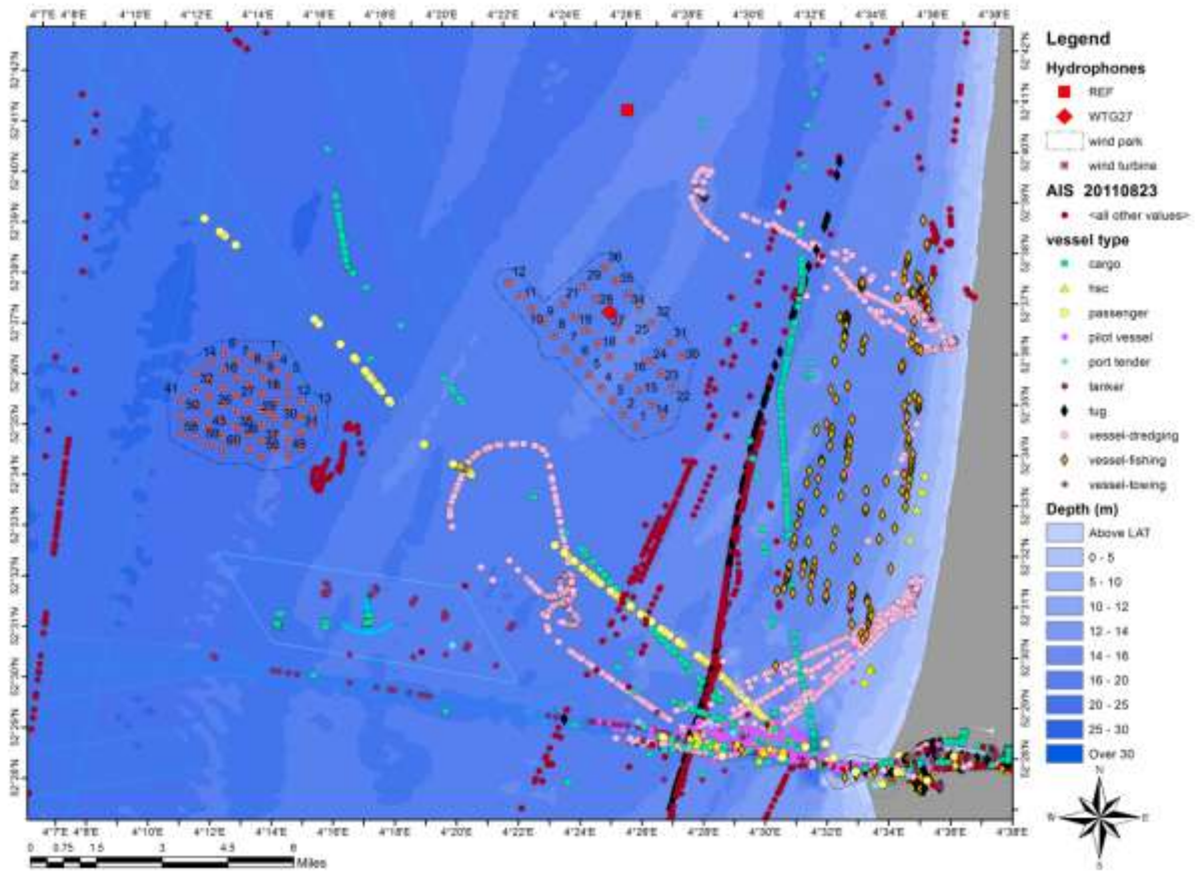

Figure 7 A randomly selected AIS-record with the shipping activity over 24 hours on 24 August 2011 around the OWEZ wind farm area.

Figure 8 Catamaran vessel (type "WindCat") used to transfer personnel for maintenance and repair to wind turbine terminals (particulars: Design 2010, constructed of aluminium. Dimensions: length overall 18.0 m x width 6.1 m x depth 1.8 m. Main engines 2 x MTU V8, 960 HP each with Servogear gearboxes. Propulsion 2 x Servogear variable pitch props with Scanmar controls).

1.6 Assessment of the effects of turbine noise and available reference tools

Knowledge on the effects of sound in general on the hearing sense and the detection system is limited. Marine animals use sound to communicate, forage and navigate and are likely to be disturbed by noise in their environment, and intense sounds may cause negative physiological, auditory, and behavioural effects (Richardson et al., 1995). Data on the characteristics of underwater noise developed by offshore wind farms at the scale similar to OWEZ are few and limited. Madsen et al., 2006 reviewed the acoustic data of a number of cases built in the first phase of offshore wind farm technology, including the two largest offshore wind farms off the Danish coast (Horns Rev1 160 MW and Nysted 166 MW). They reported that noise levels were low and that measurements at 100 m from a turbine did not exceed 120 dB re 1 μPa^2 (RMS) and peaked in the low-frequency range of 60-200 Hz, with some sharp peaks at 60 and 180 Hz indicating tonal type of contributions.

1.6.1 Auditory thresholds and hearing boundaries

Southall et al., 2007 reported the hearing thresholds for marine mammals and introduced the M-weighing filter to compensate for the lower sensitivity at the lower and upper ranges of the hearing spectrum. Toothed whales were divided in classes relative to their hearing and echolocation sonar characteristics and based on reported auditory thresholds hearing boundaries were defined. For main marine mammals categories boundary parameters were defined to be used in the M-weighing filter function. For harbour porpoise these boundaries were 200 Hz and 180 kHz and for pinnipeds in water 75 Hz and 75 kHz. As at the time of this development data on hearing impairment mainly depended on bottlenose and beluga the M-filter function (Figure 10) is rather conservative to animals with steeper cut-off trends, like harbour porpoise and harbour seal.

The auditory thresholds of harbour porpoise (*Phocoena phocoena*) and harbour seal (*Phoca vitulina)* (Figure 9a and 9b) are based on 50 % detection levels derived from the study of Kastelein 2010a (harbour porpoise) and Kastelein et al., 2010b (harbour seal). The curves show a decrease of 70 dB and 20 dB for respectively harbour porpoise and harbour seal in the expected turbine frequency range and confirm the requirement of a weighing filter not as conservative as the M-filter function.

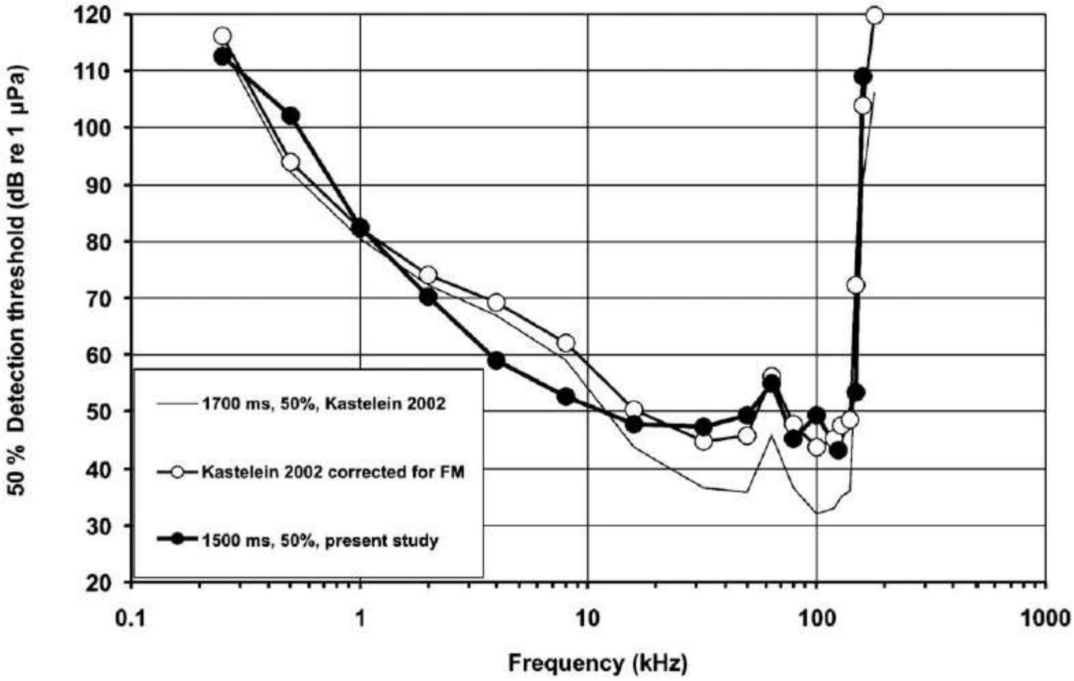

Figure 9a Overview of detection thresholds for harbour porpoise (Phocoena phocoena) with frequency-modulated tonal signals (Kastelein et al., 2002) and was corrected to match the study with various signal duration (Kastelein et al., 2010a).

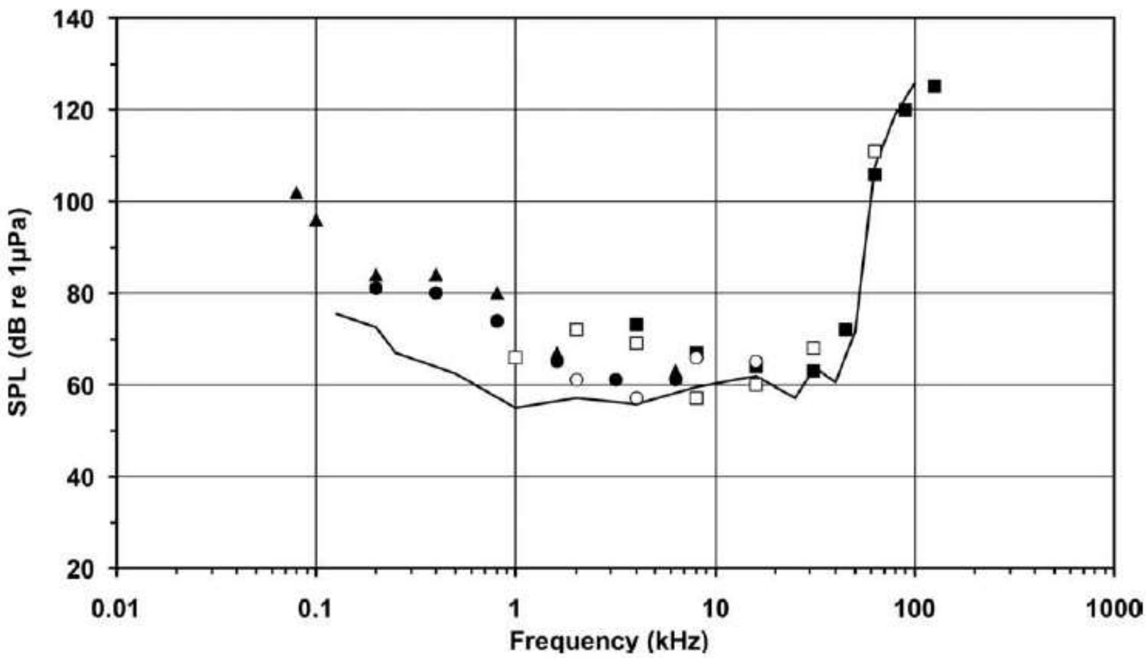

Figure 9b The average detection thresholds for harbour seal based on two animals (Kastelein et al., 2009a and b) and pure tones and 900 ms narrow-band FM displayed the outcome of other studies Møhl, 1968 (■); Terhune, 1988 (□); Turnbull and Terhune, 1993 (o); Kastak & Schustermann, 1998 (▲), Southall et al., 2005 (○).

1.6.2 Weighing method and limitations

The weighing according the M-filter function proposed by Southall et al., 2007 (Figure 10) is rather conservative to animals categorised as "high-frequency specialists" like harbour porpoise. Since this proposal the application of this filter, in particular to harbour porpoise was questioned. Instead the weighing according the hearing thresholds, in particular in the range where the sensitivity is sharply reduced, is regarded as the most appropriate approach. For these circumstances the weighing of turbine noise against the hearing curve is followed according to the recommendation of Verboom et al., 2012, which are based on the hearing curves by Kastelein et al., 2010a and b (Figure 9a and 9b).

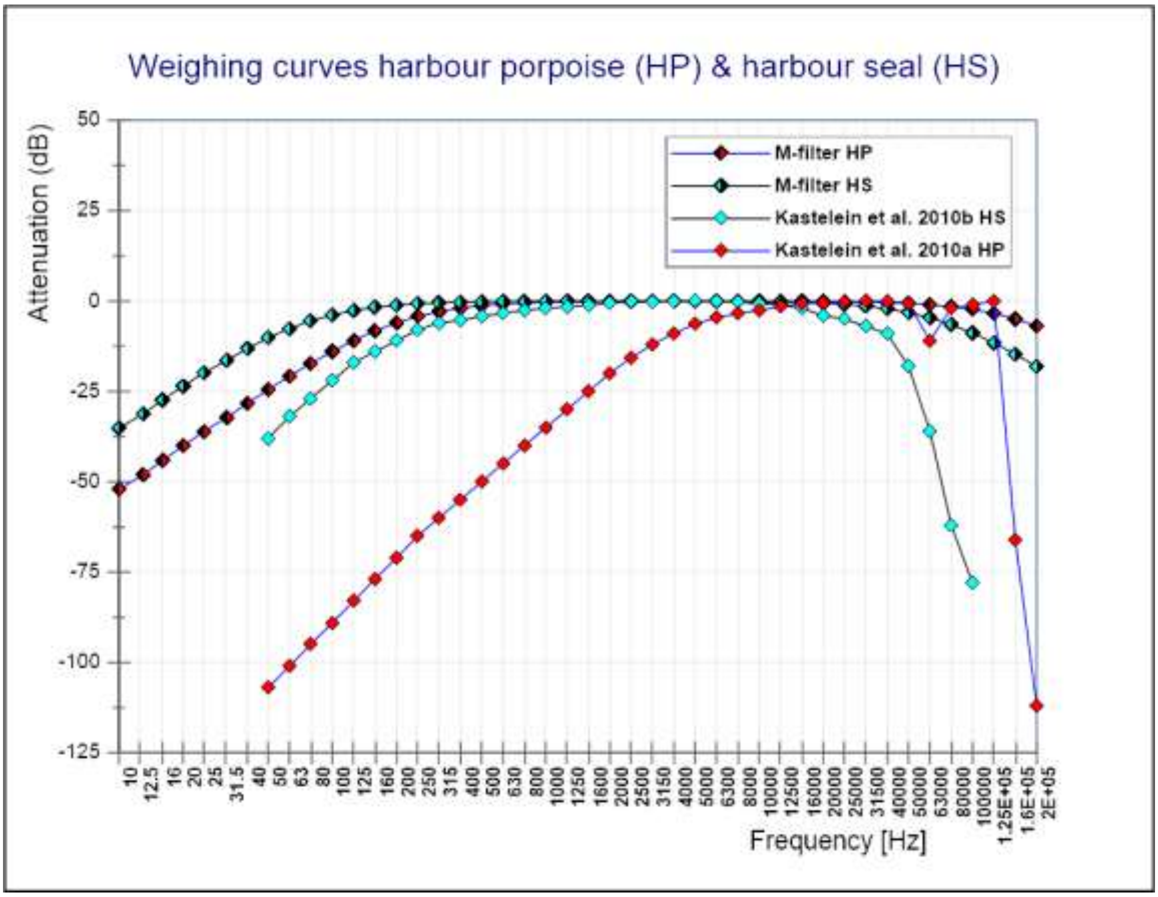

Figure 10 Weighing models for harbour porpoise and harbour seal according Southall et al., 2007 (M-filter) and Kastelein et al 2010a and b, proposed by Verboom et al. 2012.

1.6.3 Threshold references of temporary hearing losses in marine mammals

The noise of turbines is likely to peak in the lower sensitivity range of the auditory range and the produced levels are not likely to impair hearing losses (Madsen et al., 2006). Although these noise levels were found low, the expected growth of offshore wind production (37 times the present offshore wind power production) and the spreading of wind farms over a wider area of the North Sea are motives to carefully address the long term exposure of noise produced by turbines.
Studies on the auditory effects focus on the threshold range where the hearing sensitivity is temporarily reduced (Temporarily Threshold Shift ≈TTS).

TTS-analysis introduces a number of variables/factors that all play their role in the origin of TTS, such as:

- type of sound/noise to which the animal is exposed and the frequency range where the noise peaks;
- the Sound Exposure Level (SEL), which is the accumulated exposure level determined by the Sound Pressure Level (SPL) and the duration of the exposure (in dB re 1μPa^{2}s);
- the interval time between the exposures.

Reference data on TTS in marine mammals exposed to low frequency noise such as the noise produced by turbines are not available. The references closest to this frequency range are the TTS-studies on harbour porpoise and harbour seal of Kastelein et al., 2012a and b. In these studies the occurrence of TTS was determined against a 4 kHz 1-octave centered "white noise" with different combinations of SPL and exposure periods. The results illustrated in Figure 11a and b are based on the exposure of a harbour porpoise and a harbour seal to three different sound pressure levels (SPL 124, 136 en 148 dB re 1 μPa^2) all at a six incrementing exposure periods (7.5, 15, 30, 60, 120 en 240 minutes). Pre and post auditory thresholds were measured and the difference represents the TTS-value in dB.
Kastelein et al., 2012 concluded that the sound pressure level and exposure duration do not play an equal role. The regression angle of the TTS-trends depends on the SPL of the fatiguing noise and shows that TTS-onset is most sensitive at low SPL and longer duration.

1.6.4 TTS-on set assessment and selection of references

A single control to measure TTS in a broad exposure range as proposed by Verboom et al., 2012 is discouraged by the Kastelein 2012 conclusion. Following the aim to assess long-term effects of turbine noise exposure the TTS-onset reference was adapted to the expected turbine noise level (SPL 124 dB series, Figure 11a). The trend of TTS-series results in a TTS-onset in harbour porpoise of 141 dB 1 μPa^{2}s (Figure 11a) and 132 dB 1 μPa^{2}s after weighing.

For harbour seal the TTS series based on SPL 124 dB did not lead to a conclusive TTS-onset level (Figure 11b). Instead the SPL 136 dB series is the best match, with a TTS-onset reference of 163 dB re 1 μPa^{2}s. For harbour seal the weighing does not lead to a reduction, both weighed and unweighed results are equivalent.

1.6.4.1 Other noise sources

Noise sources of shorter duration or with sound levels > 124 dB will be assessed using the average TTS-onset in harbour porpoise of 150 dB 1 μPa^{2}s, as proposed by Verboom et al., 2012. For harbour seal the proposed reference of 163 dB re 1 μPa^{2}s will be used unless the SPLs exceed the SPL 136 dB series.

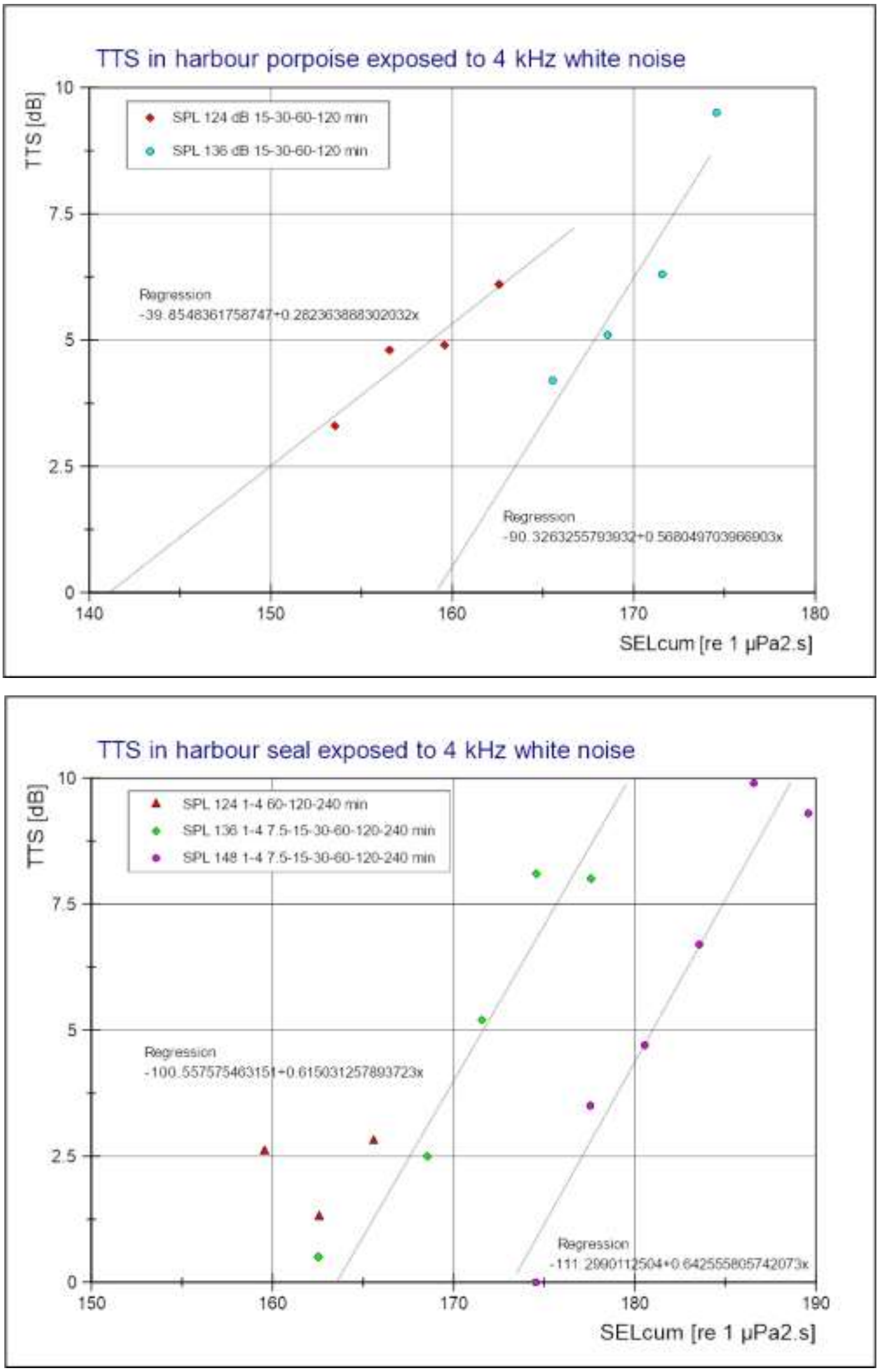

Figure 11a and b Unweighed TTS-results and onset trends for harbour porpoise (upper) and harbour seal (lower) according Kastelein et al., 2012a and b.

The advantage of using the references for the auditory thresholds (Kastelein et al., 2010) and TTS-studies (Kastelein et al., 2012a and b) is that they are based on similar conditions and methods and conducted with the same animals, although the numbers are limited to single specimen.

1.6.5 Limitations and uncertainties in the TTS-assessment

There are a number of uncertainties and limitations in the proposed methods:

- The TTS-onset are based on a fatiguing noise (4 kHz 1-Octave white noise), while the turbine noise frequency range is ≤200 Hz range;
- The characteristics of the fatiguing type of noise ("white noise"-type) and turbine noise are not similar (tonal structure);
- Available literature on TTS-onset in the frequency range of expected turbine noise range (0.2 kHz) is lacking;
- The TTS-references are maximised to 240 minutes and do not cover long term exposures, while exposures >240 minutes are likely to produce a stronger effect as indicated by Kastelein et al. 2012;
- The TTS and auditory studies are based on a single specimen;

TTS in bottlenose dolphin reduced at 3 kHz and Finneran et al., 2010 showed a declining trend of 40 dB at 200 Hz, which matched the auditory threshold curve (Figure 27). As these species have a similar drop-off in the lower frequency range, we assumed this approach valid for the target species of the assessment. The auditory thresholds of harbour porpoise and harbour seal show a decrease of respectively 62 dB and 8 dB between 0.2 and 4 kHz.
Based on the declining TTS-trend in bottlenose dolphin we applied a 30 dB compensation. Note that a reduction of 10 dB increases the time to reach TTS-onset with a factor 10. For harbour seal there is no support in literature to apply such a reduction.

1.6.6 Hearing abilities of fish and the effects of man-made noise

Many fish species are sensitive to low-frequency sound (Hawkins, 1981) and have the ability to produce sound to communicate. Fish are using two sensing organs, the inner ear to detect sound and the lateral line system to detect particle motion. "The evolutionary history of hearing is a rich and fascinating pageant. The inner ear and the closely related mechano-sensory lateral line show a tremendous diversity among living and fossil vertebrates" (Braun & Grande, 2008). This diversity statement indicates a wide range of specialists in the perception of sound, the hearing sensitivity and frequency bandwidth.
Fish are divided into two main groups in terms of sensitivity to sound, "hearing generalists" and "hearing specialists". Most hearing specialisations have a swim bladder modification in the background. The gas-filled swim bladder organ is used as controlled buoyancy to manoeuvre vertically in the water column. Chapman & Hawkins, 1973 reported the auditory thresholds for Atlantic cod (*Gadus Morhua*) and concluded that the swim bladder has as an accessory role in the perception of sound. An additional function of this organ is that it is used to enhance the sound perception, but also to produce sound to communicate (Hawkins, 1981). Fish has the ability to contract the swim bladder by muscle tissues oscillations, which causes a controlled oscillating discharge and as a consequence an oscillating sound production. Most teleost fish have swim bladder specialisations that enhance the sound perception in terms of frequency bandwidth and sensitivity, but Sand and Enger, 1973 showed that fish with unmodified swim bladder systems like cod also have the ability to enhance sound perception. The importance to fish of time varying signals is shown by the fact that most fish sounds are made up of trains of pulses (Hawkins & Rasmussen, 1978). Hawkins, 1981 discussed the aspect whether fish would distinguish sounds on the basis of time structure rather than frequency structure, and suggested that they may have the ability to filter time patterns from background noise. So auditory thresholds based on detection of temporal structures could be much lower. However, most auditory experiments have been

done with pure tones, which have little meaning for fish. The fish auditory system seems to be capable of temporal summation. Fay, 1998 suggested that the auditory system of goldfish (*Carassius auratus*) is especially well adapted to temporal resolution. He showed that this species can discriminate very rapid amplitude modulation using temporal variations in the signal rather than spectral cues and concluded that this perceptual behaviour is shared with humans and other vertebrates.

Information on critical ratio is only available for cod (*Gadus morhua*) and salmon (*Salmo salar*). Available information on critical bandwidth concerns mainly higher frequency studies not applicable in this perspective. Examples of fish sorted as hearing specialists are clupieds, such as Atlantic herring (*Clupea harengus*) and sprat (*Sprattus sprattus*), while dab (*Limanda limanda*) is known as hearing generalist with the lateral line as main sensing system. The auditory thresholds of three fish species, Atlantic cod (*Gadus morhua*), Atlantic herring (*Clupea harengus*) and dab (*Limanda limanda*) are illustrated in Figure 12.

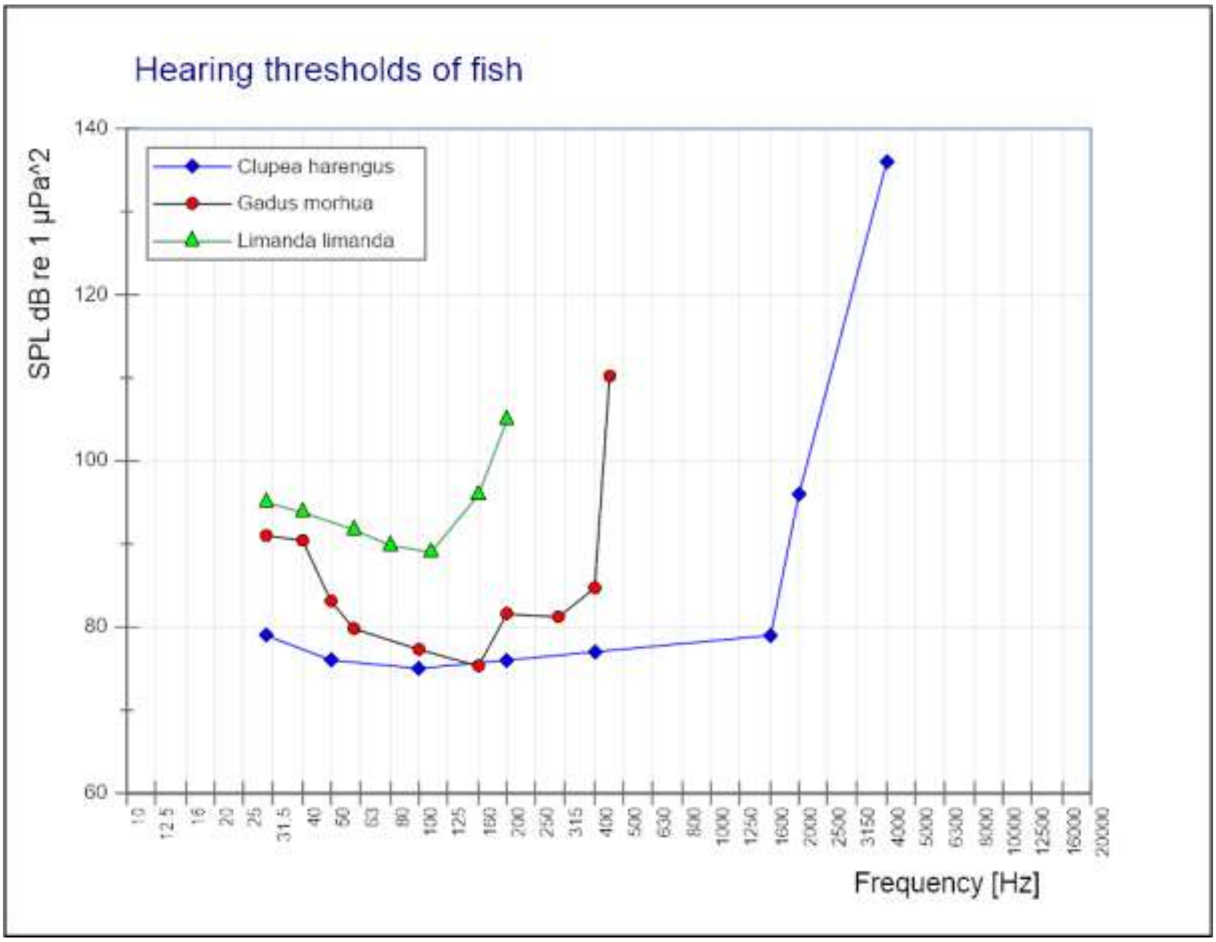

Figure 12 Auditory thresholds of three fish species, Atlantic Cod (Gadus Morhua) produced by Chapman and Hawkins, 1973, dab (Limanda limanda) produced by Sand and Enger, 1973, and Atlantic herring (Clupea harengus) published by Enger, 1967.

The threshold for cod was based on 43, for herring on 36 and for dab on 3 specimen. Chapman and Sand, 1974 found that plaice (*Pleuronectes platessa*) and dab (*Limanda limanda*) were sensitive to sounds in the frequency range from 30 to 250 Hz with highest sensitivity around 110–160 Hz. The report however also suggests that dab (*Limanda limanda*) responded to particle motion rather than pressure.

The auditory thresholds of Atlantic cod and Atlantic herring were used in the analysis of the effects of turbine noise on these species.

Several reports suggested that herring would also be able to detect ultrasound type of signals (>20 kHz) as they would then be able to detect the echolocation sonar of their predator (Mann et al., 1997, Wilson and Dill, 2002). However, Mann et al., 2005 applied the Auditory Brainstem Response method (ABR) to measure the auditory threshold of Pacific herring (*Clupea pallasii*). They determined no response in the ultrasound range, but mainly between 100 Hz and 5 kHz and concluded the test signal of the earlier ultrasound studies must have had a broad-band frequency element.

1.7 Developments of methods for acquiring turbine noise

The first pilot results of operational OWEZ wind farm noise, executed from a vessel, were reported in 2008 (de Haan et al., 2008) and showed that wind farm noise at low wind speed condition could not be detected at distances > 200 m. Incidental noise of auxiliary engines produced by the yawing of WTG11 after maintenance was received at 1100 m and peaked at 1600 Hz with 13 dB above the noise level (Appendix F First measurements 2007). As the methods of measuring the noise from off a vessel would hamper recordings at nominal turbine power condition (wind speed $15.m^{-s}$) a self-contained measuring system, carried on a floatation was developed in 2009.

There were two measuring systems developed:

- Two identical self-contained hydrophone/recording systems for short-term operations (36 hours). One moored in close range of a wind turbine (100 m) and a second in a reference location measuring background noise;
- A permanent system measuring data over a longer time period of 12 months, installed at larger distance from the turbines (400 to 500 m).

The short-term hydrophone systems supported a measuring period of 36 hours at minimum and covered the hearing sensitivity range of harbour porpoise up to 150 kHz. Meanwhile, data on similar projects showed that wind turbines produced mainly noise at frequencies <1 kHz, which enabled a lower sampling rate with a lower storing capacity of the recording equipment. Three short-term sessions were foreseen at three different wind speed categories. The final measurement system consisted of a submerged part with the recording and measuring equipment fixed on a frame connected to floatation at the surface to recover the equipment and to carry a GPS receiver to synchronise the measurements to UTC.

In 2010 the permanent hydrophone system was installed on the OWEZ meteo mast at the west side of the OWEZ area and powered from the local facility. The distance between the hydrophone and the closest wind turbines was 541 m to WTG7 and 391 m to WTG8. The intension of earlier work plans was to monitor simultaneously the noise in a permanent position over a year as well as to record samples at closer distance from a turbine. The basic idea for a permanent hydrophone channel was more a strategic than a technical motive as the meteo mast structure contained a number of unknown self-noise sources. The instrumentation on the meteo mast contained a twin set of bird radars to monitor the tracks of birds around the wind farm and hardware of meteo sensors and ADCP equipment. To buffer the incidental 220 V AC power failures the supply part of the equipment is provided with a UPS (Uninterruptable Power Supply) with frequency converters producing high-frequency interference in air and inductions on the AC power network. We achieved the highest possible immunity of the sensitive acoustic equipment on which very low level of hydrophone voltages were measured and digitised, but were not able to eliminate to a 100 % level. Some 50 Hz interference had to be accepted. At high wind speed conditions the flexible mechanical structure of the 120 m high meteo mast dangles in the wind and the displacements cause impulsive noise of parts that were not mechanically secured (such as the fixation of the hoists). As the meteo mast could only be visited at sea sates < 1 m the contribution of self-noise at higher wind speeds

could not be determined and remained unknown. The permanent hydrophone equipment consisted of two measuring modes, a peak detector channel, triggered when the noise would exceed a threshold and a 10 min interval channel, both operating simultaneously. The development did cost more effort than foreseen in all phases of installation, maintenance and data transfer. The system produced 9 months of data, and failed at the end of 2012. To assess the 700 Gb of data an automated software functionality was needed, but this tool was not available before the start of the close range measurements in 2013. The manually sampled data showed a huge contribution of ship noise, of which some were identified fishing vessels of which the chains from the beam trawl gear could be clearly heard. Fishing inside the 500 m boundaries is not permitted, the VMS (Vessel Monitoring System-records of 2010 (van Hal et al., 2012), however, showed that fishing vessels fished very close along the western boundary of the OWEZ wind farm. These observations were confirmed by the noise of fishing gear recorded at 20 m from the OWEZ meteo mast. The sound of the chains of fishing gear was detected in the noise of passing vessels indicating a range of at least 50 m from the received position.
With the data collected at the meteo mast position the propagation range of turbine noise up to a distance of 391 m can be determined (distance between the hydrophone deployed near the meteo mast and the closest wind turbine, WTG8). The value of this assessment is limited as the recordings are not supported by a simultaneously recorded background noise channel from a second channel positioned in a reference position.

Since 2011 workshops among institutes active in the acoustic field were held in order to develop a common guideline for methods and analysis of wind farm related noise. These workshops took place in Delft in February 2011 and in Hamburg, June 2011. Imares took part of these meetings. TNO organised the first meeting and published the final guidelines in the report of de Jong et al., 2011 (Section 4.6.4, measuring underwater noise during the operational phase).

The main summarised TNO-recommendations relevant for this project are:

- At least two fixed measurement locations. One in a reference location at a distance of 4 km from the wind farm. A second at a distance of 100 m from a turbine;
- Multiple observations with representative turbine operations with a period of at least 24 hours.
- The observations can be organised in intermittent periods of 5 s per minute to reduce the amount of stored data;
- The noise will be analysed as broad-band Sound Pressure Level averaged over at least 5 s (SPL_{5s}). Of these samples the spectra will be analysed Third-Octave band spectra (20 Hz-20 kHz). The resulting spectra will be reported in a frequency/time graph with the Third-Octave spectra on the Y-axis. Narrow-band analysis in a frequency range of at least 20 Hz to 1600 Hz to detect gearbox frequencies and tonals;
- Additional information on the physical conditions, turbine production data.

The set-up of the applied IMARES methods meets these guidelines with a single exception: We did not report the data in a frequency/time graph, as the amount of data required computer arithmetic power and memory even outside the range of 64 bit operating systems and 8 Gb RAM memory. Instead we applied Third-Octave analysis over long time intervals (12 hours) to investigate the frequency domain. A minimum recommended recording period of 24 hours was extended from 36 hours (proposed in the workplan) to a period of 80 hours to reduce the effects of unpredictable changes in the route towards a recording mission, the availability of a support vessel and weather changes. In this way the certainty to meet a nominal power generation condition was increased.
We added the results of the first measurements executed in 2007 to this report (Appendix F First measurements 2007). There are a number of motives to review these measurements and add this as a supplementary outcome:

- Other measurement locations and hydrophone positions were applied:

    - They were executed at the south-western side of the OWEZ area in slightly deeper water (+ 2 to 3 m compared to the position of WTG27);
    - The measurements were executed at symmetrical distances from WTG09 and WTG10 and not opposite a single turbine position (WTG27) as in the present set-up;
- They follow the TNO-recommendation of measuring at multiple locations (de Jong et al., 2011);
- The results represent the condition before the filling of the monopiles with concrete in 2010;
- They were executed at distance of around 500 m, which is presently estimated to be the threshold distance where turbine noise becomes masked in the background noise;
- A clear detection was captured at 1100 m of noise attributed to the yawing of a turbine, which was not observed in the present results in a much closer range (100 m);
- The present acoustic analysis technique further improved and the analysis procedures reported in the progress report published in 2008 did not follow the present acoustic convention/metrics.

As the methods of the first measurements differed from the present method and represent short intervals of 29 s per record the results are proposed as indicators.

2 Materials and Methods

2.1 Measurement positions

Measurements were executed simultaneously in two positions. The first at a 100 m distance from Wind Turbine Generator nr 27 (WTG27), which is situated on the north-eastern inner row of the OWEZ wind farm, 52°37.0122'N and 004°25.2897'E (Figure 2) at a water depth of 18 m. Background noise was measured 7.4 km to the north of the WTG27 location, 052°41.00'N and 004°26.00'E. These data were used as background noise reference not exposed to wind farm noise. The eastern boundary of the sub-lane towards the main shipping lane (Figure 2) lies 4.4 km west of the WTG27 hydrophone location and 7.4 km of the hydrophone deployed in the reference position (REF). The shortest distance from the WTG27 hydrophone to the main shipping lane is 15.5 km.

The measurement location near WTG27 enabled the highest flexibility of vessel operations during the deployment/recovery of the equipment, and had the lowest risk of damage to the turbine moored power cables. The WTG27 measurement location also provided shelter against fishing vessels, which fish closely along the boundaries of the wind farm (VMS-records). The distances of adjacent wind turbines to the WTG27 measurement location were 581 m to WTG26, 711 m to WTG28, 1074 m to WTG19 and 825 m to WTG34.

2.2 Description of measurement equipment and deployment

A functional diagram of the deployed recording system is given in Figure 13. The system consisted of a set of inflatable buoys and a moored section containing the recording equipment and the main anchor. All parts were chosen and rigged to produce the lowest level of self-noise, so no metal connection parts were used. The parts at the water surface consisted of a small float at the far end with a vertical rod, commonly used as floatation on set nets (type "joon"), with a passive radar reflector on top, a buoy type Fender F8, carrying a GPS receiver and a larger buoy type Fender F13. The surface parts were connected to the moored parts using a 14 mm Dyneema braided anchor rope with a breaking force of 145 kN.

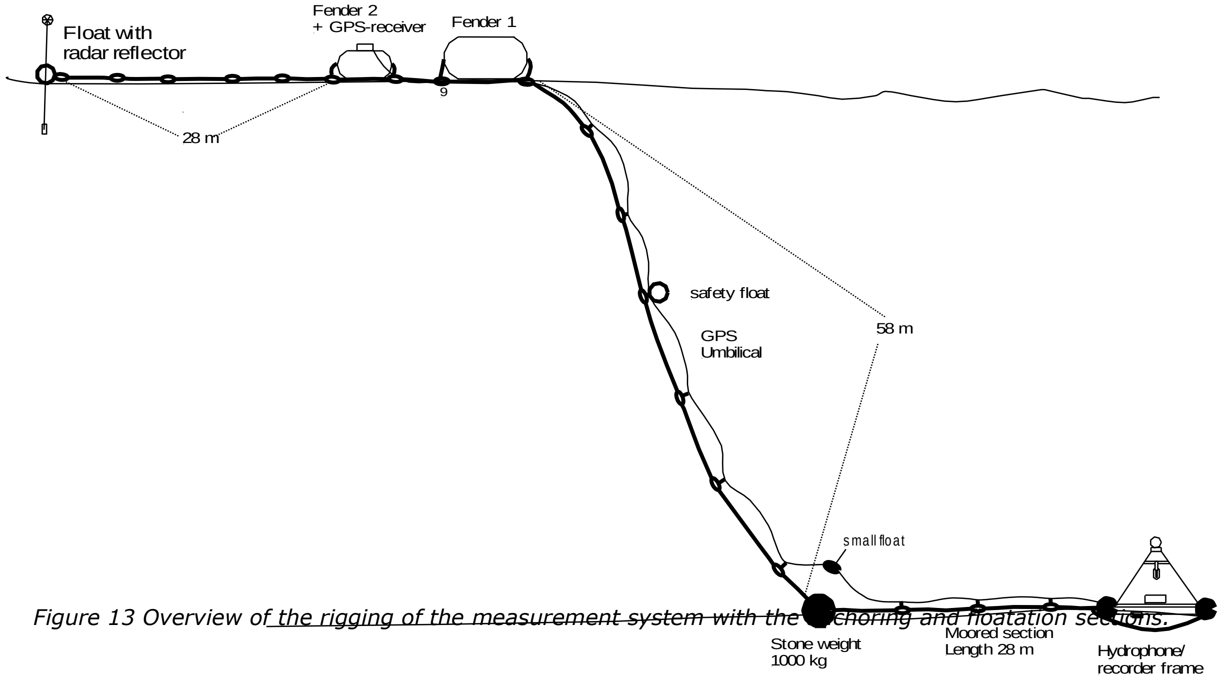

Figure 13 Overview of the rigging of the measurement system with the anchoring and floatation sections.

The moored parts consisted of a stone anchor of 1000 kg, a galvanised steel frame with a square base of 1.4 x 1.4 m (Figure 14) carrying the recording equipment and the hydrophone. To minimise the operational risks a single hydrophone was used, which was fixed in the centre axis 1 m above the base of the frame with the sensor part pointed downward. The recording equipment was built in a stainless steel housing of 350 mm diameter and 220 mm height. Each corner of the square base was provided with concrete weight of 100 kg in total. The overall height of the frame was 1.7 m.
The measurement equipment was deployed using MS "Terschelling" (Figure 14), which is equipped with a Dynamic Positioning Class 2 System, DPS-2, enabling safe operation on high sea state conditions as well as accurate positioning the equipment.

Figure 14 Deck operations on board MS "Terschelling" shortly before the deployment of the equipment in the OWEZ wind farm 100m east of WTG27.

2.2.1 Recording and data conditioning

A RESON TC 4032 hydrophone with a built-in 10 dB pre-amplifier was used for the measurements (hydrophone sensitivity curves are added in Appendix D). The hydrophones were connected to an ETEC EC6073 splitter module, which facilitated as splitter for signal transfer and powering of the hydrophone. The hydrophone signal was conditioned using an ETEC EC6078 pre-amplifier. The high- and low-pass filters were set to a filtered frequency range of 10 Hz to 50 kHz (the filter type is 8-pole Butterworth). The amplification of the signal was set to 16 dB in total (10 dB in the ETEC pre-amplifier and 6 dB in the Avisoft digitizer). The conditioned signal was digitized using an Avisoft Sigma/Delta analogue/digital converter, which was equipped with an anti-aliasing filter to suppress the influence of aliased high frequencies. The sample rate of the measurements was set to 50 kHz. The converter was connected to a USB-port of a mini PC, on which the digitized data were stored as WAV-files in parts of 1800 s elapsed time.

2.2.2 Calibration Reference data

To scale the linear hydrophone voltage to the exponential dB-scale a reference acoustic sound source was used, which produced an accurate level at 250 Hz. Prior to the deployment both systems were calibrated using a certificated sound source, a GRAS 42 AC pistonphone and a Class 1 B&K 2239 Sound Level Meter. The pistonphone is coupled to the hydrophone and the Sound Level Meter is attached to the side gate of the coupling device (Figure 15).

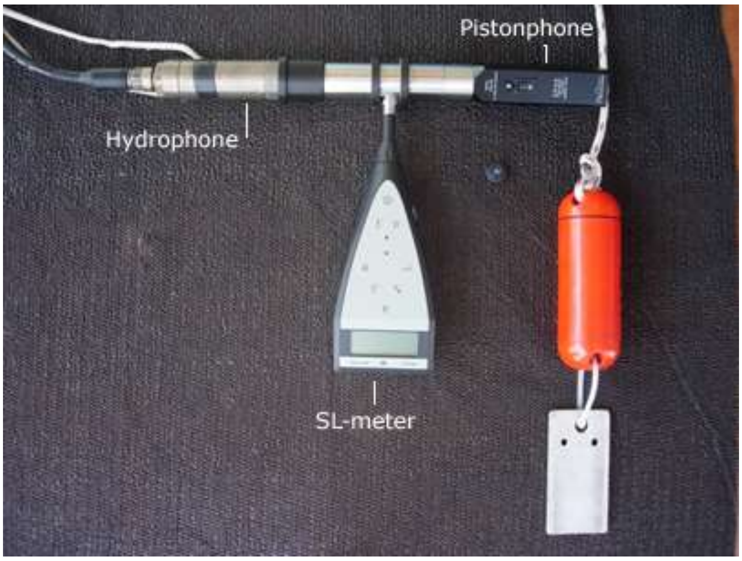

Figure 15 Hydrophone calibration set-up with a Reson hydrophone TC4032 coupled onto the G.R.A.S. 42 AC pistonphone and the sound level meter type B&K 2239 coupled onto the side gate of the coupler. On the right side a 10 kHz Ducane NetMark 1000 pinger occasionally used as reference source on acoustic measurement campaigns.

This instrument was calibrated by the manufacturer on 24 October 2012 (Appendix D). The calibration measurements were executed at the start of each mission with the equipment fully prepared on the deck of the vessel. After completion the equipment was deployed in the given positions. As these data are measured in air the conversion of 20 to 1 μPa^2 referred underwater sound reference implies an addition of 26.02 dB to the monitored values.
An overview of the measured levels of reference data (including a 10 dB gain setting) per mission is listed in Table 1. The reference data showed that on both missions an equivalent level was measured, indicating unchanged performance of both hydrophones at the start of the missions.

Table 1 Reference data per mission

Mission (nr)	Datum	REF File (nr)	Ref level (dB re 20 μPa^2)	Ref level (dB re 1 μPa^2)	WTG27 File (nr)	Ref level (dB re 20 μPa^2)	Ref level (dB re 1 μPa^2)
1	16-01-2013	T0047	129.6	155.62	T001037	130.2	156.22
2	06-02-2013	T0003	129.6	156.22	T0002	130.2	156.22

2.2.3 GPS synchronizing of the PC internal clock

A BTU-353 GPS-receiver was used to receive satellite UTC timing information and to set the PC internal clock to UTC on deviations >1000 ms. The output of the receiver was connected via a serial RS 232 to USB link to the USB gate of the computer. The GPS-receiver was packed in a plastic container and fixed on top of the smallest Fender buoy (Figure 13). The signal connection between the GPS-receiver and the moored equipment was through the twisted pairs of an underwater mini TV cable of 200 m length.

2.3 Timing and wind farm production conditions

The measurements were conducted in two periods/missions, the first (Mission 1) from 16 to 20 January and the second (Mission 2) from 6 to 10 February 2013. The timing of deployment was chosen according the weather forecast with rising wind 24 hours after deployment and reasonable chances of capturing conditions with the maximum power production level of the generator. The measurements covered a period of 83 (Mission 1) and 88 hours (Mission 2).

2.3.1 Wind conditions

In both periods there were low wind speed conditions with the turbine in idle mode. On these conditions the starting effects and occurrence of additional noise or tonal sources were examined. On the first Mission the ideal condition occurred with the wind not scattered but tuned from the east with a force slowly rising over time (Figure 16). On the second Mission the wind was mainly from the north to northeast with the wind increasing shortly after deployment (Figure 17). The wind speed peaked for about 16 hours, starting 6 February 16:40. After this period the wind speed declined slowly over time, causing the WTG27 to stall for 5 ½ hours with zero power on the 9th of February. The wind direction sensor identified as "MET01-South" refers to the sensor mounted on the meteo mast at the south side at 70 m altitude. This sensor was used for wind direction as the sensor of WTG27 does not provide an absolute compass angle.

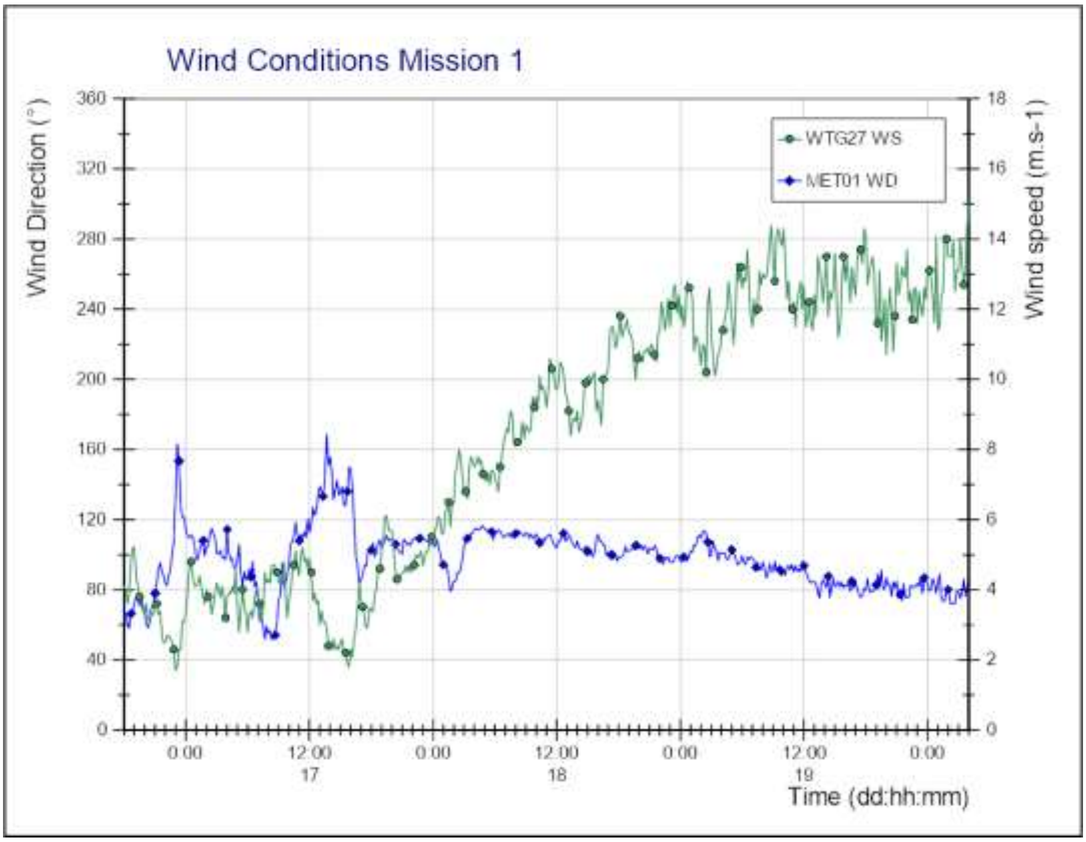

Figure 16 Wind conditions during the first measurement period (Mission 1).

Figure 17 Wind conditions during the second measurement period (Mission 2)

2.3.2 Wind farm operational data

Wind and turbine data were derived from the OWEZ wind farm operator. These data concerned the generated turbine power, rotor rotational speed, wind speed and direction, rotor blade pitch angle and the yawing activity. For all channels the averaged, maximum and minimum values over 10 minutes were provided. The wind and power data were used as reference to the turbine noise data. The rotor blade pitch and yawing operations are controlled by respectively hydraulic and electric auxiliary engines and the indicated activation events were used to identify these noise sources.

2.3.3 Turbine power range

On both Missions the WTG27 turbine reached the maximum power condition. The wind speed conditions and the developed turbine power are illustrated for Mission 1 and 2 in respectively Figure 18 and 19. On the first period the WTG27 turbine power reached its maximum at a wind speed of 14 $m.s^{-1}$ and this condition was reached at the end of the cycle for about 20 hours (Figure 18). Based on the more variable wind conditions the power production on the second period was more diverse and reached the maximum range at 15 $m.s^{-1}$ (Figure 19).

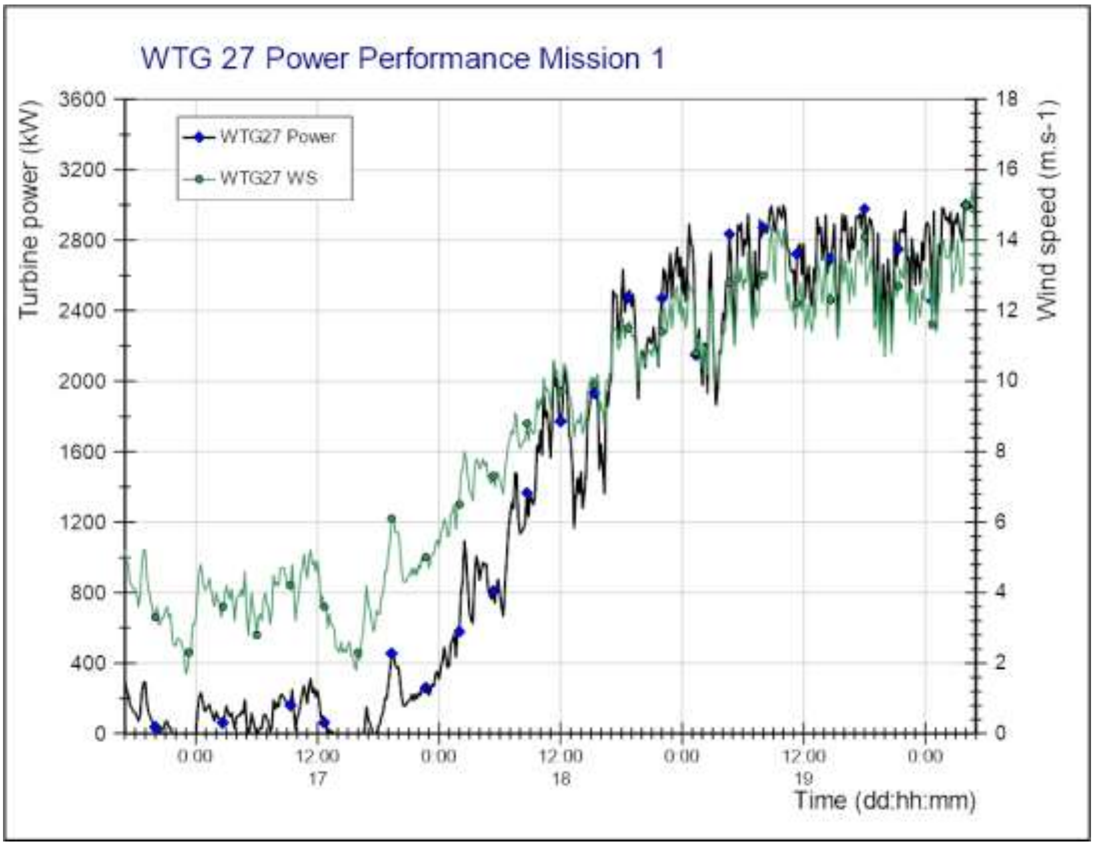

Figure 18 WTG27 turbine power and wind speed (WTG27 WS) on Mission 1.

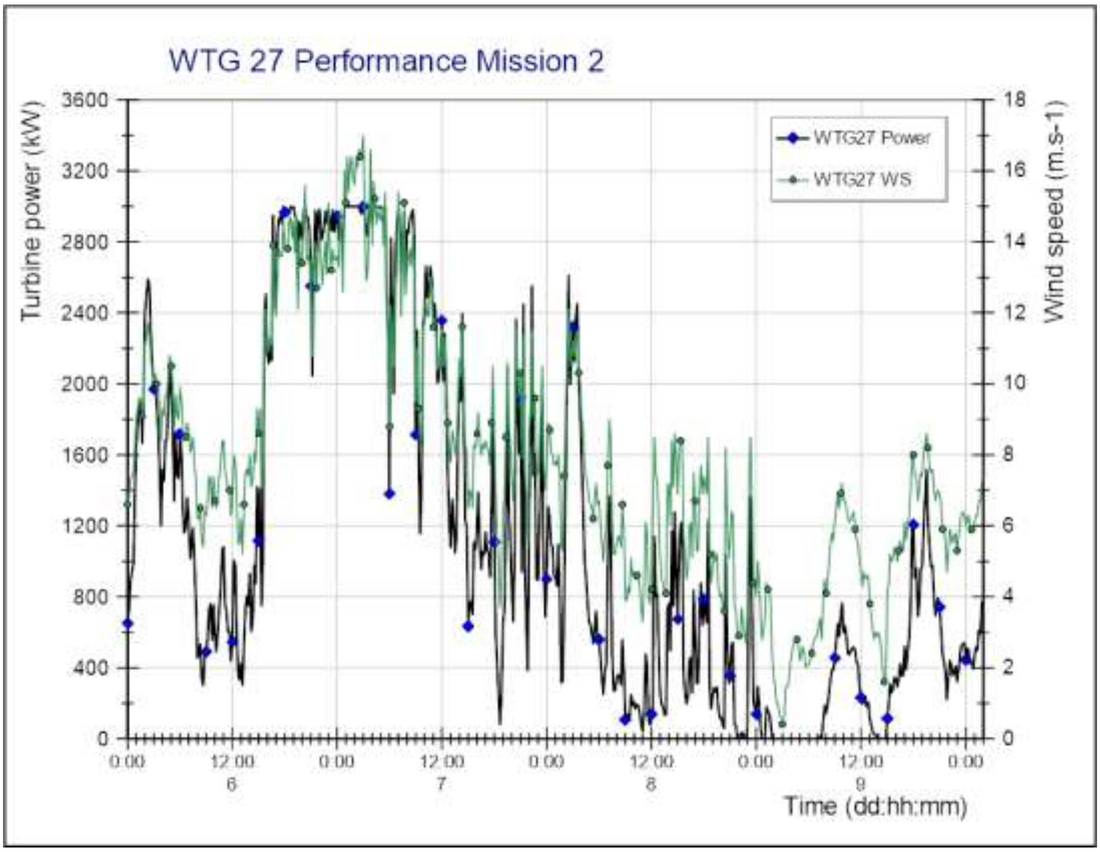

Figure 19 WTG27 turbine power and wind speed (WTG27 WS) on Mission 2.

2.3.4 Wind speed versus power production

The wind speed data from the sensor mounted on the WTG27 nacelle were compared to other wind speed channels to check the relation with the developed power and to justify the sorting turbine noise data as a function of wind speed.

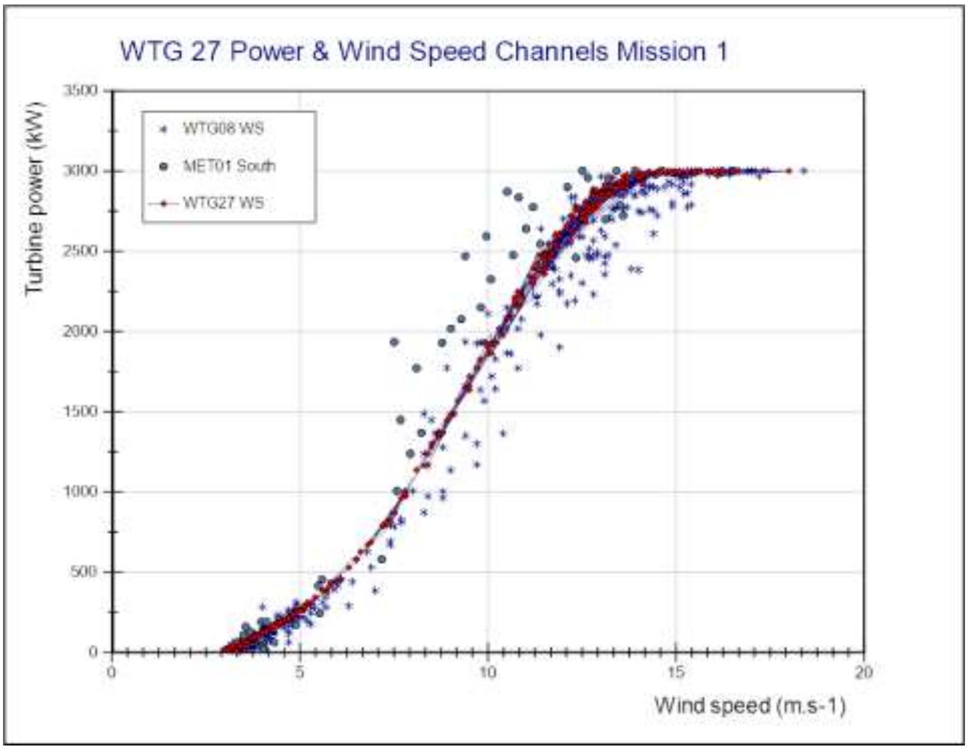

Figure 20 Turbine power as a function of wind speed channels on the first period (Mission 1).

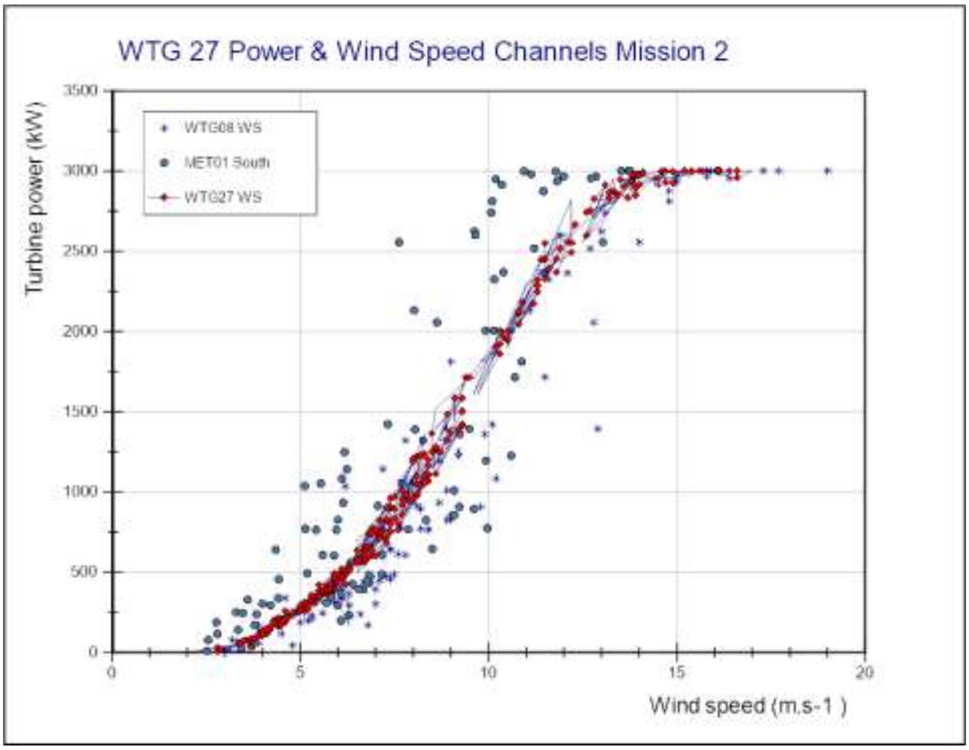

Figure 21 Turbine power as a function of wind speed channels on the first period (Mission 2).

The wind speed data of both periods illustrated in Figure 20 for Mission 1 and Figure 21 showed that the wind sensor of the WTG27 nacelle had the strongest relation with the turbine power.

2.3.5 Wave height Conditions

As a consequence of the different wind conditions in both periods the contribution of the ambient noise differed per period. In the first period the wave height developed under the highest wind speed condition was limited to 0.8 m (Figure 22), while in the second period a similar wind force from northern direction raised the wave heights to a level of 3 m (Figure 23). Under these different conditions the ambient noise level related to sea state was higher than on the first period.

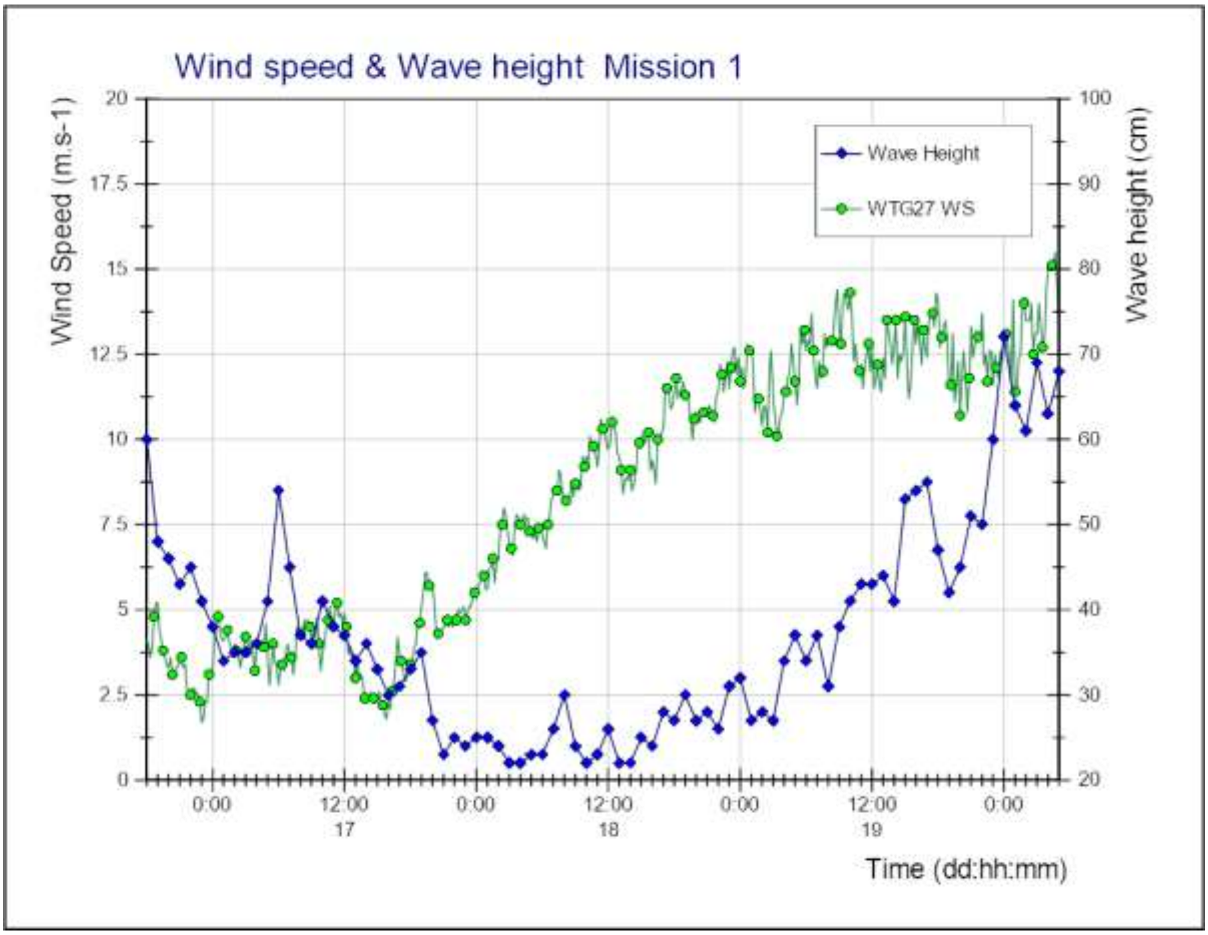

Figure 22 Wave height and wind speed (RWS IJmond station) on Mission 1

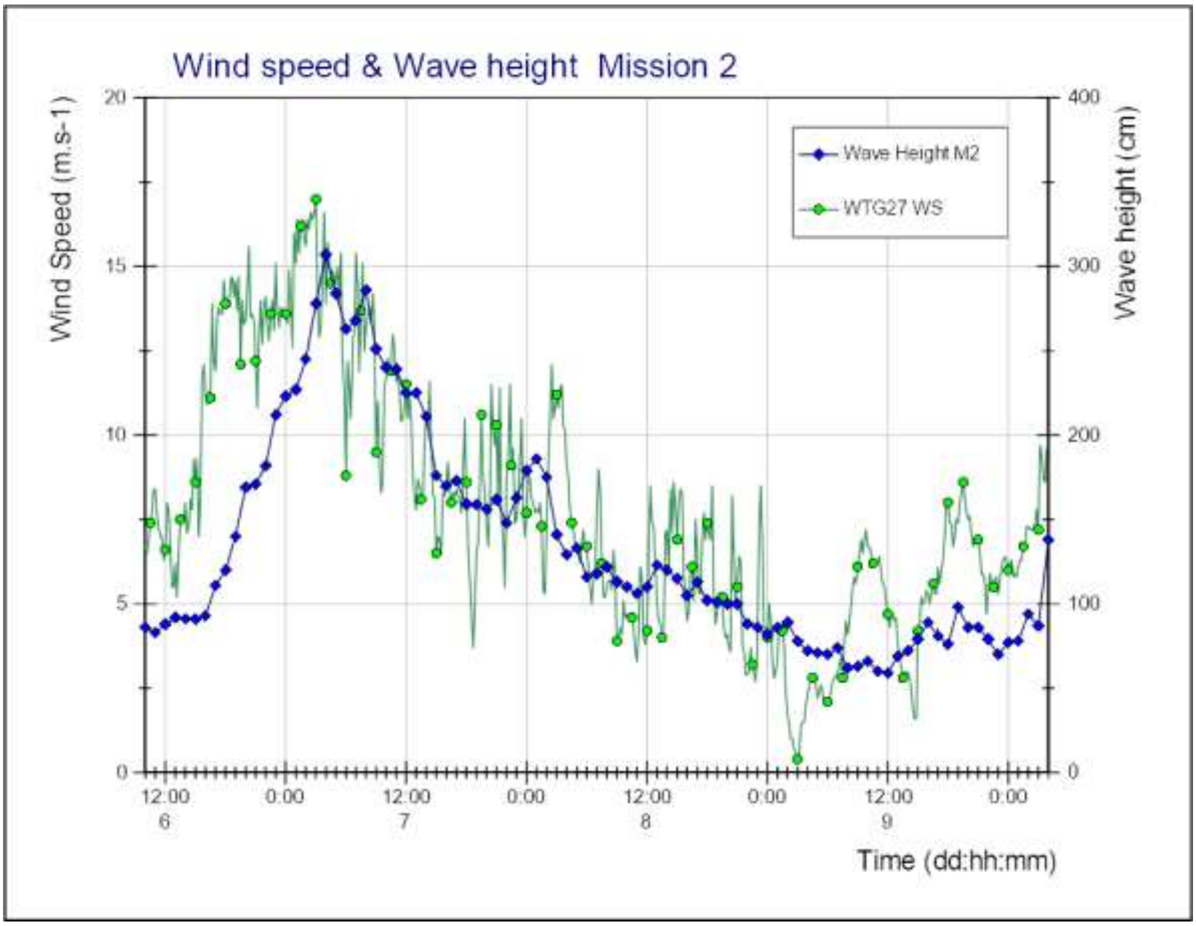

Figure 23 Wind speed and wave height (RWS IJmond station) on Mission 2

2.3.6 Turbine control systems

As mentioned in Section 1.3 the turbine power production is provided with two control systems to protect the turbine against overload conditions and to optimise the efficiency of the production in the lower power range. The angle of the rotor blades and the angle of the nacelle towards the direction of the wind are controlled using two auxiliary engines. An example of one this operation is given in Figure 24.
The rotor blade angle is controlled hydraulically, the angle of the nacelle electrically. The maximum power range of the generator is limited to 3000 kW by the rotor blade angle control and a frequency control system at the turbine side. The threshold of this condition is at a wind speed of 12 to 13 $m.s^{-1}$, above this threshold the maximum power is maximised to 3000 kW.

The overview of Mission 1 (Figure 24) shows the rotor blade angle was active during the low wind speed conditions and at the upper range of the generated power. In order to be able to detect the noise from a fixed time cue the Vestas operator simulated the yawing and pitch control on special request on 17 January 2013. At that particular moment the wind conditions were low and so the background noise level related to sea state, enabling the optimum detection condition.
On the simulated pitch & yawing operation the rotor blades were set to an angle of 60 °, corresponding to the idle mode condition (Figure 24). The yawing activities for the first period are shown in Figure 25 and expressed in seconds of activations per 10 minute period. The illustration shows that yawing occurred throughout the whole period and that the relation with turbine power is not clearly expressed. The data of the yawing event captured on the first measurements in 2007 at a distance of 1100 m is used as indicator (Appendix F First measurements). As this noise level peaked in the 1600 Hz Third-Octave band with 113 dB re 1 μPa^2 it is expected that the contribution of yawing will be clearly detected at 100 m in the present set-up.

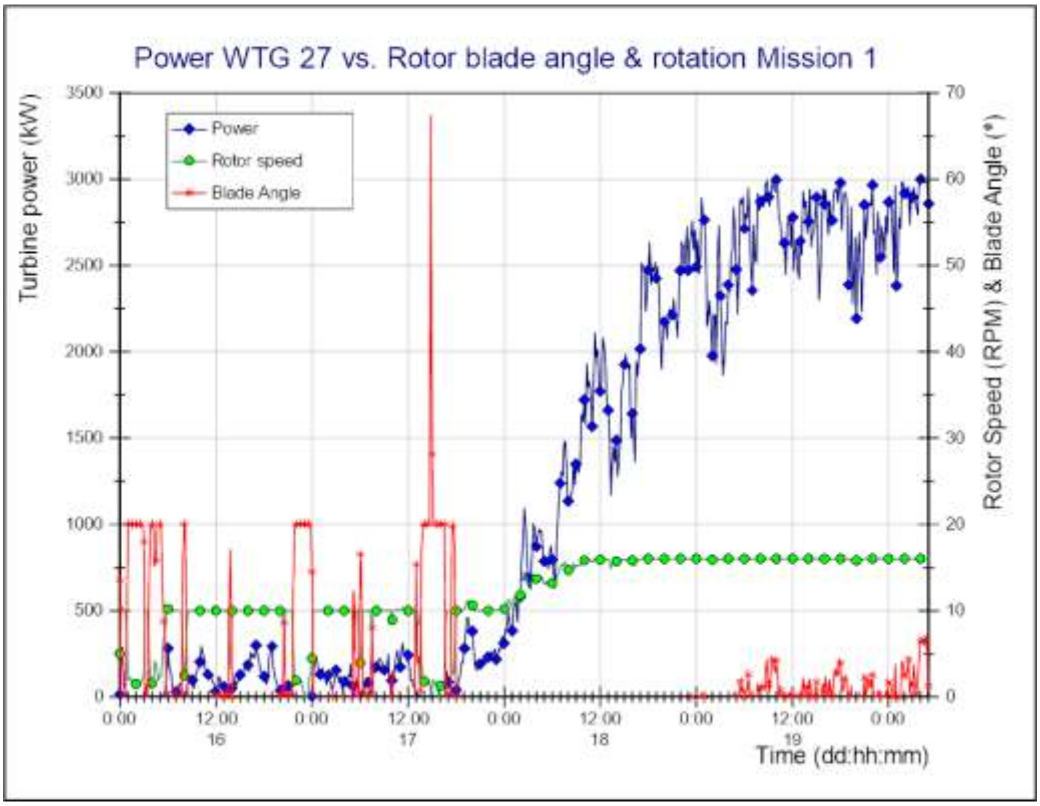

Figure 24 Rotor blade angle operations on the first period (M1)

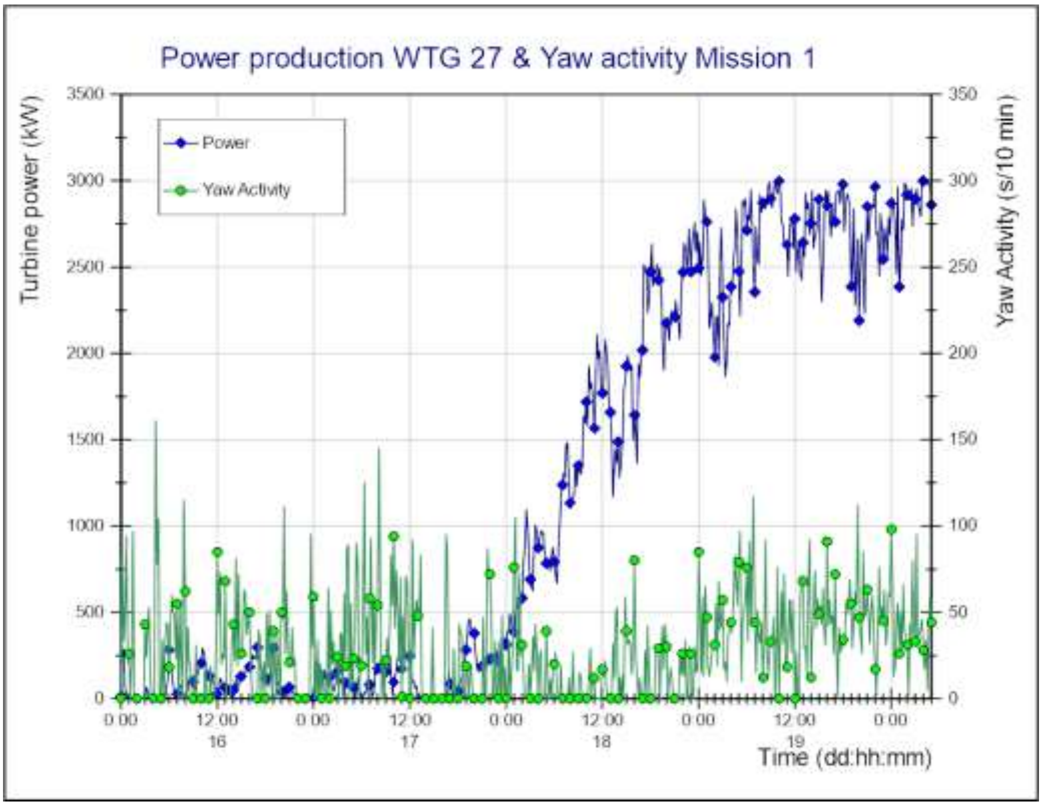

Figure 25 Yawing activity on the first period expressed in seconds per 10 minute time period.

2.4 Shipping activity

The OWEZ area is close to the sea gate to Amsterdam. In this region of the Dutch coast many kind of shipping activities are concentrated. Cargo ships call in to the gateway to Amsterdam or the Tata Steel plant, Velsen. IJmuiden harbour is also one of the four main Dutch fishing ports and the home port for wind farm related shipping. All these shipping activities are most dense around the sea gate entrance (Figure 7) with the boundary of the closest sub-lane towards the main shipping route at 4.4 km west of the measured position near WTG27. The contribution of the shipping activities is geographically expressed in Figure 7 and shows a 24-hours record from the Marine Automatic Identification System (AIS) of ship traffic around the OWEZ area. The 24-hour AIS-record clearly demonstrates that the induced noise from shipping will play a role in the noise signature in the vicinity of the OWEZ location. Two types of sailing activities are distinguished in the analysis, the passing vessels with other destination than the OWEZ site and vessel traffic related to the wind farm energy production.

2.4.1 Wind farm related ship traffic

Fast sailing catamarans, type "WindCat" are used for technical support on a regular daily base between 07:00 till 16:00 hr. This catamaran type of vessel can reach a maximum speed of 30 knots and is propelled by a twin propulsion system consisting of two Volvo D12 motors with each a ZF gearbox driving a Hamilton Jet with foils (Figure 8).

The WindCat shipping activity (ID≈WindCat25) has some basic recurring elements. The operation takes place only in the day-time and only when the sea state conditions allow so (wave height < 1.5 m). On arrival at a WTG-terminal the vessel lands with the bow against the landing gate, it manoeuvers at high propulsion power to provide a safe landing of personnel and equipment pushing the bow against the landing frame to disembark personnel (Figure 26). The applied propulsion power depends on the conditions of tidal current and wave height.

Figure 26 WindCat vessel landing at a wind turbine terminal

The period of these landings involved on average a period of approximately 5 to 10 minutes, but can be extended when equipment has to be transferred. After the transfer the vessel keeps position in the area nearby, drifting with engines on or off, depending on the conditions. The transfer of personnel from the WTG-terminal onto the WindCat is in opposite order. In the two measurement periods a detailed report of traffic to and from WTG's was provided by the operator for this special purpose and concerned only a

single vessel (ID≈WindCat25). From the logs a number of 29 WindCat operations were detected over a period of 6 days, involving 25 landings at WTG terminals and 4 free-sailing operations along the three WTG rows (Appendix C, Table 10 and 11). Based on the known coordinates of the WTG-terminals (de Haan et al., 2007a&b) the distance of the WindCat vessel to the received position could be calculated and listed with the turbine operational data in Table 10 (Appendix C). The information of WindCat activity not included in the reported lists (16 and 17 January) was taken from the AIS and radar detections from the Dutch coastguard, derived from Marin, Wageningen, NL.
The data were used to determine the contribution of the shipping noise in terms of the level and as percentage of the total logged time (Appendix C, Table 8). The methods of this part of the analysis are described in Section 2.5.3.

2.4.2 Non-related ship traffic

The logs of other vessels not related to wind farm operation were achieved from the AIS (Automatic Identification System) logs of the Dutch Coastguard shore station, which are made available by Marin, Wageningen, NL. The vessel labels in the records were anonymised and also included smaller ships not detected by AIS but through radar of the Dutch coastguard station, IJmuiden. The limits of the AIS detected vessels was set to a square area of 20 km east/west and 28 km north/south. All detected samples were listed with 1 minute resolution per detected position.

2.5 Analysis procedures

2.5.1 Acoustic data

The WAV-formatted raw data were converted to binary format to process the data in the virtual analyser module (Labview, National Instruments). The records of the calibration files and their corresponding reference levels were used in this module to scale the data to the dB-scale.
The Sound Pressure Level (SPL) is calculated per time unit, in this case 1 s, which returns the result as spectral noise level equivalent to the formula:

$$SPL_{rms} = 10\log\left(\frac{1}{T(1s)}\int_0^T \frac{p(t)^2}{p_{ref}^2}\,dt\right)$$ in dB re 1 μPa²/Hz

With:

$p(t)$ “rms" sample equivalent to sound pressure Pa (Pascal);

p_{ref} the minimum reference value for sound pressure in water (1 μPa);

T the integration time, in which samples are averaged.

Occasionally broad-band noise levels were averaged over 60 s to smooth the results displayed over the complete period of a mission and concerned only the illustrated data and shown in the legend of the chart. The calculated SPL-values were presented as graphical information on the display of the analyser as a function of date and time and exported to DiaDem spreadsheet software (National Instruments) to report the data.
On specific times, selected from the WTG27 turbine power and wind speed relation, Third-Octave analysis was applied to investigate the frequency characteristics of the recorded noise.

2.5.2 Analysis procedures of turbine noise

The RAW data files recorded in WAV-format were converted to binary formatted files with a header per file containing the start time of the file, the applied gain factor, the low- and high-pass filter setting, the sample rate and a text block with measurement information. The files containing the calibration references were used to scale the noise level to the dB scale with the reference values measured at the pistonphone excitation gate. These files were imported in the sound analyser virtual software module, in which the analysis was processed. The data files containing the measurement data were imported and analysed in a series streamed order sorted as a function of time. The broad-band levels were calculated in this sequence in blocks of 1 s to express the spectral levels. These levels were exported to a spreadsheet (DiaDem, National Instruments) to process the results to reports and to sort the acoustic data as a function of wind speed. As the start of the acoustic recordings was random the time axes of the WTG27 and REF acoustic 1 s data were synchronised to the 10 min cycles of the turbine and meteo data. The wind speed data of the WTG 27 sensor (WTG27 WS) was rounded off to integers to which the WTG27 and reference acoustic data 1 s-samples were sorted. After sorting the acoustic data were averaged per 10 minutes and synchronised to the time scale of the wind speed data, which also represent the average over 10 minutes. The sorted averaged results were statistically tested for the 95 % Confidence Intervals, after which these results were plotted as a function of wind speed (Described in Section 2.7.3.).
Third-octave analysis was applied (ANSI S1.11-2004, Order 3, Type 1-D,) to identify the possible noise source of ship-noise and turbine noise and to weigh the results against the hearing capabilities of marine animals, in particular harbour porpoise and harbour seal. The frequency characteristics of the noise were analysed in Third-Octave bands as well as in narrower bands using Fast-Fourier transformation (FFT) was applied to examine the energy of the turbine noise in more detail, particularly when tonal contribution was suspected.

2.5.2.1 Third-Octave band analysis

Third-Octave analysis was applied on data samples of 1 s, which were averaged over a variable time period of 10 or 60 s depending on the target condition. Turbine noise filtered in Third-Octave bands was assessed in three ways. The complete data set was analysed per 12 hours of day- and night-time blocks in steps of 10-min intervals. Each result is the average of a Third-Octave of 1 s samples, linear-averaged over 10 s. The averaged 10-minute results were reported in a graph representing a 12-hour period. The second, more selective approach was executed as a function of the turbine power range and taken when ship noise was not present. In this step four different power ranges (Zero, Low, 1000, 1500, 2000 and 3000 kW) were taken as reference. In this step each result is the average of 1 s Third-Octave samples linear-averaged over a period of 60 s. To improve the confidence level the highest power production condition was also analysed of a longer time period of 30 minutes. In third mode 1 s Third-Octave samples were analysed over 30 minutes in steps of 1 minute-intervals. Shorter events, such as the analysis of the starting of the turbine from idle mode were averaged over a period of 10 s.
The records of ship noise events were added to illustrate the difference in the characteristics of the noise.

2.5.2.2 Narrow-band analysis

Noise was analysed in narrower bands of 1 Hz by applying Fast-Fourier Transformation (FFT) to observe the details of the turbine noise characteristics. The result after FFT of a 1 s time window equals the spectral level commonly used to express noise type of sound.
The averaged time length was 10 s in most cases and data was averaged in steps of 1 s to meet the spectral levels according a linear averaging mode with 50 % overlap.

2.5.3 *Analysis of procedures of shipping noise*

The analysis of the noise level attributed to WindCat operation was expressed as an average broad-band spectral noise level (summed levels from all Third-Octave Bands) over the interval the noise was most significant (Appendix C, Table 10). Third-Octave analysis was applied to compare the energy of the WindCat noise in the frequency domain against the turbine noise shortly before or after the WindCat noise was detected. The Third-Octave analysis involved a linear averaged result of 1s time blocks over 60 s in most cases (incidental 10 s or 1 s in cases of shorter peaks). The time markers of the Third-Octave references are the centers of the averaged interval.

2.6 Effects on harbour porpoise, harbour seal and cod

Third-Octave noise levels of wind farm related sources were weighed against the auditory thresholds and the time to reach TTS-onset calculated. The auditory thresholds were based on the latest results of hearing studies with narrow-band signals of harbour porpoise (*Phocoena phocoena*) and harbour seal (*Phoca vitulin)* (Kastelein et al., 2010) and TTS research of Kastelein et al., 2012a and b. According the aim to impact of turbine noise to harbour porpoise in the perspective of the expected future growth of wind turbine power production we did not apply the single averaged TTS-onset reference as proposed by Verboom et al., 2012. For harbour porpoise we used the TTS series (124 dB re 1 μPa^2) closest to the expected SPL of turbine noise (Figure 11a). The TTS trend estimates a TTS-onset in harbour porpoise of 141 dB 1 μPa^{2}s and 132 dB 1 μPa^{2}s after weighing, which is 9 dB lower than the proposal of Verboom et al., 2012. For harbour seal the outcome of the SPL 124 dB series did not result in a valid trend (Figure 10b). For this species the TTS-onset based on the SPL 136 dB series had to be used, resulting in a TTS-onset of 163 dB re 1 μPa^{2}s. For this species the weighing did not affect the TTS-onset value.
Finneran et al., 2010 (Figure 27) reported a declining TTS-trend in bottlenose dolphin < 3 kHz with a attenuation of 40 dB at 0.2 kHz. As TTS-on set in harbour porpoise in this frequency range is lacking (Section 1.6.3) we adjusted TTS-onset estimates to the reduced sensitivity accordingly and applied a 30 dB compensation. Note that a reduction of 10 dB increase the duration to reach TTS-onset a factor 10. For harbour seal there is no support in literature to apply additional compensation. As the exposure to WindCat noise is relatively short we followed the proposal of Verboom et al. 2012, which implies a weighed TTS-onset in harbour porpoise of 141 dB 1 μPa^{2}s.

The study of Hawkins et al., 1973 on the hearing of cod (*Gadus morhua*) was taken as reference to test the results on a "hearing generalist" fish species and the reference of Enger, 1967 was applied to test the result on a "hearing specialist" fish species. For this part of the analysis the highest turbine noise levels and shipping noise events were used and referred to the reference background noise at that particular time.

2.7 Validation of the results

2.7.1 *System performance tests*

The performance of the data recording and analysis tools was tested against a TNO-reference in a broad range in 2010 and a second time shortly after the two measurement campaigns on 16 April 2013 with the equipment used on the trials. The outcome of these tests is listed in Appendix E, Validation of results. The equipment was exposed to a noise and tonal type of signals projected in the indoor basin facility of TNO Defence, Security and Safety, The Hague, Netherlands. The anechoic basin has a rectangular shape of 8 x 10 m and a depth of 8 m. The walls of the basin are rigged with panels with wedges of cork-made pyramids to absorb reverberations.

The set-up of the final test was an exact copy of the hardware and software applied in the presented results. Consequently this test is a solid validation of the presented results. The only differences in the applied and tested systems were the hydrophone cables, which were too short (2 m) to deploy the hydrophone in the basin. Secondly the GPS-receiver hardware and the recording computer were not part of the tested system. Instead small battery-powered netbook computers were used to record the raw data files. The tested systems were exposed to a “Pink Noise” type of signal in the frequency range of 20 Hz to 20 kHz and a burst of ten 15 kHz cycles. The signals were projected using a type J9 equivalent transducer. The TNO-reference hydrophone was a RESON T4032 type with a 10 dB built in pre-amplifier, equivalent to the hydrophones applied in the OWEZ- project. Both hydrophones were fixed together with foam as isolator and deployed at a depth of 2.5 m at a distance of 1.45 m from the transducer. The outcome of the tests showed that the tested systems responded to the exposures with acceptable deviations (Appendix E, Figure 75 and 76). Deviations < 200 Hz were the highest, but the uncertainty in this range is probably related to the limited dimensions of the basin limiting the wavelength of the frequency and the dimensions of the basin. Given the ratio of velocity of sound in water and the frequency of sound, the threshold frequency based on basin length of 10 m length is 150 Hz. Frequencies below this threshold cannot fully develop and this probably the underlying cause of the deviations measured below 200 Hz. The sensitivity of the hydrophones specified by the manufacturer was adjusted to the results of the reference measurements results (Appendix E, Table 12).

2.7.2 Calibration of the hydrophone

Before each mission shortly before the deployment reference calibration files were recorded as first data files on the recording equipment to scale the noise levels of the recorded data to a certificated reference measured with a B&K Sound Level Meter, type B&K2239. As this Class 1 Sound Level Meter is the basic scaling reference of the results, the instrument was recalibrated on 24 October 2012. The instrument was also used on the reference test at TNO, The Hague on 16 April 2013 (Appendix D, Calibration Certificate).

2.7.3 Statistical confidence tests

To determine the variance of the results of broad-band spectral levels and to validate the amount of recorded data per wind speed range Confidence Interval tests (95 % CI) were applied on the calculated average values of broad-band spectral noise levels of the WTG27 and REF system after the noise data were sorted per wind speed bin. For the methods part of the tests the outcome showed that the acquired data per wind speed category was sufficient to support the conclusion based on two measurement campaigns.

3 Results

A common observation for both measured periods is that the noise level curves include a high number of incidental high peaks, most of them identified as ship noise (Figure 29 and 32). Lower peaks following the tidal frequency pattern are attributed to sea state noise with the wind speed and direction, wave height and tidal current as determining factors. Turbine noise contribution was detected in the Third-Octave bands < 315 Hz, while ship noise contributed in wider frequency range. Occasionally the noise of shipping passing the OWEZ wind at long distance was detected sequentially in both measured positions (Figure 30 and 48).

3.1 Mission 1

3.1.1 Turbine Noise Broad-band levels and estimated unmasked propagation distance

The spectral broad-band SPL's averaged over 60 s received in the background reference (REF) and WTG27 measurement positions are illustrated for Mission 1 and 2 in respectively Figure 29 and 32 as well as the details of a shorter 20 hours interval in the first Mission (Figure 30). In the first period the noise increased slowly in time as a function of the increasing wind speed.
The main observation of smoothed results is that the turbine noise levels are already significant at 15 % of the electric installed power and that turbine noise has the highest increase in the lower range between 500 and 2000 kW. Above this range the noise hardly increased. High incidental peaks were recorded in both positions indicating contribution of ship noise. The overview of power ranges filtered in Third-Octave Bands (Appendix B, Table 5) illustrates that the biggest effect is found when the turbine power increased from "low" (30 kW) to 1000 kW. Some of the high peaks are clearly attributed to vessels passing the area and these detections were further analysed using the AIS-records (Section 3.3).
The 95 % confidence test of broad-band spectral noise levels sorted per 10 min wind speed (Figure 31) shows that turbine noise is ramping up in the wind speed range of 6 and 12 m.s^{-1}. Based on this test the mean turbine broad-band noise level in the wind speed range of 12 to 15 m.s^{-1} is 122.5 dB re 1 μPa^2/Hz and a background noise level of 115.3 dB re 1 μPa^2/Hz. Based on a 15 Log R propagation loss (Thiele 2002, in Thomson et al., 2006) the mean unmasked turbine noise distance is 402 m.

3.1.2 Frequency characteristics

The frequency characteristics of turbine noise analysed in Third-Octave filtered spectral noise levels in steps of 12 hours show that the contours of the turbine noise are expressed in the 16, 50, 100 and 200 Hz Third-Octave bands (Figure 34 to 40).
A significant contribution in the 16 Hz Third-Octave band was present in the first 12 hours of the first period at a very low power production (Figure 34 and 35). The contribution of ship noise is significant in all cases with some very strong masking events and reported in section 3.3. The turbine noise spectra taken at a range of power conditions (Figure 41 and 42) show that the largest increase is in the lower power range and that the noise produced at 1000 kW is already at the far end of the noise level range. The summed noise levels of the Third-Octave Bands are listed against the turbine data in Appendix B, Table 5. As soon as the turbine starts to operate (power production increased from 30 to 950 kW, Table 5) the levels in the lower frequency bands < 63 Hz increase with approximately 8-12 dB (Figure 42). The narrow-band analysis of the LF-contribution related to transmission noise is illustrated in the FFT-analysis of turbine noise at maximum power range against an idle mode condition (Figure 43) showed energy of turbine related noise strongly declines at 250 Hz.
A Third-Octave band record of 30 minutes taken on 19 January 2013 (16:25 to 16:55) with 1 minute intervals (each sample is the average of 1 s over a 10 s period) was plotted to illustrate the energy contours of the turbine noise spectrum including the average of these 30 tracks (Figure 44).

The graph shows the energy mainly peaks in the 50 Hz-, 100 Hz- and 200 Hz-bands and the readings listed in Table 2. The averaged power production conditions over the 30 minutes noise record were 2766 kW, a rotor speed of 16 RPM and a wind speed of 12.7 $m.s^{-1}$.

Table 2 Turbine noise levels at maximum power condition (Mission 1) over a period of 30 minutes

Third-Octave band (Hz)	Average (dB re 1 μPa^2)	Max (dB re 1 μPa^2)	Min (dB re 1 μPa^2)
50	111.5	113.6	109.2
100	112.4	113.3	111.5
200	114.1	115.1	112.9

On the start of the turbine from idle mode on 17 January 16:00 an impulsive "rattling" type of noise was detected at two occasions shortly before the start at 16:02 and at 16:20 (Figure 45, 46 and 47). These noises are attributed to the decoupling of rotor blade pitch mechanism. The starting from idle mode of the turbine raised the noise level with 7-10 dB, although the turbine power production was negligible (35 kW) and this increased noise level is mainly attributed to the start of the rotation and the transmission link (Appendix B, Table 6). The incidental rattling noise contribution is marginal and caused some higher frequency components around 3 kHz (Figure 45 and 46). The noise of the auxiliary engines driving the rotor blade pitch control and "yawing" system could not be detected.

3.2 Mission 2

3.2.1 Turbine noise levels and estimated unmasked zone.

The broad-band noise levels measured at 100 m from WTG27 started to rise on 6 February 15:00, 7 hours after deployment (Figure 32). As a result of the wave height peaking at 3 m in the first 24 hours (Figure 23) the sea state noise contribution was much higher than on Mission 1, in particular at the reference position. On the highest wind speed condition the noise patterns followed the tidal current frequency, indicating also a tidal current influence. The turbine noise levels were already significant in the lower range of the developed power around 1000 kW (Figure 58 and 59) and listed in Appendix B, Table 7). The turbine noise displayed in steps of 12 hours show that the contours of the energy are mainly expressed in the 50, 100 and 200 Hz Third-Octave bands (Figure 50 to 57). A contribution in the 16 Hz-band was not observed in the data of Mission 2, although periods with low power development also occurred in this period.
The 95 % confidence based mean broad-band noise levels in the wind speed of 12 to 15 $m.s^{-1}$ was 123 dB re 1 μPa^2/Hz, which is 0.5 dB above the level measured in the first period and a background noise level of 118.7 dB re 1 μPa^2/Hz. Assuming a 15 Log R propagation loss (Thiele 2002, in Thomson et al., 2006) the mean unmasked turbine noise distance is 294 m.

3.2.2 Frequency characteristics

The overview of power ranges filtered in Third-Octave Bands (Figure 59) illustrates that the biggest effect is when the turbine power increased from "low" to 1000 kW.

A Third-Octave band record of 30 minutes taken on 7 February 2013 (00:21 to 00:51) with 1 minute intervals (each sample is the average of 1s over a 10 s period) was plotted to illustrate the energy contours of the turbine noise spectrum including the average of these 30 tracks (Figure 60). The graph shows the energy mainly peaks in the 50 Hz- and 200 Hz-bands and the readings listed in Table 3.

Table 3 Turbine noise levels at maximum power condition (Mission 2) over a period of 30 minutes

Third-Octave band (Hz)	Average (dB re 1 μPa^2)	Max (dB re 1 μPa^2)	Min (dB re 1 μPa^2)
50	114.2	116.8	112.3
100	110.6	112.2	108.8
200	114.8	116.0	113.4

Compared to the results of the first period (Table 2 and Figure 44) the energy in the 100 Hz-band shifted to the 50 Hz-band. The averaged power production conditions over the 30 minutes noise record were 2862 kW, a rotor speed of 16 RPM and a wind speed of 14.3 m.s^{-1}.

The broad-band spectral noise levels sorted per 10 min wind speed averages (Figure 33) shows that turbine noise levels raised over the full wind speed range from zero to 16 m.s^{-1}.
An increase from 1000 to 3000 kW did only add a few dB's to the total summed noise level of developed noise (Appendix B, Table 7). Also in this period there were incidental noises related to propulsion noise of ships (Figure 58). The Third-Octave analysis of turbine noise at several power ranges (Figure 59) also shows the detections of ship noise of WindCats. The tanker of 98 m length passing the WTG27 hydrophone at a shortest distance of 5624 m dominated the complete spectrum and would also have masked the highest turbine noise spectrum. The first significant ship-noise event, on 6 February, between 08:00 and 09:00 was attributed to MS "Terschelling", while sailing north to Den Helder harbour after the deployment of the equipment and passing the reference hydrophone position.

3.3 Contribution of ship-noise

Shipping related noise contributed to 28.6 % of the total recorded time period of 171 hours. An overview of the shipping activity based on AIS- and radar logs is illustrated per Mission in Figure 67a and b. The logged area covered the area between N 52.77, W 004.27, E 4.58 and S 55.52, which is approximately 20 km east/west and 28 km north/south. Categories of vessels logged in the given periods consisted of smaller categories, like WindCats catamarans of 20 m length and 220 kW licenced fishing vessels to larger ships, like cargo vessels, tankers of about 100 m length.

3.3.1 Wind farm related shipping noise

Of the total measured time of 171 hours WindCat related noise was detected in 10 hours and 32 minutes, which is a contribution of 6.16 % of the total measured time (Appendix C, Table 8).
On the first days of the measurements (16 and 17 January 2013) no detailed lists of WindCat transfer schedules were available other than a brief list of ships involved and the target destiny.
The AIS-data showed these activities anonymously and are illustrated in Figure 68 and 69. On 16 January the tracks of MS "Terschelling", heading north is shown as well as a WindCat type of vessel. The WindCat vessel operated on 16 January at WTG30 and 35. The vessel left the OWEZ area around 15:30 and inspected the moored acoustic equipment for about 3 minutes at a distance of 40 m. The day after a WindCat vessel landed at WTG02 and 03, while another OWEZ related vessel was heading towards WTG11 and entered the OWEZ area around 07:00. These tracks confirm the brief communication list of that particular day and these tracks are related to MS "Tender Express". The contribution of WindCat noise on 16 and 17 January was estimated at 1 hour per day. The track of a fishing vessel was detected at the east side of OWEZ wind farm (Figure 68 and 69).
The duration of WindCat exposure on landing at the turbine gates were relatively short and involved a period of 3 to 17 minutes (Appendix C, Table 10).

The noise of the propulsion power while landing the vessel against a WTG-terminal masked the turbine noise levels in all recorded landing positions up to a distance of 3768 m from the received position at 100 m from WTG27. The 25 cases of detections with known distances are listed in Appendix C, Table 10. Two examples of WindCat noise contribution, while landing the vessel at WTG terminals are shown: case 7 with the vessel at WTG21 at a distance of 1700 m (Figure 71) and at the maximum measured range of 3768 m at WTG02 (Figure 72). These illustrations show the WindCat noise spectrum against the turbine power condition minutes before or after the completion of the landing.The turbine noise spectra illustrated in Figure 71 and 72 are well above the simultaneously taken reference noise spectra measured at 7400 m north of the OWEZ, but are completely masked by the WindCat spectra with the vessel at distances of 1700 and 3768 m from the hydrophone position. The turbine power production under these conditions was respectively 2562 and 753 kW. The Windcat contribution measured at 3768 m (Figure 72) was at low turbine power production (753 kW). At this condition the masking is near the threshold range.

WindCat activity contributed to the measured noise is listed as broad-band spectral noise levels in Appendix C, Table 10. The overview shows that the noise of a WindCat vessel, while landing at the listed WTG-terminals, masked the turbine noise in most cases with levels depending on the distance of the vessel to the received measured position and the applied propulsion power which remains unknown. The SPLs marked "Pre" and "Post" represent the summed noise levels as reference to turbine noise not including ship-noise (Appendix C, Table 10). These levels are the summed broad-band levels of Third-Octave bands taken shortly before or after the detection. They represent turbine power noise and two of these Third-Octave results (marked WTG27) are shown in Figure 71 and 72. The broad-band noise results show that the vessel noise was detected in all cases with the highest level at 1700 m, 4 to 6 dB above the turbine noise level. There were shorter distances recorded (1300 m) with lower noise levels, but the noise produced can be higher at longer distances as the noise is related to the propulsion power applied, which depends on the sea state conditions and tidal current. From the start of Case 3 up to the end of Case 5 the noise was received without interruptions, apparently including the noise developed during sailing from WTG3 towards WTG11.

3.3.2 Tonal detection

On 8 and 9 February a tonal type of noise was detected shortly after WindCat landings (Appendix C, Table 10, Case 26) the energy peaked for 5 minutes in the 800-1000 Hz band from 08:35:20 indicating tonal contribution from a transmission system and also after this event for a longer period (1 hour). This contribution disappeared at 09:44. However, according to the WindCat logs the ship's engines were switched off at 09:25. Most likely, this tonal noise is attributed to engine noise in idle mode and disappeared when engines are switched off. Narrow-band FFT analysis showed energy contributions at 750 and 900 Hz (Figure 73). This contribution was detected in other cases (while passing the hydrophone at short distance (Figure 74) mostly related to WindCat operation and appeared shortly after the landing of the WindCat vessel was completed and the noise reduced (propulsion power reduced). The noise was never detected at night, so most likely this is a noise related to the WindCat propulsion system.

In some cases (Appendix C, Table 9 case 7 and 8) WindCat landings were in close range of the received hydrophone position and shipping noise was received continuously over longer period. The free-sailing of a WindCat vessel along the rows of WTGs indicated in the ship's logs as "strings" was detected, while sailing along all strings, in particular when passing WTG27 (Table 9, case 15). At 12:16:10.5 the highest broad-band level of the series was measured, 130.5 dB re 1 μPa^2/Hz (Figure 74). At that moment the AIS-log showed that the passing distance was 150 m.

3.4 Contribution of ship noise not related to OWEZ wind farm

The contribution of acoustically detected contributions of other vessels involved 38 hours and 24 minutes, which is 22.4 % of the total measured time (Appendix C, Table 9).
An example of a strong contribution is the passage of a cargo vessel of 163 m long on 18 January 2013. The ship was heading north along the lane at the west of OWEZ towards the main coastal shipping lane at a speed of 20 knots and passed the WTG27 hydrophone at a shortest distance of 5234 m (Figure 70). The ship raised the summed Third-Octave turbine noise level (Marked "Pre") with 3 dB between 21:22 (Marked "Start") and 21:57 (Marked "Stop") with the highest peak at shortest distance +14 dB above the threshold turbine noise level measured shortly before the arrival of the ship (Figure 48 and 49) and 16 dB above the reference noise level (Appendix C, Table 11). The acoustic threshold detection distances ("Start/Stop") of the ship towards the hydrophone at WTG27 are just outside the AIS detection range. The first AIS-detection of the ship was on 21:25 at 9960 m, so the average distance to the hydrophone at WTG27 on 21:22 will be ≥ 10000 m. The final detection was around 21:54 at a distance of 10970 m. Before the ship was outside the detection range of the hydrophone at WTG27 the noise was received in the reference position (Figure 48). At the time of detection the turbine power was in the range of nominal power production. The results and turbine conditions are listed in Appendix C, Table 11.

3.5 Effects of wind farm noise on harbour porpoise, harbour seal, cod and herring

Turbine and WindCat noise results were weighed against the audiograms of harbour porpoise, harbour seal and cod. The results were used as indication which parts of the noise spectrum is audible per species. The maximum power condition marked as "H3" (Appendix B, Table 5 and 7) was used to estimate the effects of turbine noise. For the effects of WindCat shipping noise case 7 was used (Mission 1) with a WindCat at a distance of 1700 m from the received positions. The turbine noise levels are listed against the turbine production conditions in Table 10 in Appendix C. The weighed results for harbour seals showed that the filtered turbine noise and a WindCat vessel is well above the background noise reference level at 7400 m from the wind farm (Figure 63 and 64). The audible parts of turbine and WindCat noise for harbour porpoise (Figure 61 and 62) showed turbine noise is at the level of the background noise and not as audible as the noise from WindCat vessels.
Cod (*Gadus morhua*) as representative for a hearing generalist type of species will probably detect turbine noise over the full unmasked spectrum of turbine noise in particular around 160 and 200 Hz (Figure 65). Based on the publication of the hearing thresholds published by Enger, 1967 Atlantic herring (*Clupea harengus*) will be able to detect the full unmasked spectrum of turbine noise (Figure 66).

3.5.1 Impact of wind farm related noise in the TTS-onset range

The calculated duration on reaching TTS-onset in harbour porpoise and harbour seal is listed in the overview of Table 4. The overview shows the weighing of noise at highest power ("H3", Figure 42) has a strong effect of 28 dB for harbour porpoise expressing that the major part of the turbine noise energy is in low-frequency part of the hearing range, where the sensitivity declines. TTS-onset in harbour porpoise would be reached after 1 hour and 48 minutes (based on the 4 kHz defined weighed TTS-onset level of 132 dB re 1 $\mu Pa^2 s$, Section 1.6.4 and 1.6.5., Figure 11a). Additional compensation for the turbine noise frequency range of 30 dB is supported by the TTS-experiment on bottlenose dolphin (Finneran et al., 2010). Finneran et al., 2010 estimated a decrease (Figure 27) of 40 dB between the lowest measured result of 3 kHz and the frequency range of turbine noise (200 Hz). Both auditory curves of bottlenose and harbour porpoise are similar in the low frequency range, but instead of using the predicted 40 dB attenuation in bottlenose a defensive approach of 30 dB was applied following the aim of estimating the TTS-onset in a sensitive way. After a 30 dB compensation TTS-onset in harbour porpoise is reached after 75 days.

For harbour seal the TTS trend based on the 163 dB SPL was used (Section 1.6.4 and 1.6.5, Figure 11b). Based on the 4 kHz reference level of 163 dB re 1 μPa^{2}s TTS-onset is reached after 4 days, 20 hours and 40 minutes. References such as Finneran et al., 2010 to adjust for turbine noise frequency is not available for harbor seal, but according the hearing thresholds (Figure 9b) a reduction of 8 dB is likely.

The longest duration of WindCat noise exposure, while landing at the wind turbine gates, was 17 minutes (Appendix C, Table 10). The estimated duration shows that TTS-onset will not be reached with the animal at a distance of the received position (1700 m) even when the uncompensated reference of 141 dB re 1 μPa^{2}s is used.

Table 4 Estimated duration on reaching TTS-onset in harbour porpoise and harbor seal

Noise type and reference	SEL unweighed (dB re 1 μPa^{2}s)	SEL after weighing (dB re 1 μPa^{2}s)	Duration (dd:hh:mm) Harbour porpoise Ref 132 dB re 1 μPa^{2}s	Duration (dd:hh:mm) Harbour porpoise Ref 132 +30 dB re 1 μPa^{2}s	Duration (dd:hh:mm) Harbour Seal Ref 163 dB re 1 μPa^{2}s
Turbine Noise 3000 kW “H3”	122	94	00:01:48	75:05:33	
WindCat 1700 m (case 7)	129	100	00:03:58		
Turbine Noise 3000 kW “H3”	122	107			04:20:40
WindCat 1700 m (case 7)	129	120			00:06:15

4 Discussion

4.1.1 Broad-band turbine noise levels and unmasked zone

At wind speeds between 12 and 15 m.s^{-1} the maximum broad-band turbine noise measured on both measured periods were 123 dB re 1 μPa^2/Hz. On Mission 1 the maximum noise level was 0.5 dB lower. These values are based on 10 minute averages of the mean of 95 % confidence tests (Figure 31 and 33). On Mission 1 the contribution of sea state noise was the lowest with wind mainly from eastern direction (Figure 16) and wind speed slowly increasing to 15 m.s^{-1} developing towards the maximum turbine power range (Figure 16, 18 and 21). The highest measured unmasked distance range of turbine noise was measured under a very low sea state noise condition and can be regarded as a worst case condition. The lowest background noise level of 115 dB re 1μPa^2 was measured with a wave height of maximum 0.7 m at highest power production (Figure 22). On the second period winds from northern direction increased the wave height to 3 m (Figure 23). On this condition the average background noise level was 3.4 dB higher than on the first period, reducing the unmasked distance range of turbine noise.

The estimate of the unmasked turbine noise zone is supported by two references, a transmission loss model of Thiele (2002), published in Thomsen et al., 2006, predicting 4.5 dB at double distance as intermediate (15 log r) between spherical 20 log r and cylindrical spreading 10 log r (Figure 6). Another prediction for the propagation losses is obtained from the Raytrace model applied by TNO (de Jong et al., 2010). This model is based on an "image source ray" model (Urick, 1963) assuming that all factors (water depth, sound speed and density) involved play a uniform role. Based on a water depth of 20 m, a monopole source depth of 4 m and a receiver depth of 12 m this model predicts 9 dB losses between 100 and 500 m from the source in the 160 Hz Third-Octave band. Although our input circumstances are not an exact copy (the receiver depth is 1 m above the bottom) and the propagation conditions differ per location this comparison meets our present estimate based on the mean results of Mission 1 of 480 m.

This estimate is also confirmed by first measurements of 2007 conducted at another measured position opposite the western row of turbines (Appendix F, First measurements). Turbine noise could not be detected at a symmetrical distance range 481 to 567 m from WTG09 and 10 with only a minor turbine noise contribution at 481 m in the 100 Hz Third-Octave band (Figure 81).

4.1.2 Uncertainties of the estimated unmasked range

Based on the reference measurements with TNO acoustic equipment (Appendix E, Validation of Results) uncertainties of the broad band noise levels estimated related to the equipment and software tools are ≤ 0.3 dB.
When the minimum and maximum uncertainties of the 95 % confidence test are taken into account the minimum and maximum differences of turbine and background noise ranged between 6.5 to 8.4 dB (Figure 31) with an unmasked turbine noise zone 371 to 463 m. When the overall system error (0.3 dB) is taken into account the maximum unmasked distance will be 480 m.

On higher sea state noise conditions, such as on Mission 2 with wind from northern directions (Figure 23) the contribution of sea state noise was much higher, resulting in higher background noise levels and a reduced unmasked turbine noise range. According the 95 % confidence test of the Mission 2 (Figure 33) the difference between turbine and background noise contain higher uncertainties ranging between 2.6 to 7.5 dB, with a threshold distance ranging between 249 to 417 m accordingly. The maximum unmasked zone increased to 431 m when the overall system error (0.3 dB) is taken into account.

The effects on the unmasked turbine noise zone highly depends on the wind direction and ranges from 249 to 480 m from the measured turbine position of wind direction, while the presently reported maximum range of 500 m as “worst case” condition measured at lowest sea state contribution.

4.1.3 Characteristics of turbine noise

The energy of the turbine noise mainly peaked in the 50-, 63-, 100- and 200 Hz Third-octave bands as illustrated by the graphs of Figure 34-40 and 49-56 and listed in Table 2 and 3. At maximum power production turbine noise levels in the 50, 100 and 200 Hz Third-Octave bands not interfered by shipping noise were respectively 111 (StDev 2.2), 112 (StDev 0.9) and 114 dB re 1 μPa^2 (StDev 1.1).
On Mission 2 a similar observation was made with the highest level of 115 dB in the 200 Hz-band, but with higher deviation (Table 3, Figure 60).

At frequencies ≥ 400 Hz the turbine noise equalled the background noise level measured in the reference position 7.4 km north of the wind farm area (Figure 49 and 61).

Madsen et al., 2006 reported a maximum turbine noise level 120 dB re 1 μPa^2 (RMS) peaking in similar frequency range (60-200 Hz). These results were measured at equivalent measured distance from a turbine of similar physical scale (Horns Rev1 160 MW with 80 turbines of 2MW each). This relatively high noise level is most likely related to shallower water conditions (6-14 m) and so lower propagation losses.

Significant contribution in the 16 Hz-band (112 dB) equalling the energy level of the 200 Hz-band was only detected at low-power production on eastern wind with low sea state noise contribution (Figure 34). The event occurred for the duration of 12 hours and was not observed on the second period on similar power condition. As the detection extended a full tidal cycle, cut-off filter effects related to tidal increase of the water depth are excluded. Most likely this event is related to wind direction and/or probably the sea state condition or a critical load condition of the transmission system. Narrow-band analysis on the relation with the turbine transmission system would require momentary turbine raw data, which were not available.

This present result is strongly related to the physical scale of the turbines and transmission system installed, and the measurement location. The up-scale to 5 to 6 MW turbines installed at locations more off-shore could involve lower frequency contributions (≤ 16 Hz) and or a different noise signature. Although the low-frequencies ≤ 16 Hz were cut-off and filtered by the water depth, they are likely to contribute to the particle motion spectrum in the water column in close range of the turbine and also coupled from the monopole structure into the sediment.

This research showed an unexplained difference between measurements before and after the filling of all 36 monopiles with concrete. After the filling the noise of auxiliary engines were not detected and this indicates that the propagation path of turbine noise can be damped by such a measure. Monopiles of the wind farm in close range, “Prinses Amalia Wind Park” were not filled and reports on turbine noise of this wind farm could clarify this difference.

4.1.4 The contribution of wind farm related shipping noise

The total contribution to shipping noise in general was 28.6 % of the total measured time (171 hours). Wind farm related shipping dominated turbine noise 6.2 % of the total measured time.
We measured the noise production while landing the vessel at the terminal of WTG’s, of which the distances to the hydrophone position is exactly known. The measured SPLs mainly are strongly related to that particular propulsion condition. Free-sailing vessels might use different propulsion power settings. We assumed that the propulsion conditions were comparable for all measured conditions. The actual propulsion settings are related to tidal current and wave height conditions. At a range of 3768 m

WindCat contribution was detected (Figure 72). It should be noted this was at low turbine power production (753 kW). At this condition the masking is near the threshold range. At higher production power conditions, like case 7 of Figure 71, the masking (in the lower frequency bands) would not have occurred.

4.1.5 The contribution of noise of other shipping

Shipping noise, including the wind farm related vessels, dominated the noise spectrum 22.4 % of the measured time period (171 hours). The contribution of shipping noise might be higher than one would have expected, but the fact that this condition occurred already at 100 m from the target (WTG027) is a valuable additive.

4.1.6 The effects of turbine noise and available tools

The present results indicate that the low-frequency part of unmasked turbine noise is hardly audible to harbour porpoise (Figure 61). Lucke et al., 2007 exposed a harbour porpoise to a fatiguing noise similar to turbine noise and showed that masking occurred in the range of 0.7 to 2 kHz at a noise level of 128 dB re 1 μPa^2 in the 0.2 kHz band. The masking effects varied between 4.3 and 7.8 dB. No masking was measured when the fatiguing noise level in the 0.2 kHz band was reduced to 115 dB re 1 μPa^2. As this level is similar to the measured result in this band it indicates that masking in harbour porpoise is not likely to occur at positions ≤100 m from a turbine. Harbour seal, cod and herring are able to detect the full unmasked spectrum of the turbine noise.
In spite of the low level contribution turbine noise is a permanently present low-frequency noise source and already detectable at low wind speed conditions starting at 5 m.s^{-1}. This raises the question if long term exposure could lead to TTS (Temporary Threshold Shift) in harbour porpoises or seals. This condition is the threshold where a temporary reduction of the hearing sensitivity is reached and depends on the role of exposure time, exposure level and type of sound/noise. The role of time and level is expressed in the metric used for TTS, Sound Exposure level (SEL) in dB re 1 μPa^{2}s. The recovery from this offset depends if the noise disappears and that is the concern in this case, the source can be active for longer periods. Also the animal can be challenged to forage in the exposed zone of turbine noise deliberately as wind farms are hypothised to become shelter areas for many fish species.

The aim to reach an increase of 37 times the present installed offshore wind power in European waters in 2030 requires a careful consideration of the effects of turbine noise, in particular the occurrence of long term TTS in marine fauna, with main targets of this research harbour porpoise and harbour seal. Mooney et al., 2008 pointed out that the main factors determining TTS in bottlenose, the sound level and duration, don’t play an equal energy role and that this function is probably logarithmic. Also the recovery duration followed a non-linear model (1.8 dB/doubling of time). Kastelein et al, 2012a and b made a similar conclusion based on the TTS-experiments on harbour porpoise and harbour seal. This all means that the duration of the exposure has a more important role in reaching TTS-onset. The route we used to estimate the TTS-onset for harbour porpoise and harbour seal was based on the proposed TTS-onset references of Verboom et al., 2012. At present the available knowledge on TTS is not covering the frequency range of turbine noise and extrapolation to this frequency range has to be accepted. The use of the weighed Kastelein reference for other wind farm related noises, like WindCat shipping, is applied without compensation. Although the applied references contain limitations, the advantage of using the Kastelein auditory and TTS-references is that they are based on a similar method and conditions. Uncertainties and the lack of knowledge in assessing the effects of turbine noise are given in the Introduction, Section 1.6.2 and 1.6.4.

TTS-ranges in bottlenose dolphin declined at 3 kHz and Finneran et al., 2010 predicted a trend according the hearing threshold (Figure 27) with a predicted decrease of 40 dB in the frequency range of turbine noise. This prediction is in line with the auditory weighing technique proposed by Verboom et al., 2012

(Section 1.6.2, Figure 10). The auditory thresholds of harbour porpoise and harbour seal show a decrease of respectively 62 dB and 11 dB between 0.2 and 4 kHz. The weighed results of turbine noise against the background noise levels (Figure 61) shows that the audible part of the turbine noise spectrum is limited to the lower edge of the auditory spectrum where harbour porpoise has reduced sensitivity. As bottlenose and harbour porpoise have a similar drop-off in the lower frequency range we assumed a reduction of 30 dB for the harbour porpoise part of the assessment.

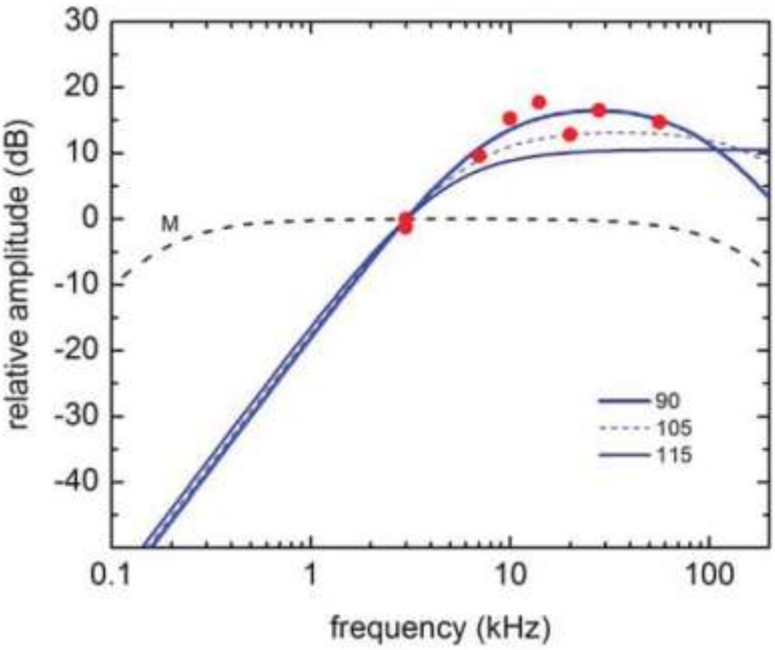

Figure 27 TTS in bottlenose dolphin (Tursiops truncatus) reported by Finneran et al., 2010 with a decreasing trend of the TTS-results (red bulleted markers). The trend declines according the auditory threshold curve in the low frequency range < 3 kHz with a decrease of -40 dB at 200 Hz. The plotted M-filter function (marked "M") is the Southall model proposed for bottlenose dolphin in the frequency range of turbine noise (200 Hz).

At present the development of models for filtering auditory thresholds of cetaceans (Finneran and Jenkins, 2012) is continuing and will evolve to a more comprehensive reference, hopefully also tested in the lower frequency range (< 3 kHz).

4.1.7 TTS-onset in harbour porpoise

4.1.7.1 Turbine noise exposure

As broad-band turbine noise levels were measured at 123 dB re 1μPa^2/Hz the TTS-onset reference measured with similar SPL was applied Kastelein et al., 2012a, Figure 11a). The trend of the TTS-series resulted in a weighed TTS-onset reference of 132 dB re 1 μPa^{2}s. The exposure to the turbine noise at maximum power production indicated as "H3" would cause TTS-onset in harbour porpoise after 1 hour and 48 minutes. This estimate does not involve a frequency compensation such as found in the TTS-study of for bottlenose (Finneran et al., 2010). The TTS-outcome appeared to follow the auditory threshold curve and the trend between the turbine noise frequency range and the lowest frequency (3 kHz) involved a reduction of 40 dB (Figure 27). Although the auditory threshold curves for bottlenose and harbour porpoise are similar we applied a 30 dB compensation. This is encouraged by the conclusion of Kastelein et al. 2010a that exposures > 240 minutes seemed to have a stronger effect.

According this procedure TTS-onset in harbour porpoise will be reached after 75 days (Table 4). Given the lack of knowledge of TTS in a range < 4 kHz a validation for this compensation is not secure. TTS-research in the frequency range between 0.2 and 4 kHz using a fatiguing noise with a tonal structure similar to turbine noise is recommended, preferably according the methods and animals tested at the 4 kHz 1-Octave band noise.

4.1.7.2 WindCat noise exposure

The daily presence of WindCat type of vessels and the noise developed when landing at the WTG terminals masked the turbine noise completely up to a measured distance of 3768 m from the received position and adds higher frequency components much more audible to marine mammals. The weighed noise levels of these vessels (Figure 62 and 64) are well above the background noise and are likely to cause avoidance responses in harbour porpoise.

The noise of WindCat vessel landing at the terminal of WTG21 at 1722 m from the received position (Table 10, case 7) would cause TTS-onset to be reached after 3 hours and 10 minutes. The records of this type of shipping (Appendix C, Table 10) show that the duration of this activity is limited to periods of 10 minutes maximum and it will be unlikely that this operation will cause TTS-onset in harbour porpoise.

The weighed results of this WindCat landing at a distance of 1722 m (Figure 62) shows that this contribution is well above the weighed background reference noise spectrum and given the energy contents this type of noise could produce avoidance reactions in harbour porpoise. Although the exposure of this type of noise is limited in time it was detected at much longer distances (3700 m). Although the operation of WindCat shipping is incidental the present results show that measures to stabilize WindCat vessels at WTG-terminals without the need of propulsion power will have a direct effect on the exposed range, in particular when the unmasked zone of the main power production engine is limited to 500 m.

Other turbine related noise sources which could have an impact on harbour porpoise, like hydraulic engine noise contribution related to the yawing of WTG27, could not be detected in the present results, although the multiple events did occur (Figure 24 and 45). The analysis based on the data used in the first progress report (Appendix F, First measurements) showed that the event of the yawing of WTG11 was clearly received at a distance of 1100 m with a peak level of 113 dB in the 1600 Hz Third-Octave band (Appendix F, First measurements). It is assumed that the 36 turbine structures are similar and that the propagation of noise from auxiliary engines will not differ per case. An explanation for this contrasting result could be the filling with concrete fixation of all 36 transient pieces in 2010, which is done after the first measurement trials of 2007. This measure could have affected the propagation of the noise through the structure-borne path.

4.1.8 Impact of turbine noise to harbour seal

The weighed results according the 4 kHz reference TTS onset of 163 dB re 1 $\mu Pa^2 s$ (Kastelein et al., 2012b) of turbine noise produced at highest power condition shows that TTS-onset is reached after 7 days and 12 hours. As the reduced sensitivity of harbour seal hearing thresholds between 4 kHz and 0.2 kHz is 8 dB, we did not compensate for frequency mismatch as applied in harbour porpoise. Given the periods of haul-outs of these animals ashore it is unlikely that TTS in harbour seal can be reached. The exposure to a WindCat vessel according case 7 (Table 10) showed that TTS-onset is reached after 9 hours and 43 minutes. Given the limited duration of WindCats during landing against a WTG-terminal not extending 10 minutes, it is unlikely this exposure will cause TTS in harbour seal.
The weighed results for harbour seal showed that the filtered turbine noise and a WindCat vessel remain significant and at 200 Hz respectively 20-25 dB above the weighed background noise level at 7400 m from the wind farm (Figure 63 and 64), which indicates these noises are clearly received and could have a behavioural response.

4.1.9 *The effects of turbine noise to fish*

Popper and Hastings, 2009 reviewed the existing literature on the effect of anthropogenic noise on fish, in particular the noise of wind farm construction ("piling") and other type of noise sources. They reviewed both the peer-reviewed and 'grey' literature, with the goal of determining what is known and not known about effects of noise on fish. They concluded that very little is known about effects of pile driving and other anthropogenic sounds on fishes, and that it is not yet possible to extrapolate from one experiment to other signal parameters of the same sound, to other types of sounds, to other effects, or to other species.

The importance to fish of time varying signals is shown by the fact that most fish sounds are made up of trains of pulses (Hawkins & Rasmussen, 1978). The fish auditory system seems to be capable of temporal summation. Research on the auditory system of goldfish (*Carassius auratus*) by Fay (1998) showed that especially this species is well adapted to temporal resolution of complex sounds. He showed that goldfish can discriminate very rapid amplitude modulation using temporal variations in the signal rather than spectral cues. When fish are producing complex temporal structured sound, there is a chance that the sensory system is well-equipped to detect these sounds, in particular under masking noise conditions, rather than being depended on a frequency dependent sensory system, which is limited by a signal to noise ratio.
Research on the auditory thresholds of fish mostly is based on frequency structured sound, while fish could be more sensitive on temporal structured sounds (Hawkins, 1981). This means that fish could have the ability to detect these types of sounds at much higher background levels than spectral based sound. The problem of estimating how far away a fish can detect a particular sound is fraught with difficulties and requires more information on the temporal structure of the sound and also the ability of fish to detect temporally structured sounds against a noise background. The weighed results of turbine noise on cod and herring show that these species are able to detect the noise.

The only other species, beside cod, for which there are Signal to Noise data available is salmon (*Salmo salar*). This species has a much lower hearing sensitivity than cod and shows masking only at quite high levels of sea noise (Hawkins and Rasmussen, 1978). The fish were exposed to a range of low frequency tones and responded up to 380 Hz and particle motion rather than sound pressure. They concluded that fish are sensitive to substrate borne sounds. This may also be valid for flatfish with only the lateral line as main sensing system, such as dab (*Limanda limanda*) that has a lower sensitivity to sound (Figure 12) than the other referenced species (cod and herring), but this "hearing generalist" responded to particle motion rather than sound pressure (Chapman and Sand, 1974). The measured results indicate that the lower part of the origin of frequencies related to the turbine transmission system were cut-off as a function of the local water depth at the turbines and received position. Although these frequencies did not propagate, they are still pronounced as frequencies of particle motion in the water column and in the top layer of the sediment were flatfish is taken shelter. There is a lack of knowledge on the range and the effects of substrate-borne sound and particle motion.

Within the mainframe of the OWEZ research program the behaviour of individual fish to wind turbine noise was studied on cod (*Gadus morhua*) and sole (*Solea solea*) and summarized in section 5.1.3.

5 References to other OWEZ/IMARES research projects

5.1.1 *The effects of the OWEZ wind farm on harbour porpoise (OWEZ_R_253_T1_20120202)*

The detected of harbour porpoise activity (Scheidat et al., 2012), based on recording in- and outside the OWEZ wind farm showed the presence had a seasonal relation with a high activity in the winter months and low in the summer. These results were obtained using T-POD instruments, which are autonomous

recorders only sensitive in the harbour porpoise frequency range (130 to 150 kHz) and provided with electronic filtering techniques to filter out echolocation signals from other noise. The raw data files of these instruments do not provide information on individuals but show the activity of received harbour porpoise echolocation signals (click trains) as a function of time. The detections include a record of high activity over 5.5 hours (Scheidat et al., 2012, Table 5). A number of instruments were deployed in a reference positions outside the OWEZ area and two sets were deployed inside the wind farm close to turbine structures. A T-POD (AT4) was deployed at 446 m from WTG9 and 257 m from WTG10, while a second (AT5) was positioned 297 m from WTG33 and 547 m from WTG34.
As a wind speed condition was not reported and required to link the detections to a turbine noise condition the raw data of the detections were re-assessed and linked to the OWEZ turbine productions data. This assessment showed that the series of 5.5 hour (332 minutes) on TPOD AT5 (Scheidat et al., 2012, Table 5) was logged between 24 February 2008 18:34 and 25 February 00:05.
According the OWEZ production data the wind speed measured on the nacelles of WTG33 and WTG34 the average wind speed over the 5.5 hours period was 10.4 (WTG33) to 10.2 $m.s^{-1}$ (WTG34) with a produced power of 1765 to 1743 kW. The averaged wind direction based on the logs of the sensor information logged at the IJmuiden harbour (identified as K13) was south to southwest.

On the average wind speed condition of the TPOD detections the turbine noise (mean 95 % Confidence Interval) will raise 5 dB above the background noise level (Figure 33). Given the 5 dB difference between turbine noise and background noise at a wind speed of 10 $m.s^{-1}$ (Figure 33) the radius of the unmasked masking zone around WTG 33 is 315 m. The overview of Figure 28 illustrates the position of T-POD AT5, 297 m from WTG33, the estimated unmasked exposed turbine noise zone (black marked circle) and the assumed sensitivity ranges of the AT5 T-POD (red and white marked circles).

Figure 28 Deployed position of T-POD AT5, the unmasked turbine noise zone of 315 m (black circle) and the assumed sensitivity range of the AT5 T-POD (100-200 m), indicating that the logged animals could have been located in the zone masked by background noise.

In the estimated unmasked zone we assumed the sea state and turbine noise conditions at WTG27 measured on northern wind direction is applicable to the south to south-western conditions at WTG33. The distance between the marked hydrophone position east of WTG27 (Figure 28) and TPOD AT5 is 788 m.
This additional result excludes idle mode condition of WTG33 for the duration of the detections, but there is no solid evidence that these animals were inside the unmasked turbine noise zone during the detections. The illustration of Figure 28 shows that the TPOD was positioned on the edge of the masking

range and that the sensitivity range of the instrument in this particular case is not the most important issue. We assumed a detection radius of maximum 200 m, but field trials estimating the detection ranges of TPODs by visual tracking (Kyhn et al., 2012) showed that the detection ranges varied between 22 to 104 m. The sensitivity of TPODs was tested in a tank (Kyhn et al., 2008) and varied per type and instrument between 123 and 132 dB re 1μPa^2 (p/p). This observation involved two different water depths with one rather shallow and three different TPOD versions (1, 3 and 5). The data amount related to the AT5 type 3 version is the smallest of all and showed a deviation of 6 dB equals the presently reported difference between turbine and background noise. This experiment shows that TPOD instruments need to be deployed in closer range of a turbine and the performance needs to be calibrated, preferably by simulation in the field.

5.1.2 Habitat preferences of harbour seals in the Dutch coastal area: analysis and estimate of effects of offshore wind farms (OWEZ_R_252 T1 20120130)

The population of harbour seals is divided over two locations, the Wadden Sea with 6000 individuals (based on counts in 2008) and the Dutch Delta area with approximately 200 individuals. Satellite tracks showed that the seal can travel 50 to 100 km offshore and that the distance of the OWEZ location towards the two main colony locations are within range.
The study on the abundance and distribution of tagged harbour seal (*Phoca vitulina*) (89 individuals) showed that a relation with operational wind farm noise could not be found. This study was based on 29000 tracking locations acquired in the period 1997 to 2008.

5.1.3 Individual behaviour of fish in the wind farm (OWEZ_R_265_T1_20100916)

The tagging experiment on sole (*Solea vulgaris*) in response to the operation of the wind farm (Winter et al. 2010) indicated that the majority of sole movements take place at spatial scales larger than the wind farm area of OWEZ. Some individuals use the wind farm area for periods up to several weeks during the growing season. The results indicate that sole behaves indifferent to the wind farm.

Atlantic cod (*Gadus morhua*) (47 specimen) were tagged with transponders of a telemetry system. The receivers of this system were positioned in the vicinity of 16 of the 36 turbine structures, at a distance of approximately 10 m, just outside the stone-bed structure. The detection range of the equipment is specified as 100-500 m. The experiment covered a period of almost a year and was executed between September 2008 and June-July 2009. The results showed a large variation of individual behavior 30 % were detected for only a few days and probably extended the range outside the OWEZ area. A large share (55 %) were detected over a period varying between two weeks to two months, while 15 % were detected in the wind farm for 8-9 months. The presence of cod was also compared with the mode of operation of the turbines (idle mode). The conclusion was that no relation could be found in the presence of the fish and the operational mode of the turbines.
This outcome shows that the cod (55 %) was exposed to turbine noise for a longer period of time (8-9 months) and that the behavioral aspects could not be related to turbine noise, although this species is sensitive to the full unmasked part of the turbine noise spectrum (≤ 315 Hz).

5.1.4 The effects of the wind farm on fish (OWEZ_R_264_T1_20121215_final_report_fish)

The study on fish (van Hal et al. 2012) was divided in four sub-projects that might contain information to support the predicted effects of turbine noise. The first sub-project was a demersal fish survey with demersal fish caught at distances of 300-500 m from the wind turbines. This study indicated that demersal fish were in the farm and no obvious differences were found for these species compared to reference areas outside the farm. This indicated neither avoidance, potentially due to turbine noise, nor attraction to the farm area.

The second sub-project, a pelagic survey studied pelagic fish at a similar distance from the turbines. For species like Atlantic herring (*Clupea harengus*) and sprat (*Sprattus sprattus*), it was shown that they occur in the wind farm area in comparable numbers as in the outside reference areas. Neither for pelagic species an avoidance at the distance of 300-500 m from the turbines was shown. These results of both sub-projects are similar to studies on the Danish Horns Rev 1 (Leonhard et al., 2011) and the Belgian Thornton bank and Bligh bank wind farms (Vandendriessche et al. 2011). In Horns Rev 1 day-night migration of pelagic fish was observed, at day-time higher abundance and biomass was observed inside or close to the wind farm, whereas during night the opposite distribution pattern was observed (Leonhard et al. 2011). But this seems unlikely to be an effect of noise emission by the farm.
At a closer distance, gillnet catches and observations (Diving and Camera) supported the presence of fish within a couple meters of the turbines (Bouma & Lengkeek, 2009). Indicating no avoidance related to sound emission. The species that indicated a lower presence in the near surrounding are more likely to prefer the sandy bottoms rather than the hard substrate near the monopiles. None of these fish studies referred to wind conditions at the time of sampling. The camera observations were done under low sea state conditions, while the fishing activities were executed low to moderate wind conditions. The gillnets fished periods also involve rougher weather conditions. The camera observations also showed the presence of harbour porpoise and harbour seal inside the wind farm. But these observations were based on excellent conditions and less valuable as reference for the conditions turbine noise is developed.

6 Conclusions

6.1 Turbine noise characteristics

Low-frequency turbine noise is developed as soon as the turbine starts to produce power and becomes substantial in the range of 500 to 2000 kW. Turbine noise is mainly peaking in the 50, 100 and 200 Hz Third-Octave bands (Mission 1,Table 2, Figure 44; Mission 2, Table 3, Figure 60). On Mission 1 a 30-minute period (Figure 44) with no shipping noise interference the SPLs in these dominant bands were respectively 111 (StDev 2.2), 112 (StDev 0.9) and 114 dB re 1 μPa^2 (StDev 1.1). On Mission 2 a similar observation was made, but with higher variation (Figure 60). Incidental contribution in the 16 Hz band occurred for the duration of 12 hours on Mission 1 at low turbine power condition and eastern wind with low sea state noise (Figure 34). This contribution did not occur on northern wind and similar turbine power conditions
At frequencies ≥ 400 Hz the turbine noise equalled the background noise level measured in the reference position 7.4 km north of the wind farm area (Figure 44 and 60).

Turbine related noise produced by the auxiliary engines, clearly detected in the first measurements of 2007, was not detected in the data of 2013. The omission could be attributed to the concrete filling of all 36 monopolies in 2010, provided no other measures were undertaken on the engine structures. This suggests that such a measure could damp the propagation of this type of engines.

6.2 Propagation estimate

The maximum unmasked range of turbine noise is based on the highest wind speed (12-15 m.s^{-1}) continuously from eastern direction causing lowest sea state noise contribution (Figure 22). On that condition the averaged difference between turbine and background noise levels ranged between 8.1 and 8.4 dB. According the intermediate of spherical and cylindrical spreading model of 15 Log R (Thiele in Thomson et al., 2006) and the 95 % confidence test (Figure 31) the unmasked estimated zone is 449≈463 m. When the maximum system error (0.3 dB) is taken into account the maximum unmasked range is 480 m, while we propose 500 m as worst case condition.
On the trial with northern winds and higher sea state (Figure 23) the unmasked zone was less pronounced and based on the 95 % confidence test (Figure 33) the unmasked zone ranges between 272 to 417 m, with 431 m as maximum when the system error (0.3 dB) is included.

6.3 Contribution of wind farm related shipping

Wind farm related shipping, contributed with an exposure of 6.2 % of the total measured time (171 hours) by the transfer of personnel to WTG's, which was daily on our measurement trials. Turbine noise will probably be masked beyond 500 m, but propulsion noise during the landing of the ship at the WTG terminal could be detected at a much longer distance (3700 m), which was the upper limit of the measured range.

6.4 Contribution of other shipping

Incidental shipping noise had a high contribution in terms of exposed time (22.4 % of the total measured period) and distance to the received position. The highest levels were measured with larger vessels (≥ 100 m). The ship was heading north along the lane at the west of OWEZ towards the main coastal shipping lane at a speed of 20 knots and passed the WTG27 hydrophone at a shortest distance of 5234 m (Figure 70). This vessel masked turbine noise received at 100 m distance for a period of 40 minutes.

6.5 Effects wind farm noise to marine animals

When turbine noise is weighed against the auditory thresholds of harbour porpoise, harbour seal cod and herring it showed that harbour seal (Figure 63) and both fish species (Figure 66) will most likely be able to detect the noise. Harbour porpoise can hardly detect turbine noise (Figure 61).

6.5.1 TTS-onset in harbour porpoise exposed to turbine noise

Following the aim of assessing the impact of long-term turbine noise exposure we applied the most sensitive approach available in literature. TTS-onset in harbour porpoise exposed to turbine noise in the highest range ("H3") is reached after 75 days (Table 4). Although this result shows that a permanent exposure to turbine noise could lead to TTS-onset, it is unlikely harbour porpoise will remain stationary for such a period in the exposed area. As TTS-onset also depends on the recovery intervals and the spatial and temporal distribution of harbour porpoise in close range of turbines is unknown, additional information is needed to support to enforce this statement. TTS-onset in harbour porpoise exposed to WindCat noise

The exposure to noise of WindCat vessel landing at the terminal of WTG21 at 1722 m from the received position (Table 10, case 7) would cause TTS-onset to be reached after 3 hours and 10 minutes. The records of this type of shipping (Appendix C, Table 10) show that the duration of this activity is limited to periods of 10 minutes maximum and it will be unlikely that this operation will cause TTS-onset in harbour porpoise.

6.5.2 TTS-onset in harbour seal exposed to turbine noise

The weighed results according the 4 kHz reference TTS onset of 163 dB re 1 $\mu Pa^2 s$ (Kastelein et al., 2012b) of turbine noise produced at highest power condition shows that TTS-onset is reached after 7 days and 12 hours. Given the periods of haul-outs of these animals ashore it is unlikely that TTS in harbour seal can be reached. There is no proof of presence of animals through tracking data inside the wind farm area (Section 5.1.2 OWEZ_R_252 T1 20120130). TTS-onset in harbour seal exposed to WindCat noise

The exposure to a WindCat vessel according case 7 (Table 10) showed that TTS-onset is reached after 9 hours and 43 minutes. Given the limited duration of WindCats during landing against a WTG-terminal not extending 10 minutes, it is unlikely this exposure will cause TTS in harbour seal.

6.6 Limitations of the presented results

6.6.1 Turbine production data

The data of the turbine production are based on 10-minute averages. As raw data were not available frequency related analysis of the received underwater noise and rotational momentary conditions of the transmission system of the turbine could not be executed.

6.6.2 WindCat noise estimates

The SPLs mainly refer to the propulsion condition of free-sailing vessels use different propulsion power settings. We assumed that the propulsion conditions were comparable for all measured conditions. The actual propulsion settings are related to tidal current and wave height conditions.

6.6.3 TTS-onset estimates

Although we are confident on the outcome of the approach and the extrapolation included a number of uncertainties:

- TTS-onset references were tested against a fatiguing noise with a single frequency with the SPL and duration as variables;
- Literature on TTS-onset in the frequency range of turbine noise (0.2 kHz) is lacking;
- The characteristics of 4 kHz fatiguing type of noise and turbine noise are not similar;
- The TTS-references do not cover long term exposures and are maximised to 240 minutes, while exposures >240 minutes are likely to produce a stronger effect as indicated by Kastelein et al. 2012;
- The TTS and auditory studies are based on a single specimen;
- We applied a 30 dB compensation for TTS-onset in harbour porpoise for frequency mismatch justified by the declining trend of TTS in bottlenose (Finneran et al., 2010). Although such compensation is supported by the 60 dB hearing sensitivity reduction, data based on tests are lacking;
- The measurement results are limited to a frequency bandwidth of 10 Hz of 20 kHz. Conclusions outside this range are not valid.

6.7 Recommendations

- Given the lack of knowledge on the effects of low-frequency type of noise, similar to turbine noise, it is recommended to conduct TTS-experiments with turbine type of noise on harbour porpoise and harbour seal following the methods of Kastelein et al., 2012.
- TTS-onset in harbour porpoise is not likely to occur, although the reported estimate suggests that TTS can be reached on long term exposure. As TTS-onset also depends on the recovery intervals after exposure additional behavioural research is needed on the spatial and temporal use of harbour porpoise and harbour seal in the unmasked zone of turbine noise.
- The results confirm that the positioning of wind farms close to shipping lanes is the best approach to mask this relatively low level noise source by shipping and so minimising the periods that turbine noise rises above the level of the background noise.

Quality Assurance

IMARES utilises an ISO 9001:2008 certified quality management system (certificate number: 124296-2012-AQ-NLD-RvA). This certificate is valid until 15 December 2015. The organisation has been certified since 27 February 2001. The certification was issued by DNV Certification B.V. Furthermore, the chemical laboratory of the Fish Division has NEN-EN-ISO/IEC 17025:2005 accreditation for test laboratories with number L097. This accreditation is valid until 1 April 2017 and was first issued on 27 March 1997. Accreditation was granted by the Council for Accreditation.

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Justification

Rapport OWEZ_R_251 T1 2013-06-17 IMARES C069/13
Project Number: 4306101813

The scientific quality of this report has been peer reviewed by a colleague scientist and the head of the department of IMARES.

Approved: Ph.D. Klaus Lucke
Senior scientist department Ecology

Signature:

Date: 14 June 2013

Approved: Drs. J. H. M. Schobben
Head department Vis

Signature:

Date: 30 August 2013

Appendix A Pictures and Figures

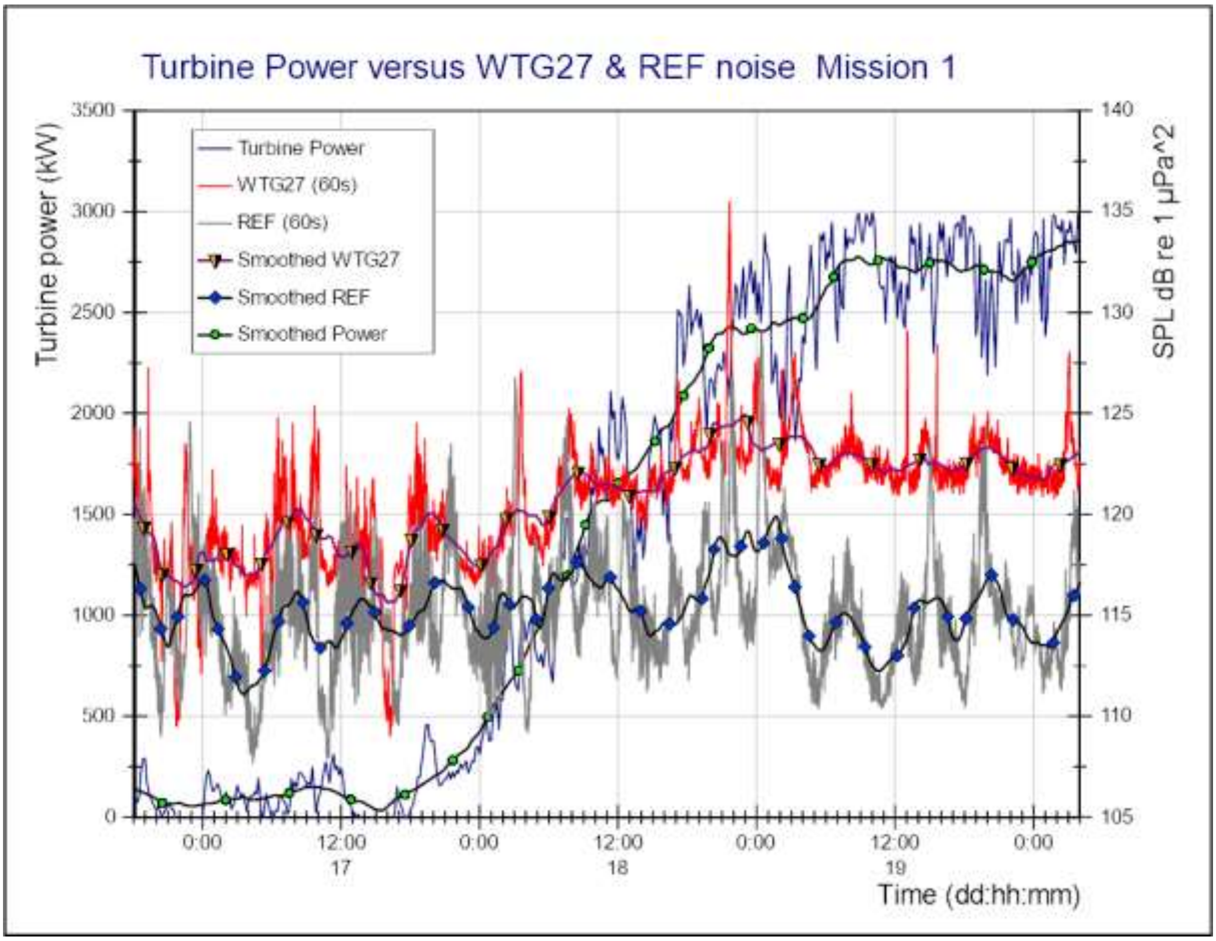


Figure 29 Broad-band Noise levels (averaged over 60 s) measured at 100 m from WTG27 and in a reference position 7.4 km to the north of OWEZ (REF). Smoothed results show that the turbine noise level is mainly determined in the power range of 500 to 2000 kW. Above this range the noise hardly increased. High incidental peaks were detected in both positions and relate to ship noise.

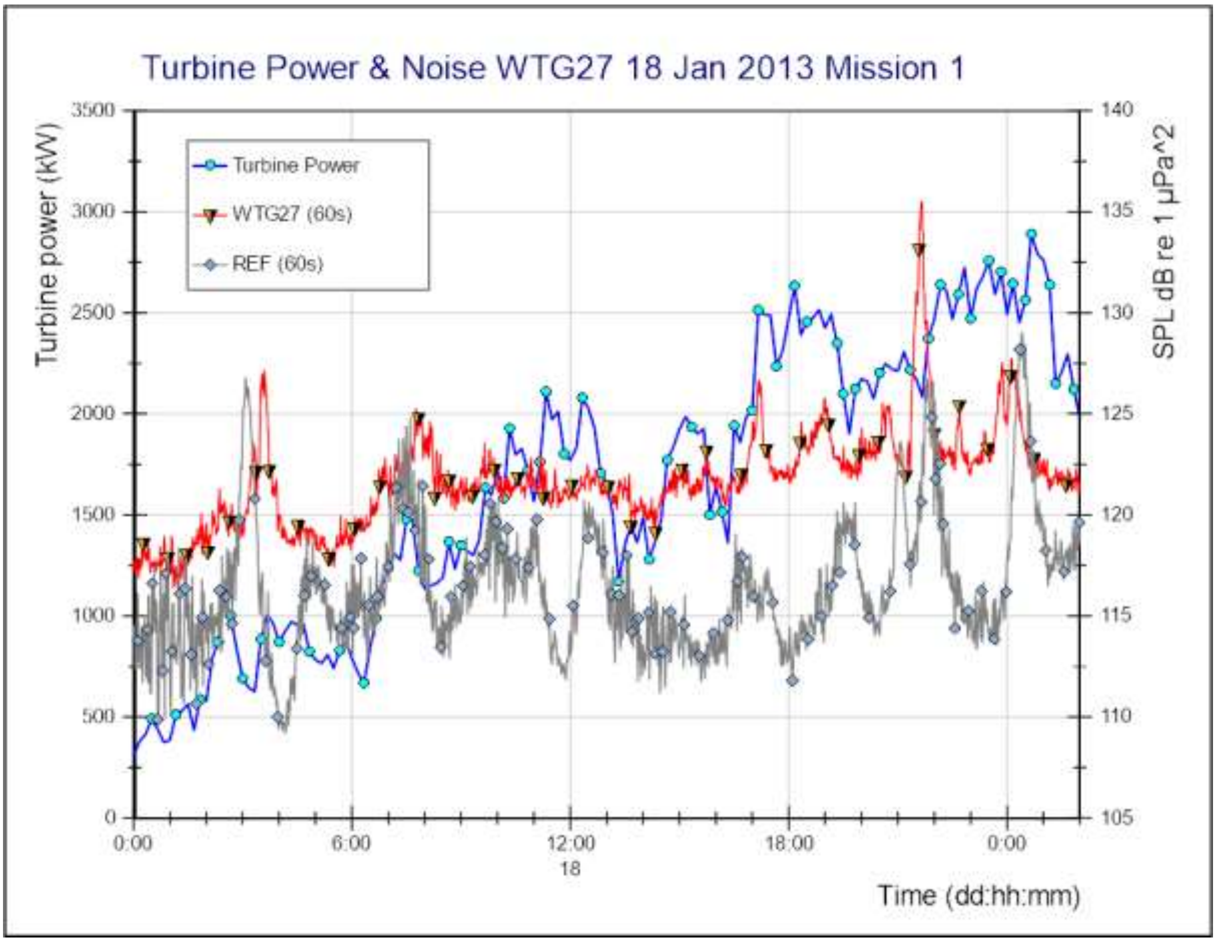


Figure 30 Overview of noise levels of 18 January 2013 (zoom-in of Figure 29) showing two incidental peaks of ship noise not related to wind farm energy production. The first case the ship sailed south with an elapsed time of 32 minutes over 7.4 km. The second case shows detections indicating multiple shipping. The detection represented a vessel sailing at the east side in northern direction and passed the WTG27 hydrophone at a distance of 4370 m.

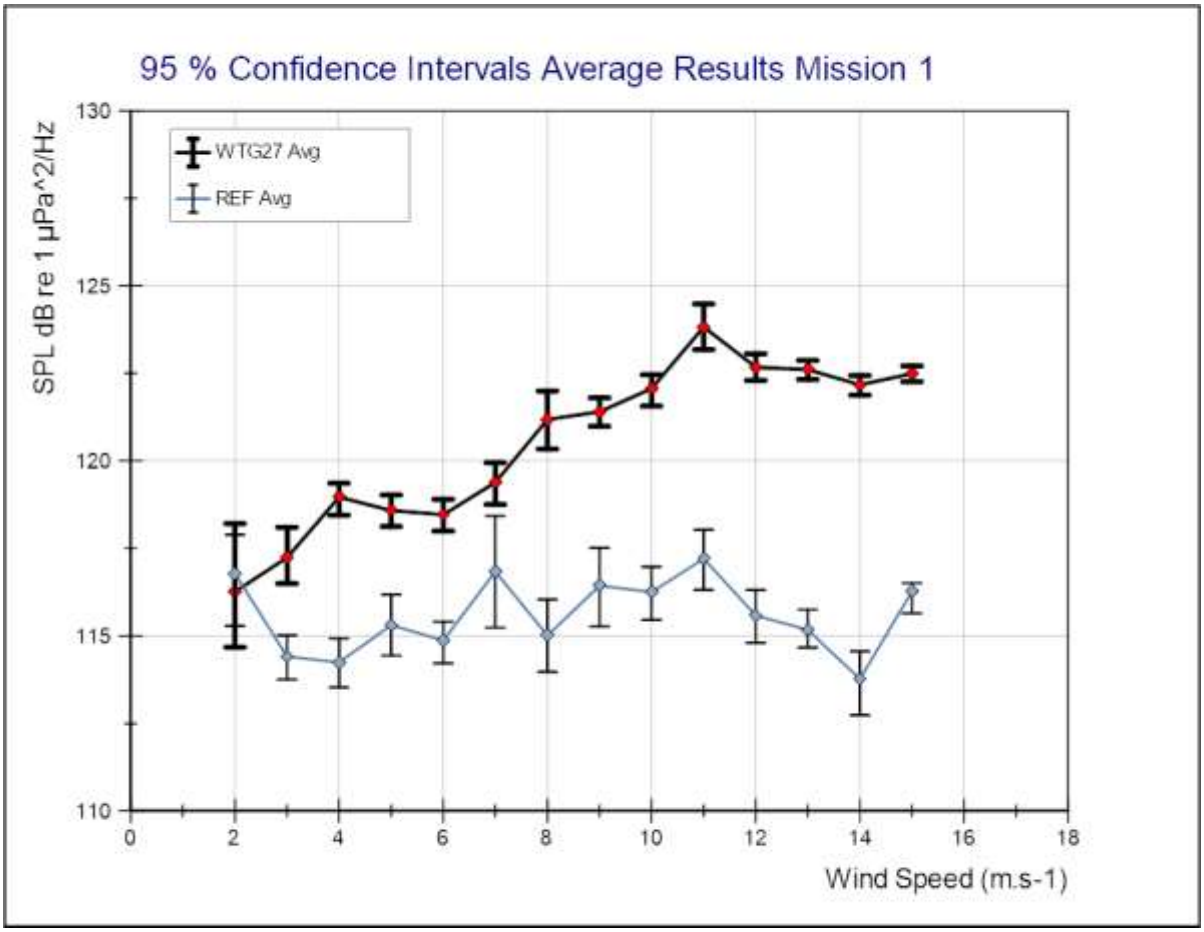


Figure 31 Broad-band turbine spectral noise levels at 100 m from WTG27 and in the reference position sorted as a function of wind speed for the first period (Mission 1). For each result the uncertainty is estimated based on a 95 % Confidence Intervals (CI) statistical test.

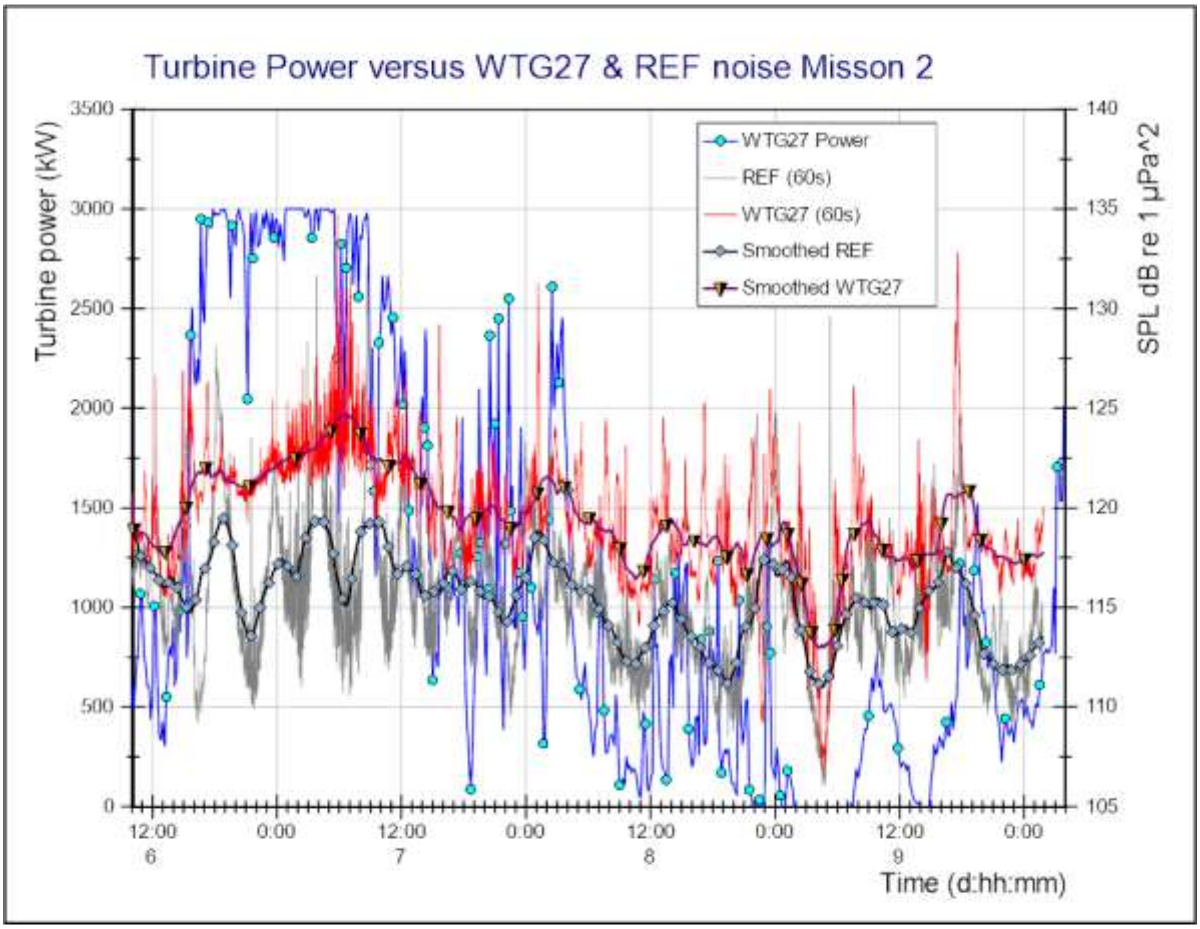


Figure 32 Broad-band noise levels (averaged over 60 s) of Mission 2 measured at 100 m from WTG27 and in a reference position 7.4 km to the north of the OWEZ wind farm (REF). In this period the wind condition increased in a shorter period, but also in this result the ramping up of the turbine noise level is the steepest in the power range of 500 to 2000 kW (6 February 13:00-17:00). Above this range the noise hardly increased. As a result of wave height the sea state noise is shown in the noise measured at the reference position. On the highest wind speed condition the noise patterns follows the tidal current frequency. High incidental peaks were recorded on both positions indicating the contribution of ship noise.
The conditions slowly improved which caused a period of idling on 9 February between 03:00 and 07:00 and at 14:00.

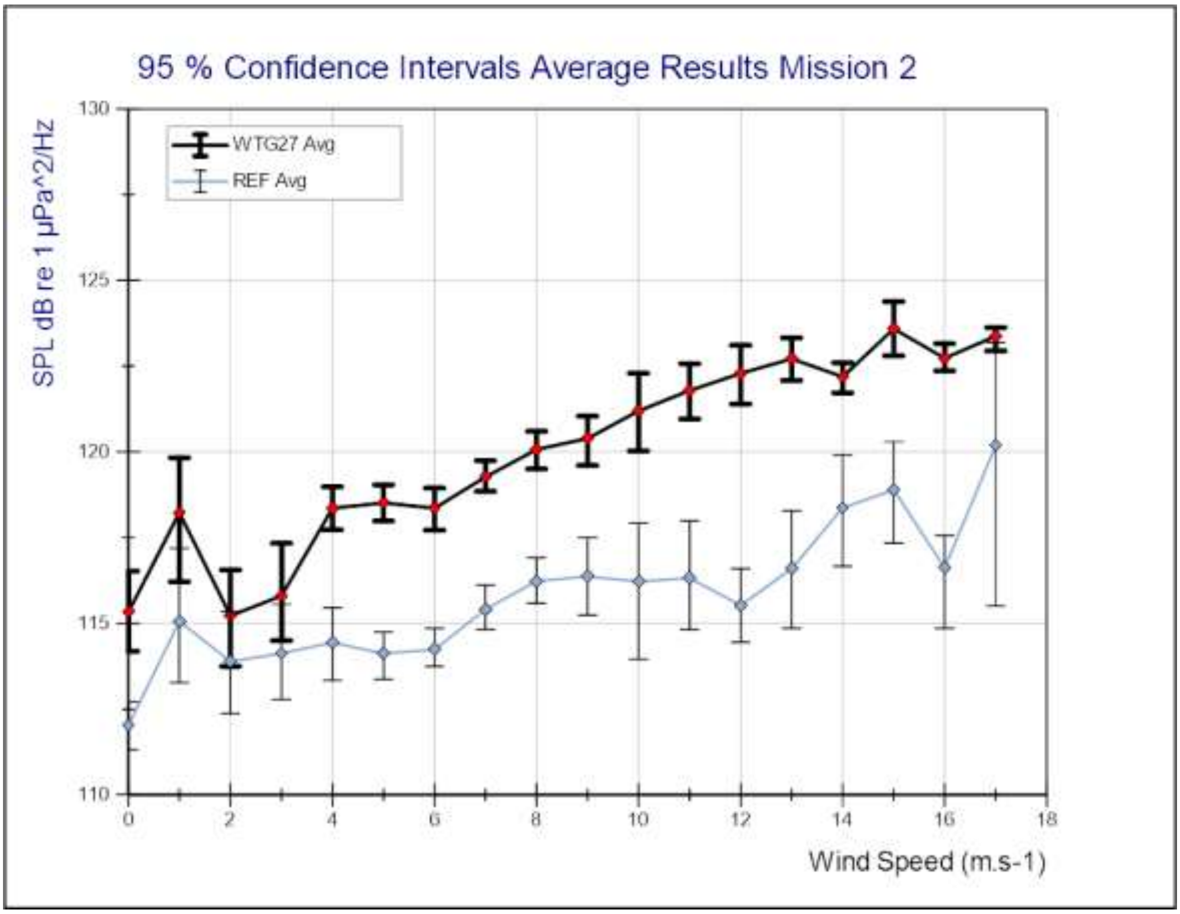


Figure 33 Broad-band turbine spectral noise levels sorted as a function of wind speed for the second period (Mission 2). For each result the uncertainty is estimated based on a 95 % Confidence Intervals (CI) statistical test. The results show that the sea state condition had a bigger effect on the levels, particularly expressed in the regression of the reference results. Under this condition the turbine noise level increased with wind speed over the full range. The maximum level compares to the outcome of Mission 1.

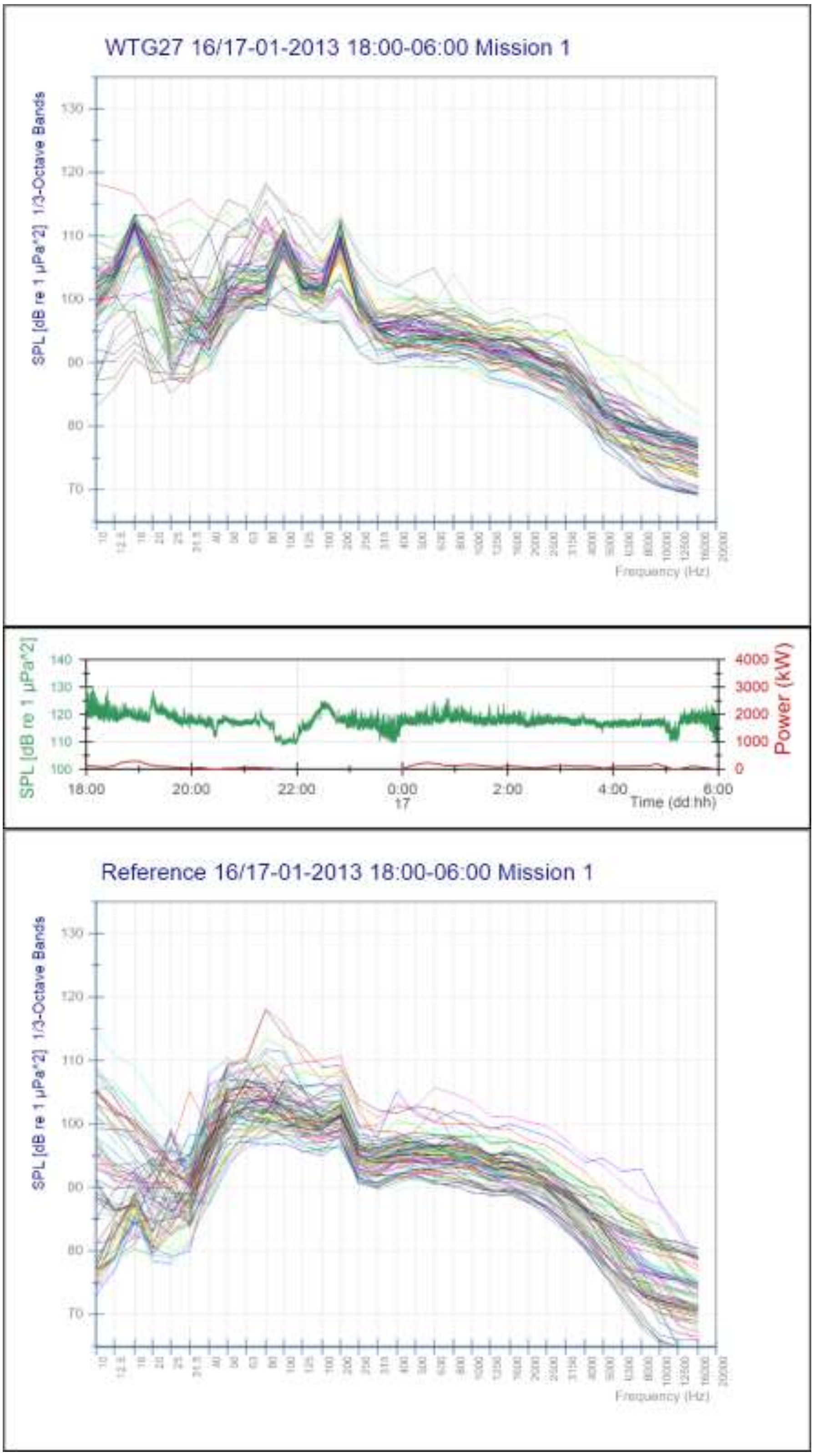


Figure 34 Third-Octave spectra of turbine noise sampled per 10 minutes over a night-time period of 12 hours. Each 10-minute sample is the linear average of a 1 s sample over 10 s. The power production in the sampled period was marginal (< 200 kW), but the turbine noise contours are well expressed in the 16 Hz-, 100 Hz- and 200 Hz-bands.

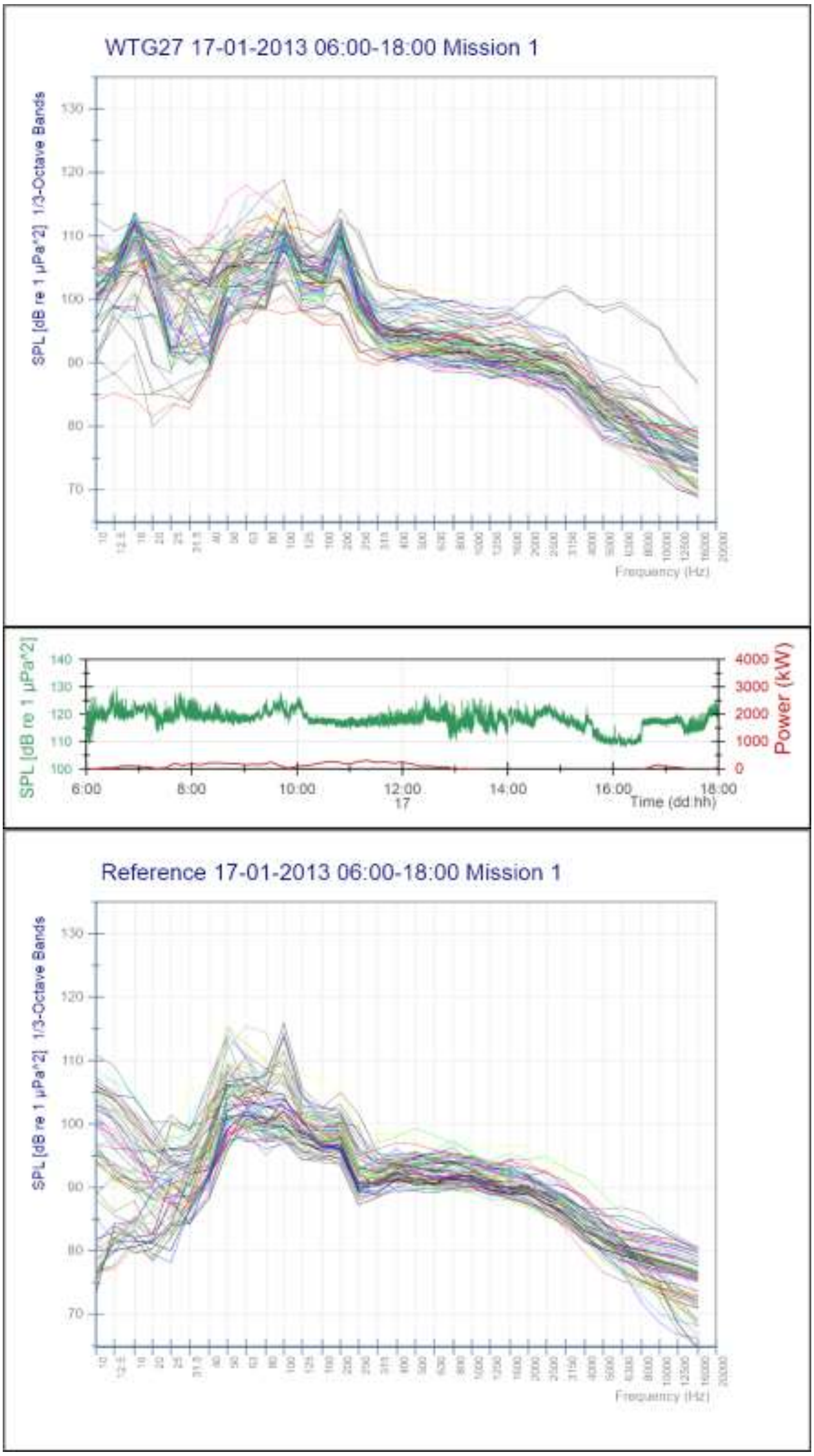


Figure 35 Third-Octave spectra of turbine noise sampled per 10 minutes over a day-time period of 12 hours. Each 10-minute sample is the linear average of a 1 s sample over 10 s. The power production in the sampled period was still marginal (< 200 kW), but the turbine noise contours are well expressed in the 16 Hz-, 100 Hz- and 200 Hz-bands. Ship noise attributed to WindCats is expressed in the HF-bands.

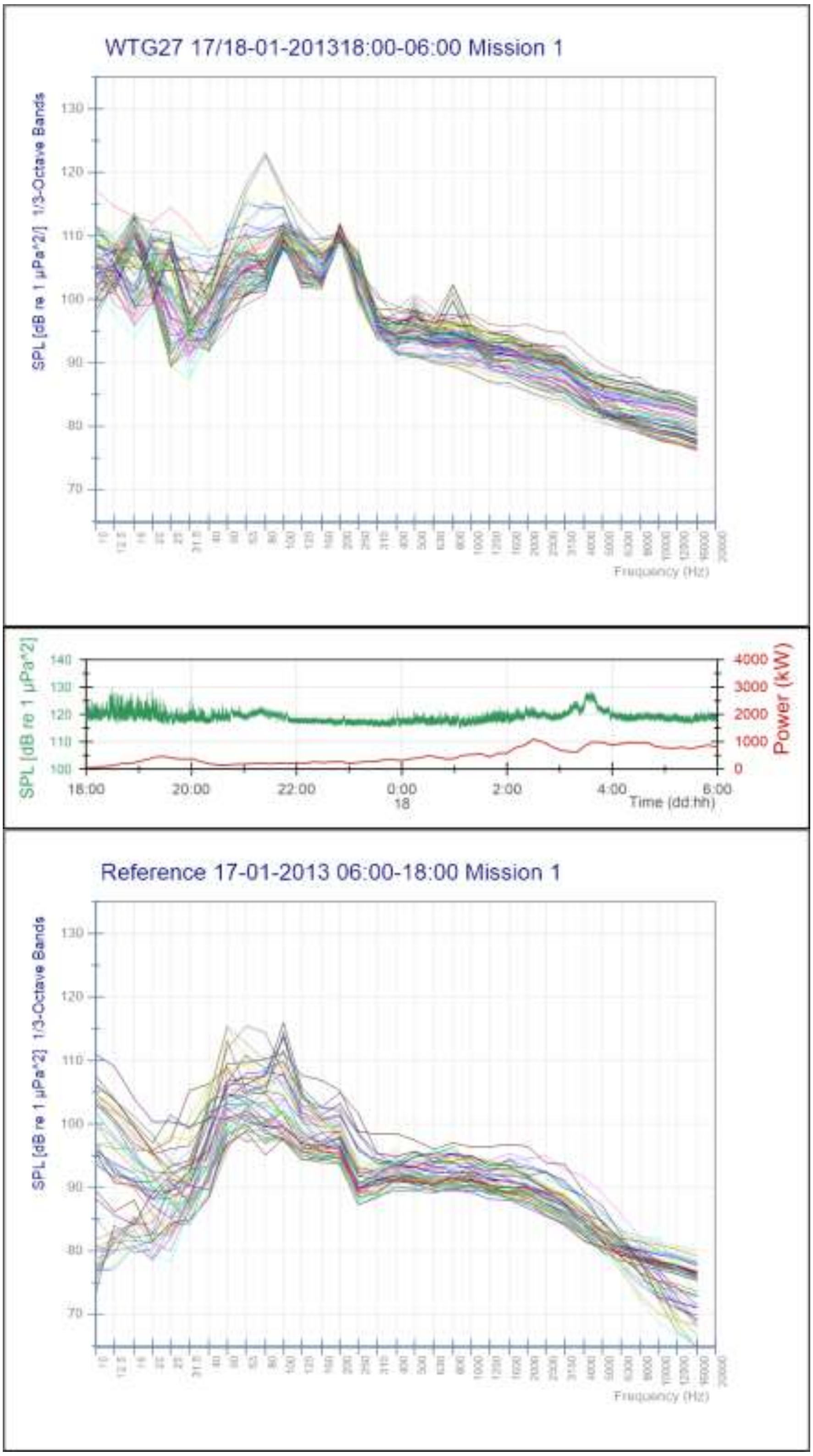


Figure 36 Third-Octave spectra of turbine noise sampled per 10 minutes over a night-time period of 12 hours. Each 10-minute sample is the linear average of a 1 s sample over 10 s. The power production in the sampled period increased to 1000 kW, but the turbine noise contours mainly expressed in the 100 Hz-band. The contribution in the 16 Hz-band disappeared.

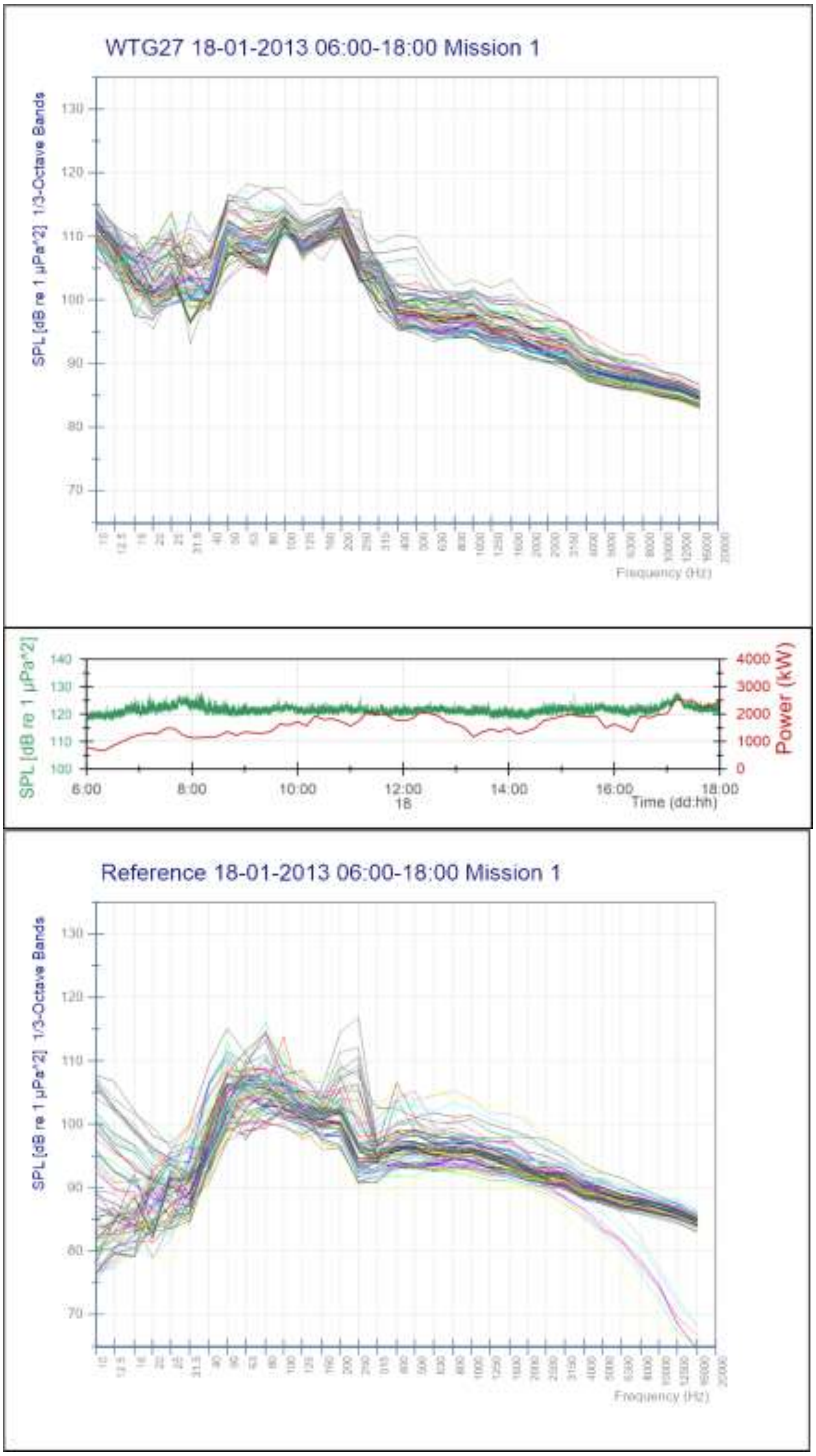


Figure 37 Third-Octave spectra of turbine noise sampled per 10 minutes over a day-time period of 12 hours. Each 10-minute sample is the linear average of a 1 s sample over 10 s. The power production in the sampled period increased from 1000 to 2000 kW, but the energy of turbine noise in the 16 Hz-band reduced. Ship noise is expressed in the reference graph.

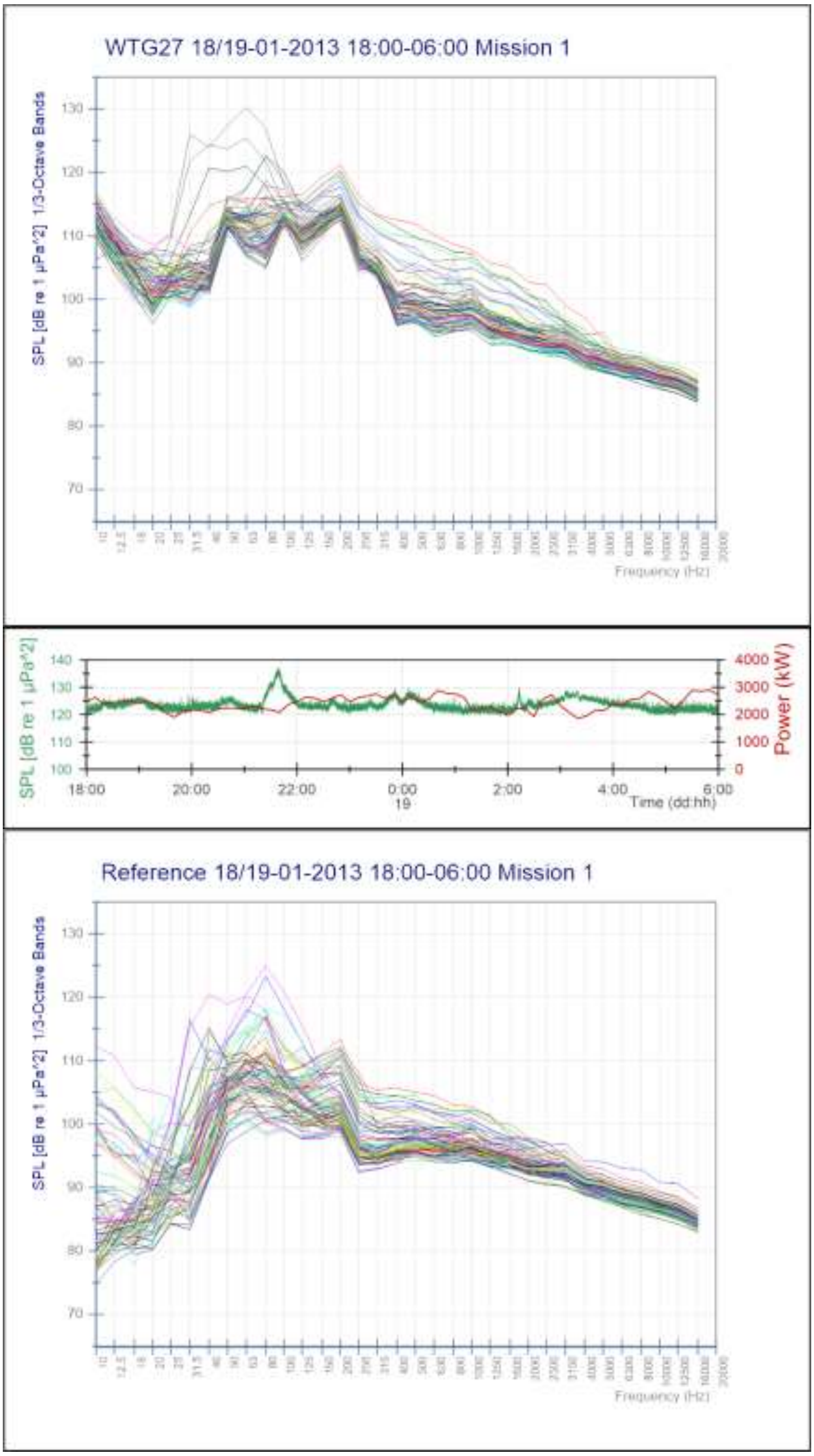


Figure 38 Third-Octave spectra of turbine noise sampled per 10 minutes over a night-time period of 12 hours. Each 10-minute sample is the linear average of a 1 s sample over 10 s. The turbine reached the max power condition and the turbine noise in the 16 Hz band disappeared. The main energy contours are around the 50 Hz-, 100 Hz- and 200 Hz-bands. Huge masking effect of ship noise in both measured positions with the peak received on the WTG27 hydrophone at 21:40.

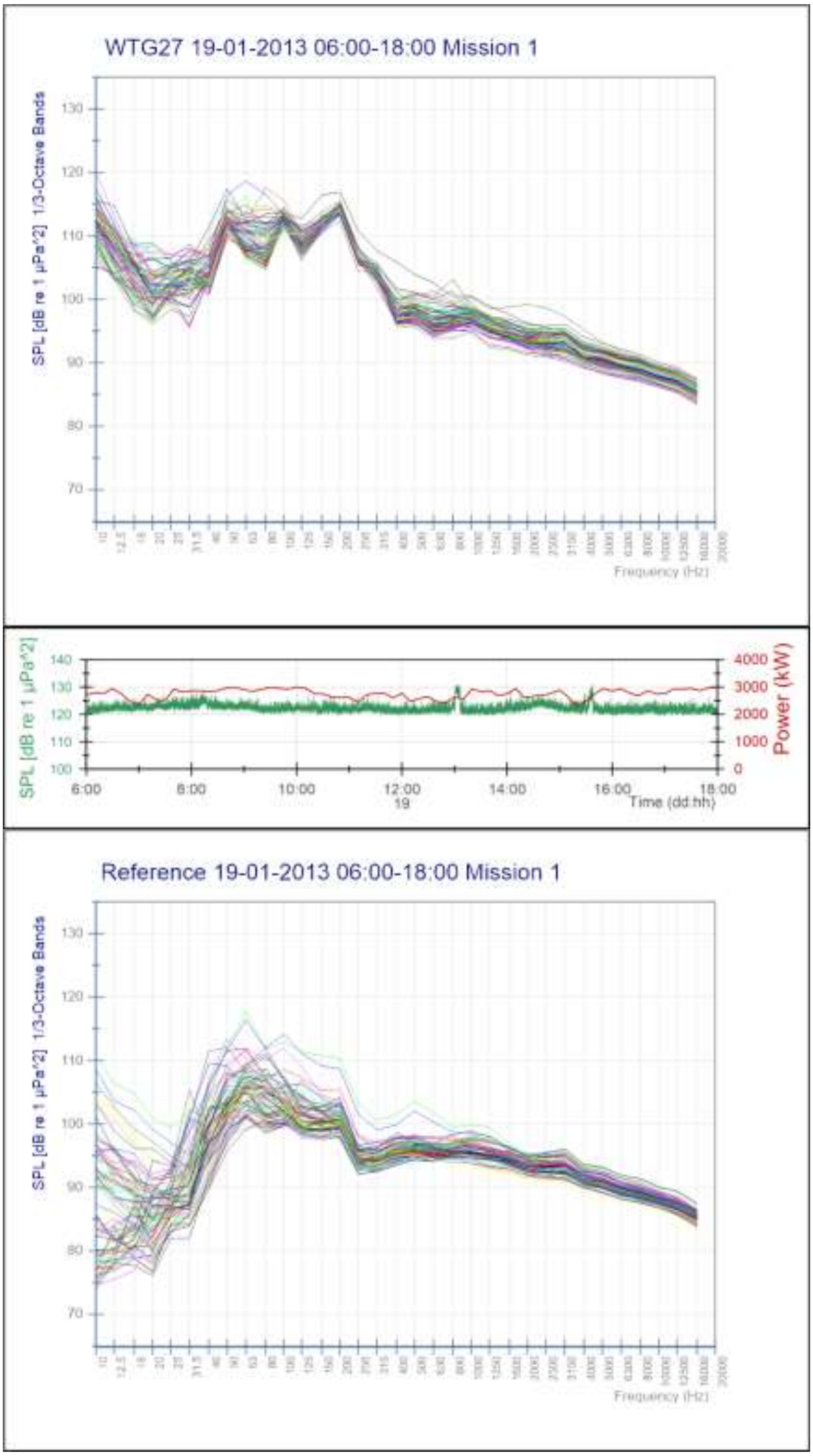


Figure 39 Third-Octave spectra of turbine noise sampled per 10 minutes over a day-time period of 12 hours. Each 10-minute sample is the linear average of a 1 s sample over 10 s. The turbine produced the max power with noise contours mainly expressed in the 50 Hz-, 100 Hz- and 200 Hz-bands. The cut-off of frequencies in bands < 16 Hz caused a gap in the energy in bands < 50 Hz.

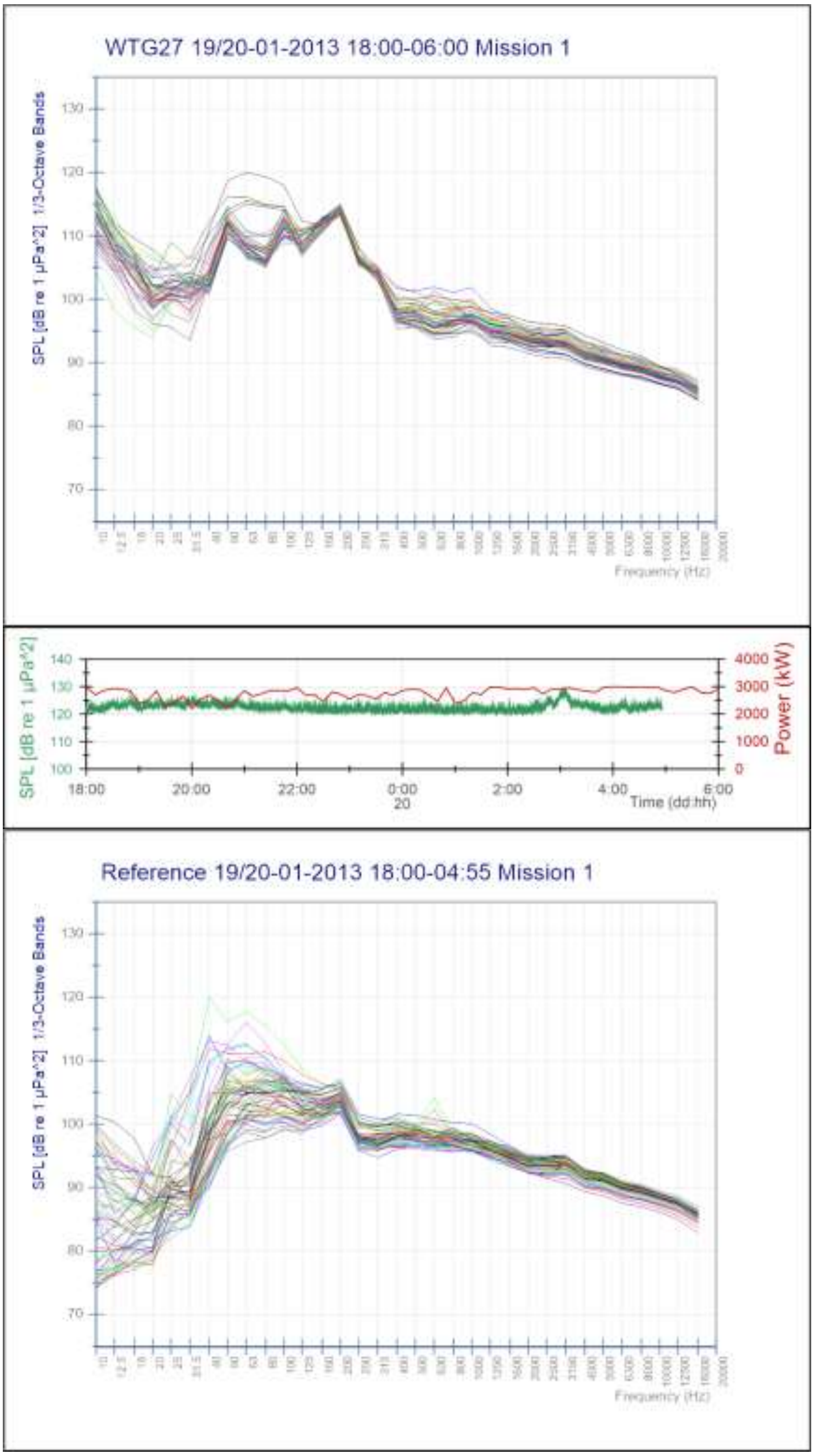


Figure 40 Third-Octave spectra of turbine noise sampled per 10 minutes over a night-time period of nearly 11 hours. Each 10-minute sample is the linear average of a 1 s sample over 10 s. The turbine produced the max power with contours of the spectrum mainly depended by energy in the 50 Hz-, 100 Hz- and 200 Hz-bands.

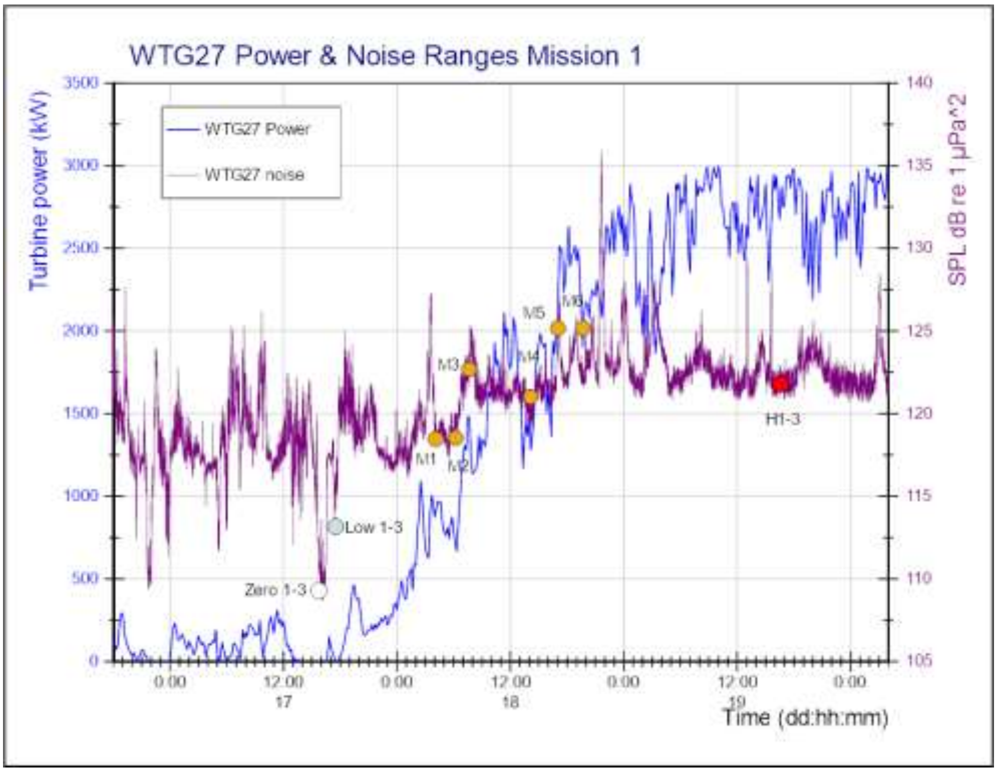


Figure 41 Broad-band noise levels (averaged over 30s) against turbine power and the marked ranges where Third-Octave analysis was applied (Figure 42).

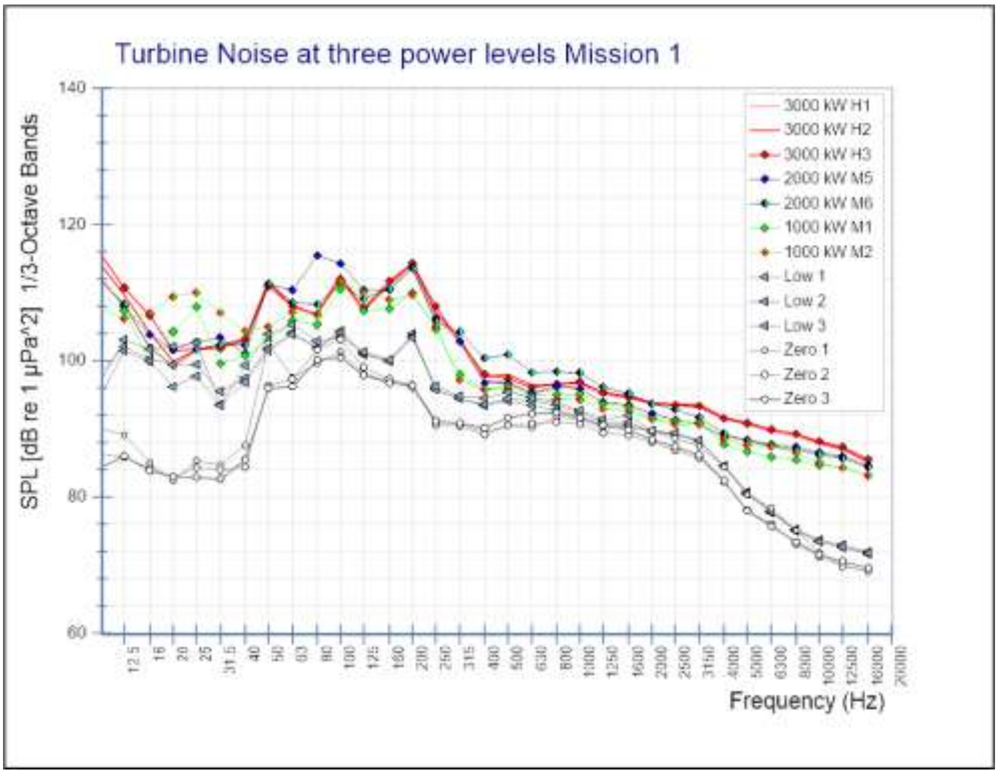


Figure 42 Turbine noise in Third-Octave bands (60 s linear averaged 1 s samples) at power ranges from zero to 3000 kW. Samples refer to the marked positions in Figure 41. The results express that the noise is becoming significant as soon as the turbine starts in the bands ≥ 50 Hz and that the noise does not increase much at power ranges above 1000 kW. Operational conditions are listed in Appendix B, Table 5.

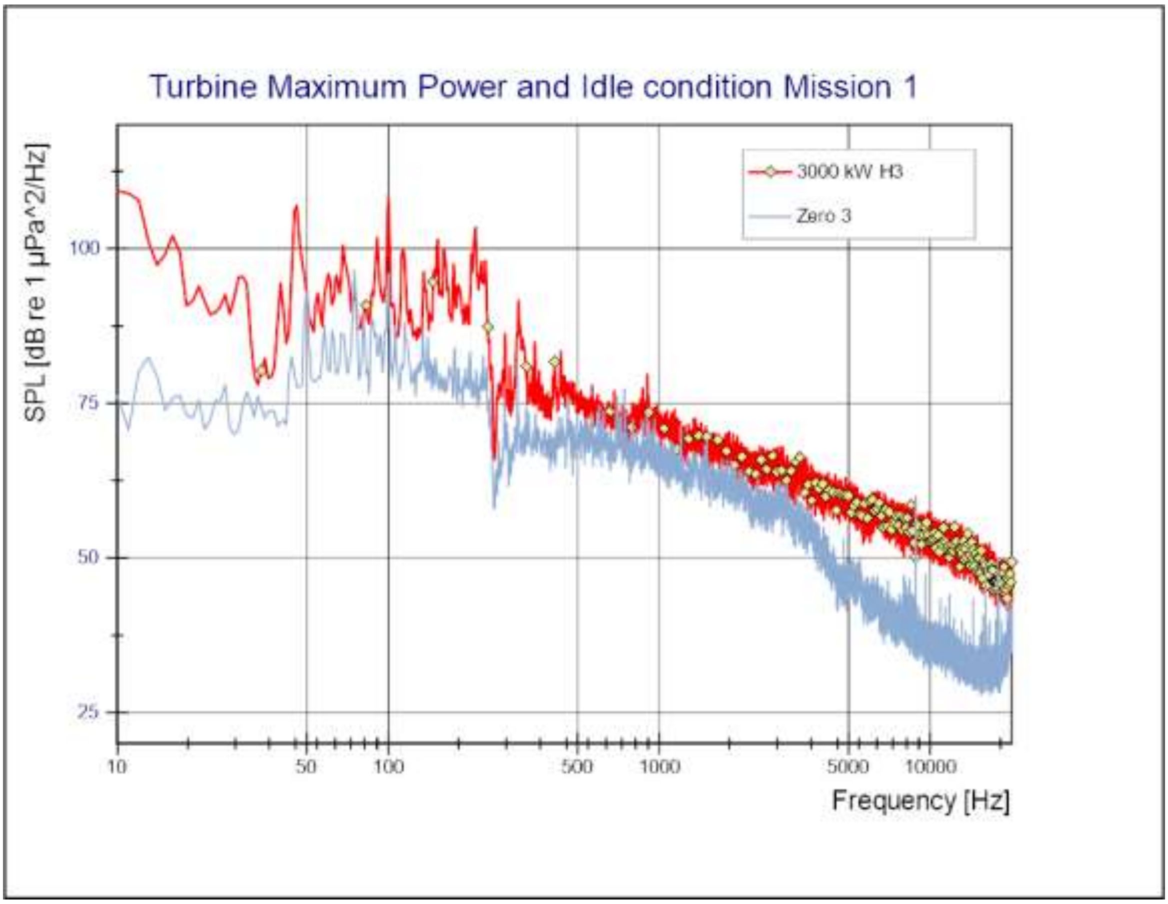


Figure 43 Overview of narrow-band analysis (Fast-Fourier Transformed, 1 s blocks, average length 10 s, 50 % overlap) of the maximum power condition taken on 19 Jan marked as "H3" in Figure 41 and 42 against the idle mode condition of the turbine on 17 January 2013 16:14 (marked as "zero 3" in Figure 41 and 42). The analysis shows the noise peaks attributed to the turbine and rotor transmission system with a strong decline at 250 Hz.

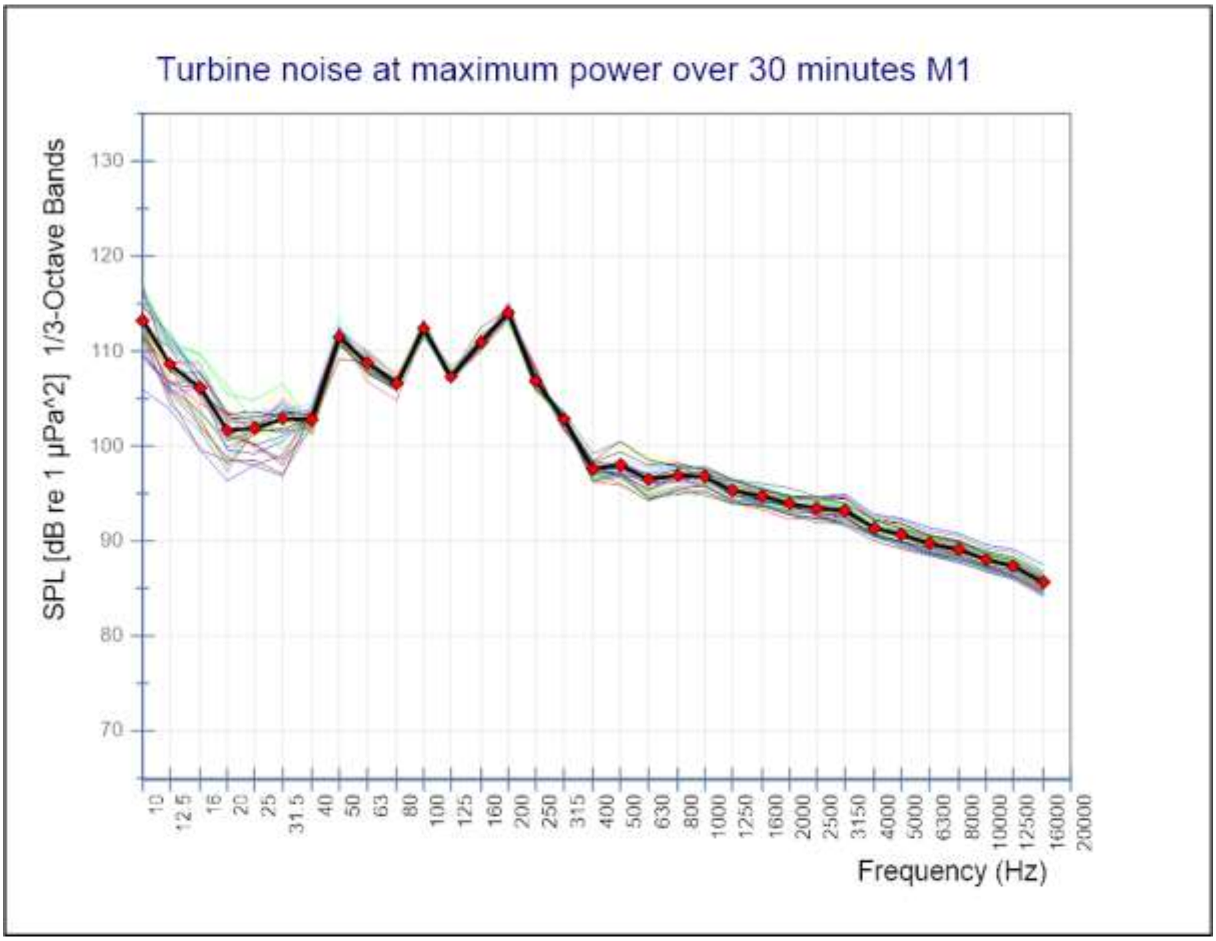


Figure 44 Third-Octave spectra at maximum turbine power condition on 19 January 2013. Each plot represents a 10 s linear averaged result of 1 s blocks with 1 minute-intervals between 16:25 and 16:55. In this period there was no contribution of ship-noise. The marked track is the calculated average. The contours of the turbine noise are mainly in the 50 Hz-, 100 Hz-, and 200 Hz:

Third-Octave band (Hz)	Average (dB re 1 µPa^2)	Max Average (dB re 1 µPa^2)	Min Average (dB re 1 µPa^2)
50	111.5	113.6	109.2
100	112.4	113.3	111.5
200	114.1	115.1	112.9

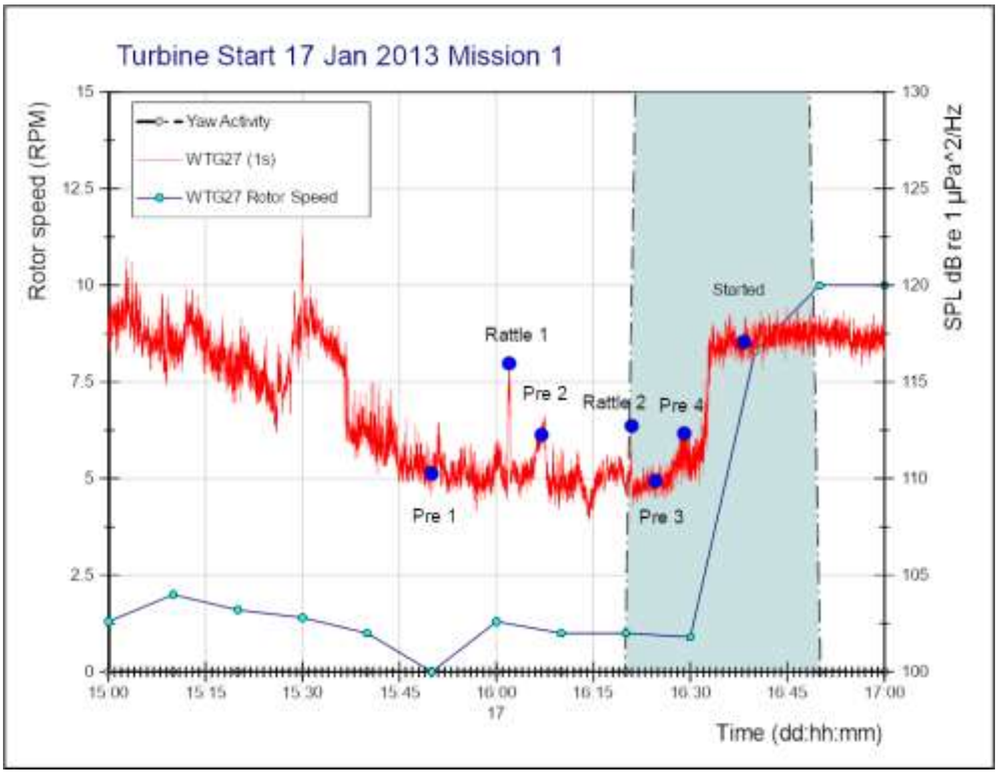


Figure 45 Activation of the turbine from idle mode on 17 January 2013 with two conditions of noises of the rotor blade piston mechanism. The marked area refers to the Yawing-activity. The turbine related data is listed in Appendix B, Table 5. The Third-Octave noise spectra at the marked conditions are shown in Figure 46.

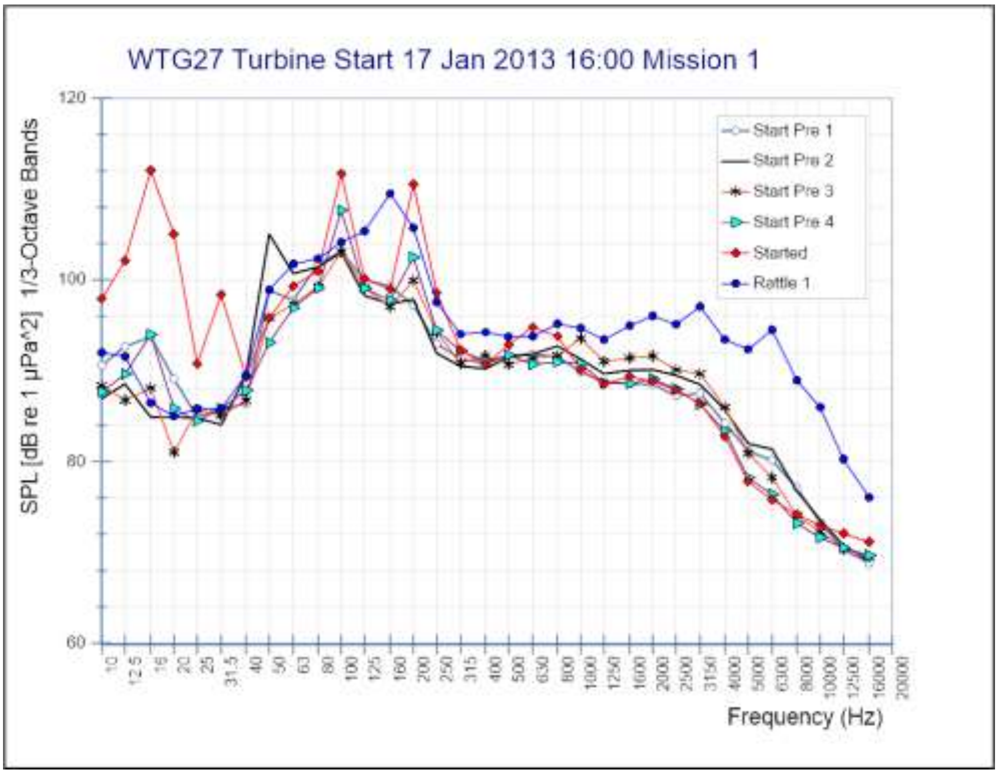
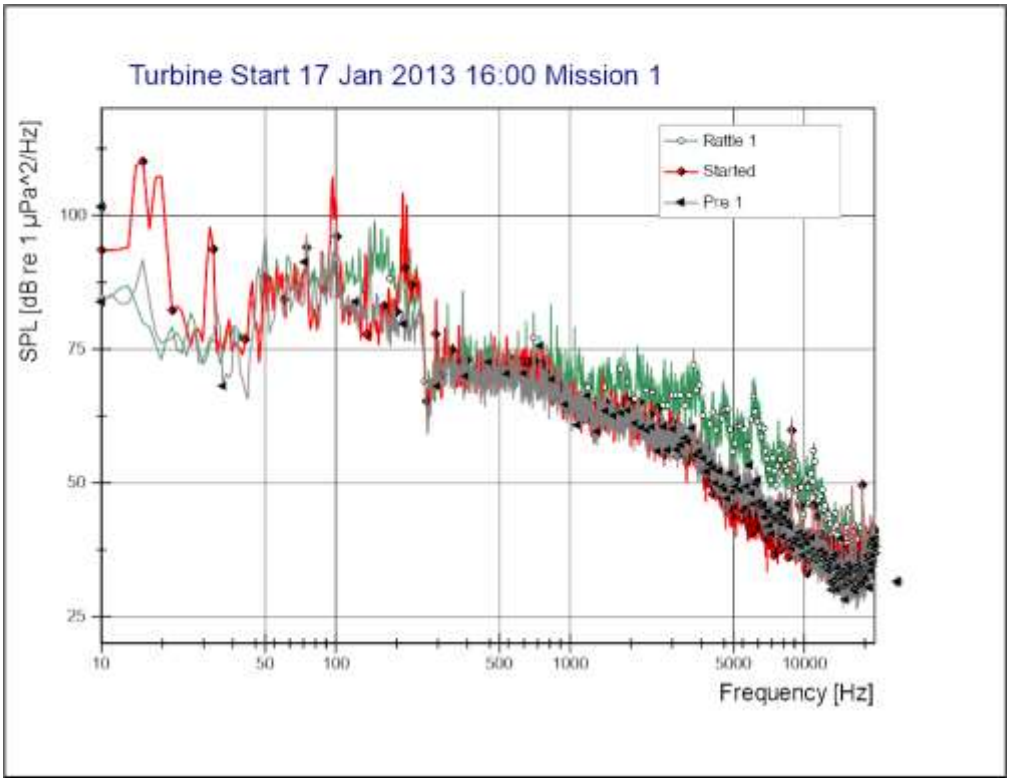


Figure 46 Third-Octave noise spectra of moments in the start-up of the Turbine on 17 January 2013. Each result is the linear average of 1 s samples over a 10 s period. Turbine noise is pronounced in the 16-, 100 and 200 Hz-bands as soon as the turbine starts to operate. The incidental rattling noise caused some increased higher frequency contribution in particular around 3 kHz.



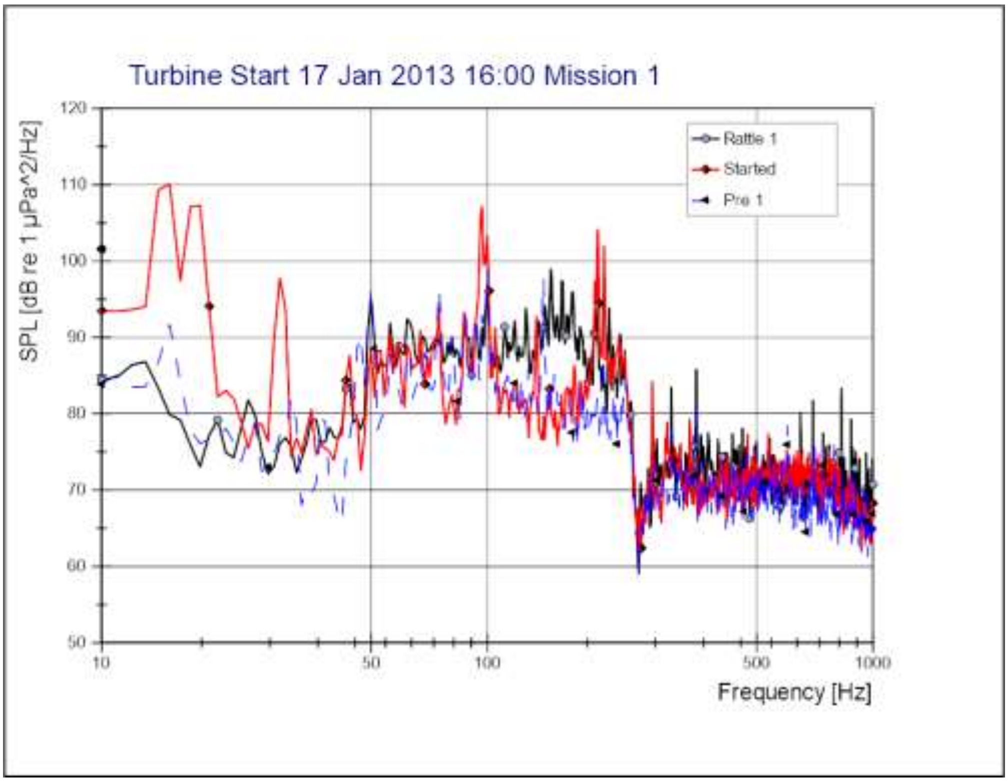


Figure 47 Turbine activation in narrow-band analysis (Fast-Fourier Transformed, 1 s blocks, average length 10 s, 50 % overlap). Samples are taken shortly before and after the start of the on 17 January 2013, showing the HF- noise developed by the rotor blade pitch mechanism with LF turbine noise peaks at 16, 29 and 98 Hz. Samples refer to the marked events in Figure 45 and 46.

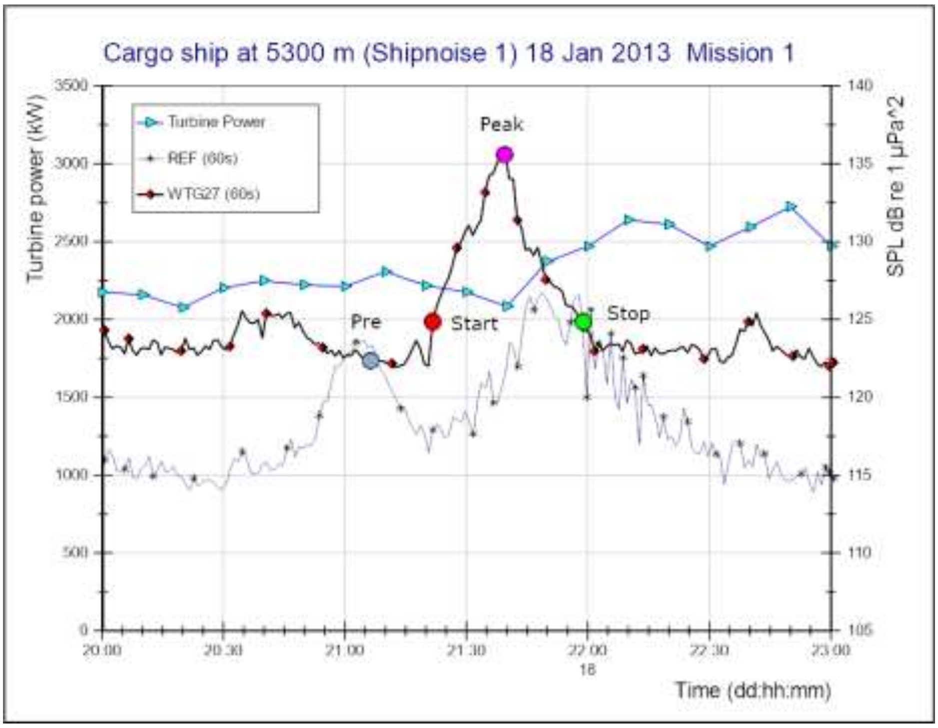


Figure 48 Detail of broad-band noise peak on the passage of a cargo vessel on 18 January. This ship passed the WTG27 hydrophone at a shortest distance of 5234 m. The vessel's noise increased the turbine level from 21:20 and 22:00. At the marked moments Third-Octave analysis was applied (Figure 49).

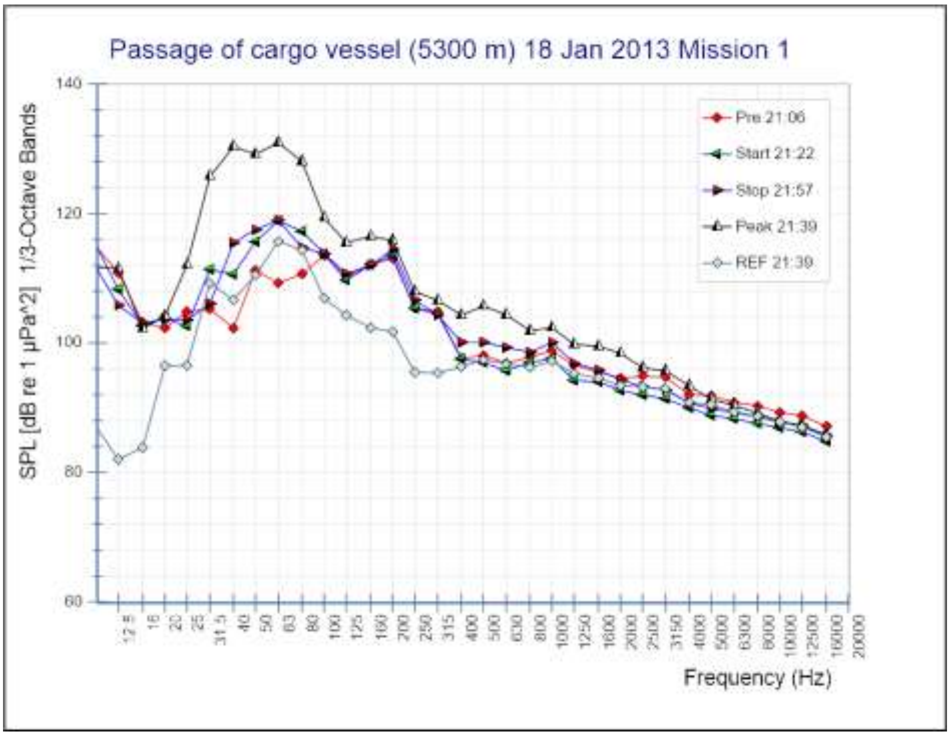


Figure 49 Third-Octave analysis on passage of a cargo vessel on 18 January. The ship passed the OWEZ area at a shortest distance of 5234 m from the received position and masked the turbine noise level from 21:20 to 21:57. The results refer to marked events in Figure 48. The condition "Pre" represents unaffected turbine noise levels shortly before the ship was detected.

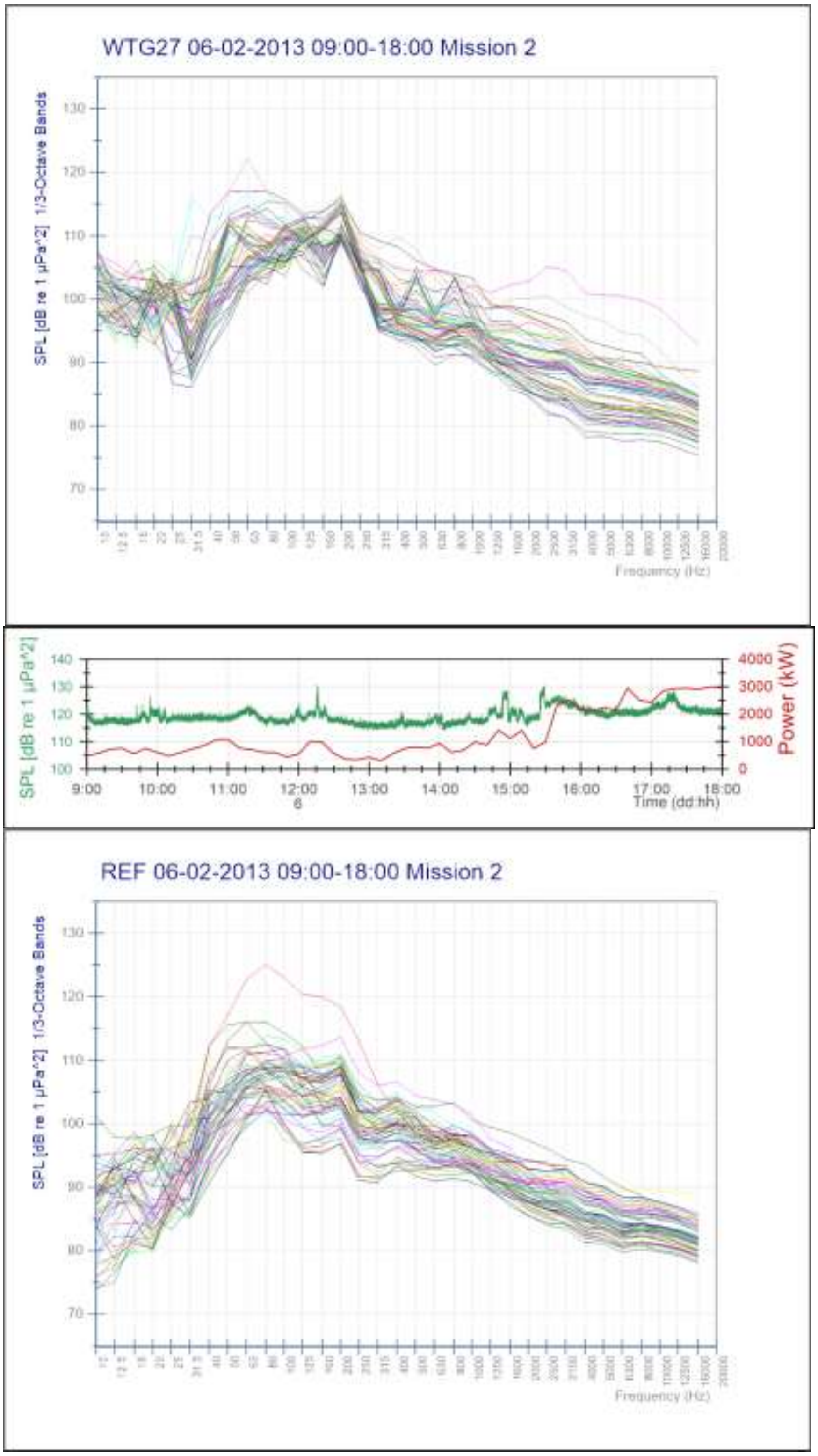


Figure 50 Third-Octave spectra of turbine noise sampled per 10 minutes over a day-time period of 9 hours on Mission 2. Each 10-minute sample is the linear average of a 1 s sample over 10 s. The turbine produced increased to maximum power condition with contours of the spectrum not as sharp as on Mission 1, but recognized in the 100 Hz- and 200 Hz-bands. The contours are partly masked by shipping noise.

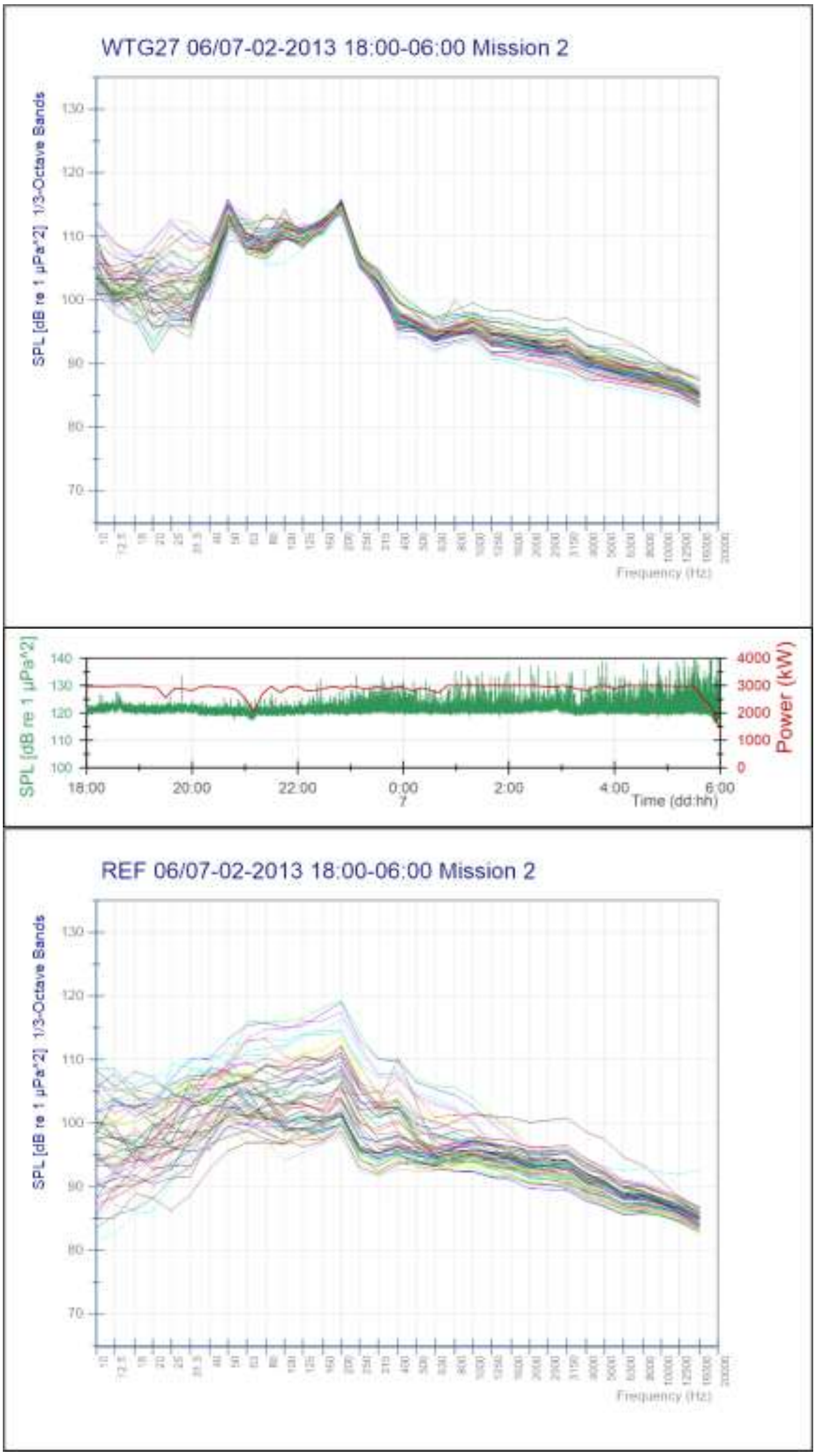


Figure 51 Third-Octave spectra of turbine noise sampled per 10 minutes over a night-time period of 12 hours on Mission 2. Each 10-minute sample is the linear average of a 1 s sample over 10 s. The turbine produced the max power with a decline at the end of the period with sharp contours of the spectrum mainly depended by energy in the 50 Hz- and 200 Hz-bands (115 dB re 1 µPa^2) and 3 dB lower in the 100 Hz-band.

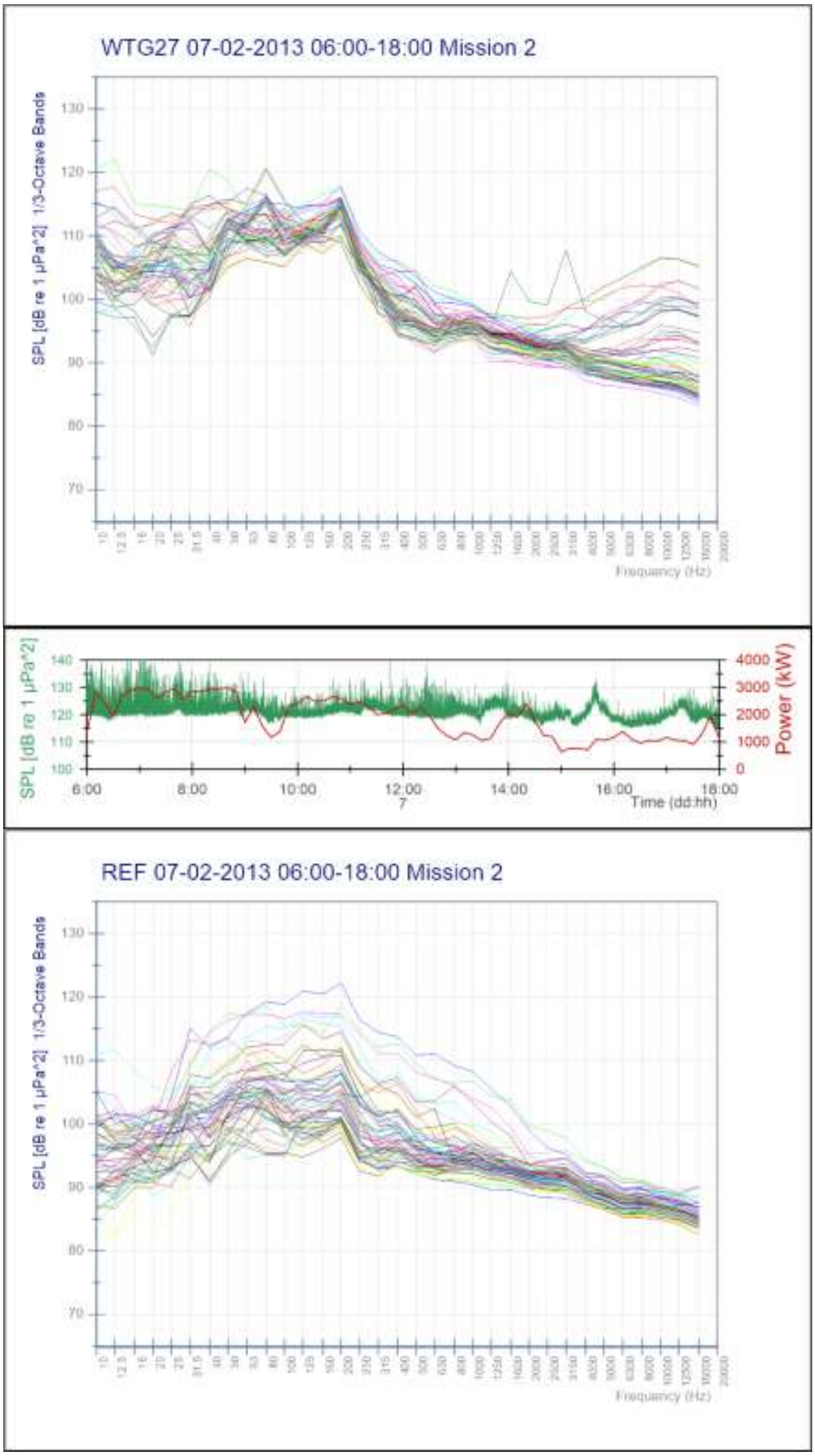


Figure 52 Third-Octave spectra of turbine noise sampled per 10 minutes over a day-time period of 12 hours on Mission 2. Each 10-minute sample is the linear average of a 1 s sample over 10 s. The turbine operated between maximum and medium power range. The contours of the turbine spectrum were partly masked by shipping noise.

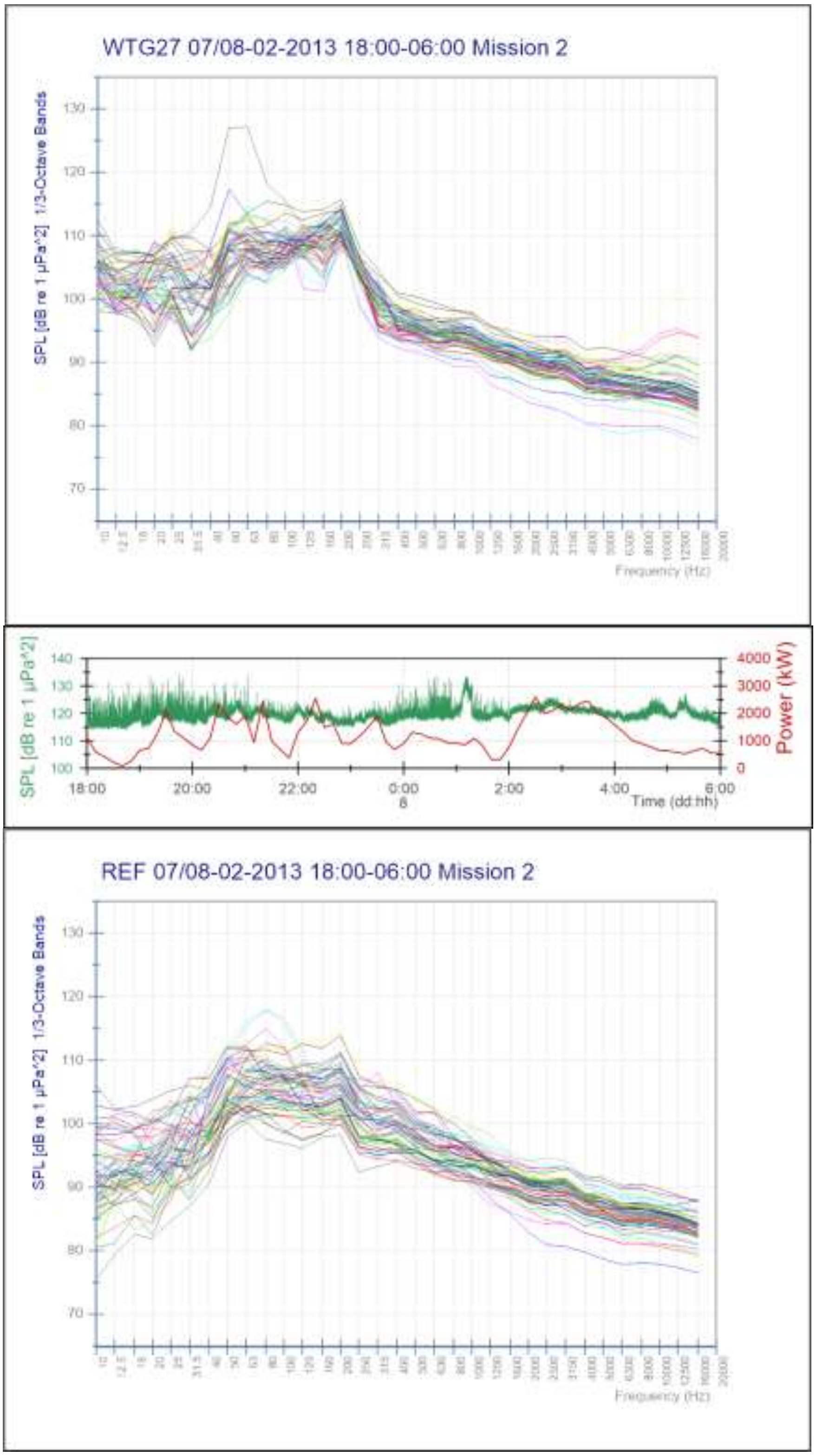


Figure 53 Third-Octave spectra of turbine noise sampled per 10 minutes over a night-time period of 12 hours on Mission 2. Each 10-minute sample is the linear average of a 1 s sample over 10 s. The turbine power was variable and operated mainly in the medium power range. The contours of the spectrum were only visible in the 200 Hz-band.

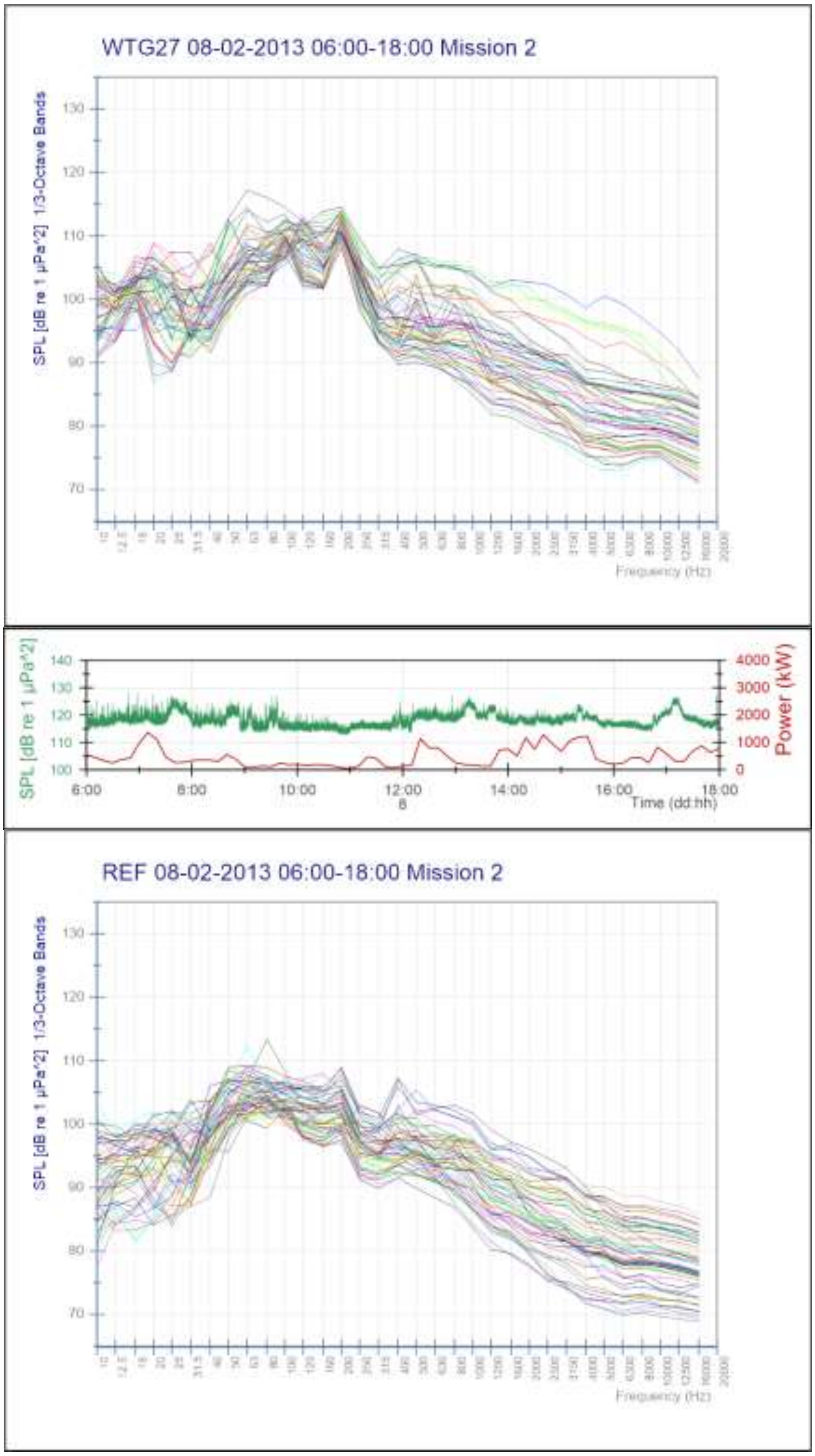


Figure 54 Third-Octave spectra of turbine noise sampled per 10 minutes over a day-time period of 12 hours on Mission 2. Each 10-minute sample is the linear average of a 1 s sample over 10 s. The turbine operated in the lower power range with maximum around 1000 kW. The turbine spectrum is recognized in the 100 Hz- and 200 Hz-bands, but the contribution of ship noise was substantial. Also detections in the 500 and 800 Hz-band are part of the observed noise.

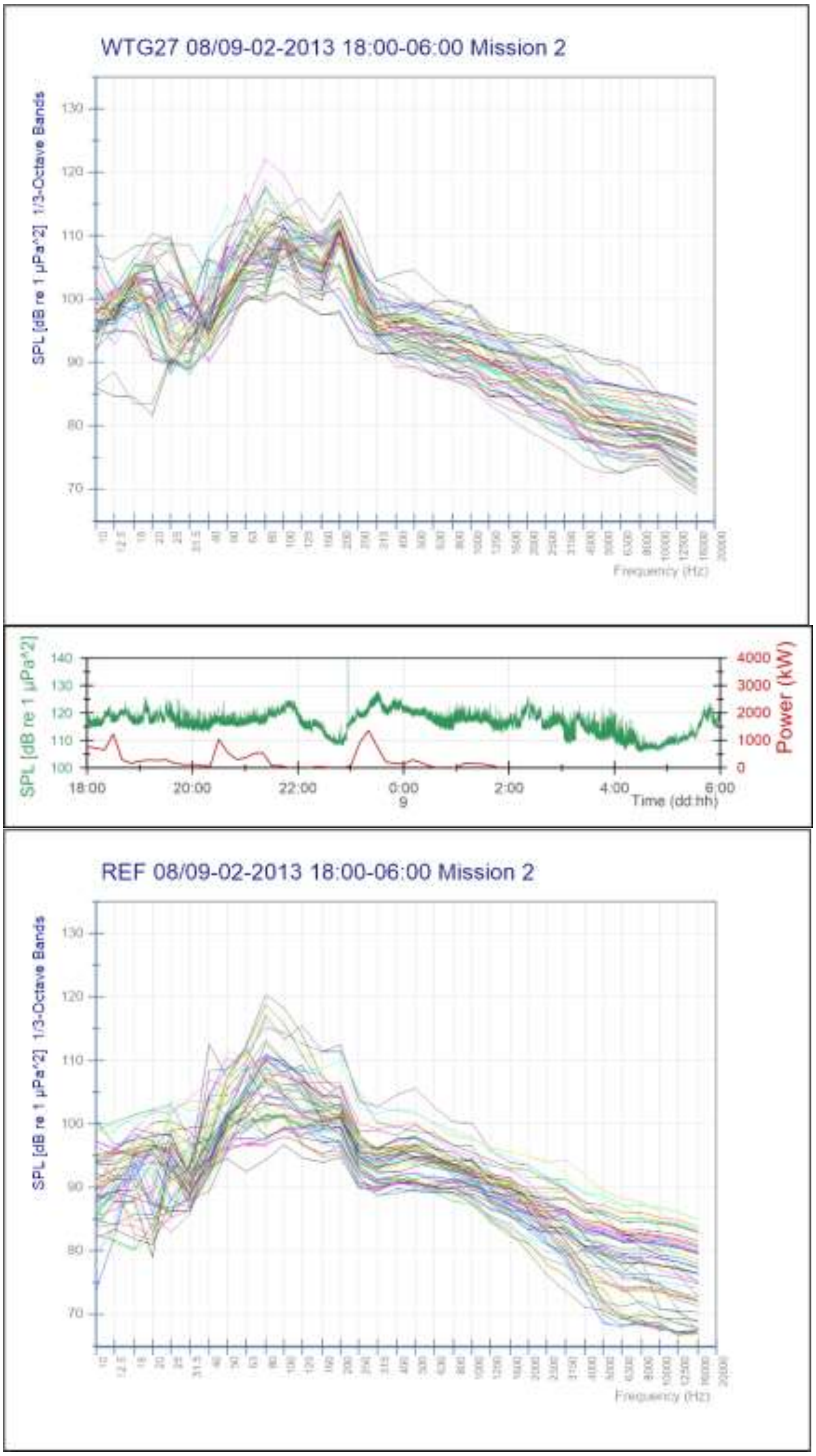


Figure 55 Third-Octave spectra of turbine noise sampled per 10 minutes over a night-time period of 12 hours on Mission 2. Each 10-minute sample is the linear average of a 1 s sample over 10 s. The turbine operated mainly in the low power range with three peaks of 1000 kW. The contours of the turbine spectrum are pronounced mainly in the 200 Hz- and to a minor extend in the 100 Hz-band.

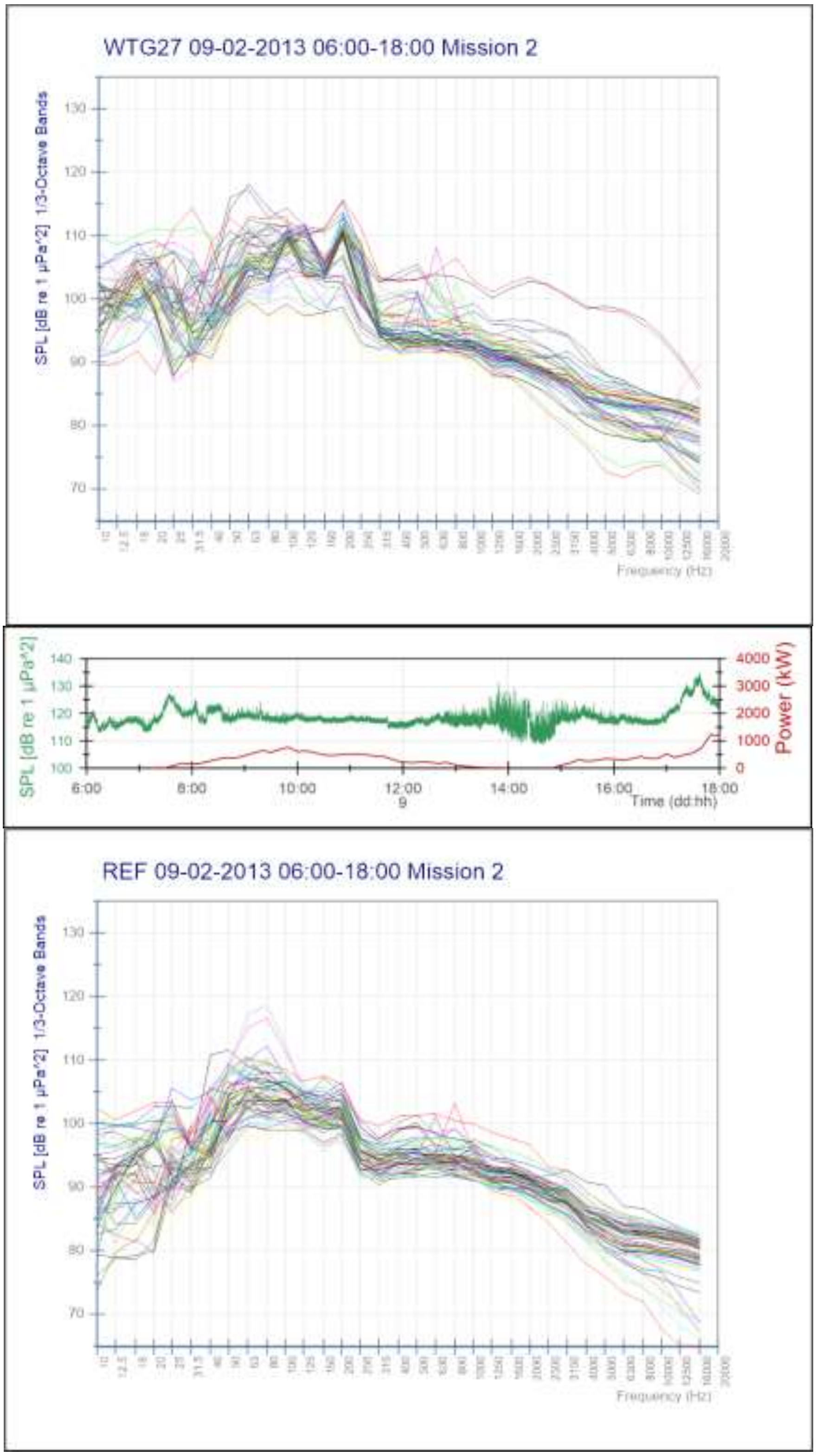


Figure 56Third-Octave spectra of turbine noise sampled per 10 minutes over a day-time period of 12 hours on Mission 2. Each 10-minute sample is the linear average of a 1 s sample over 10 s. The turbine operated in the lower power range. The contours of the turbine spectrum recognized in the 100 Hz- and 200-Hz bands.

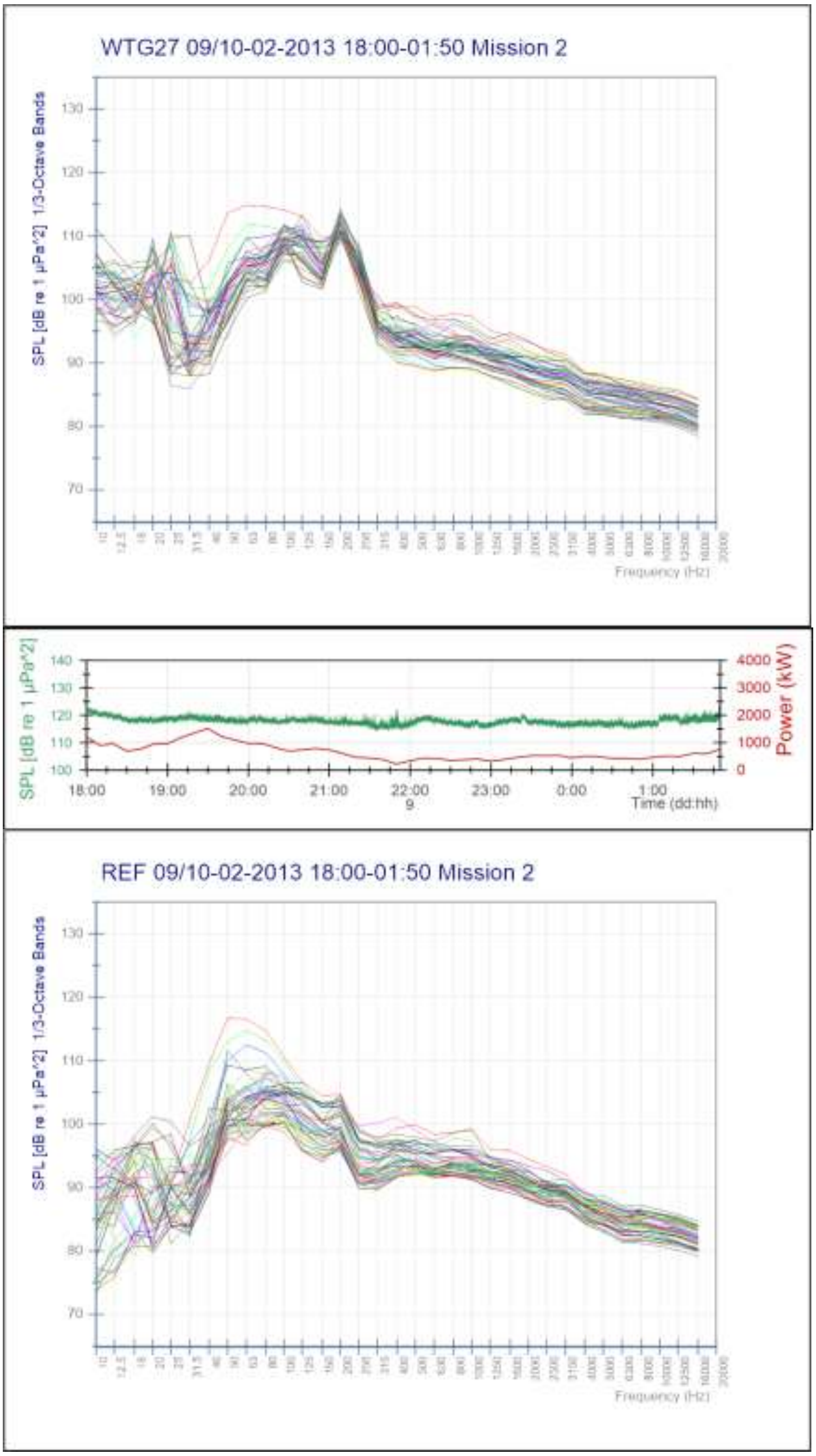


Figure 57 Third-Octave spectra of turbine noise sampled per 10 minutes over a night-time period of 7 hours and 50 minutes on Mission 2. Each 10-minute sample is the linear average of a 1 s sample over 10 s. The turbine power varied between 500 and 1000 kW. The contour of the turbine spectrum was particularly pronounced in the 200 Hz-band.

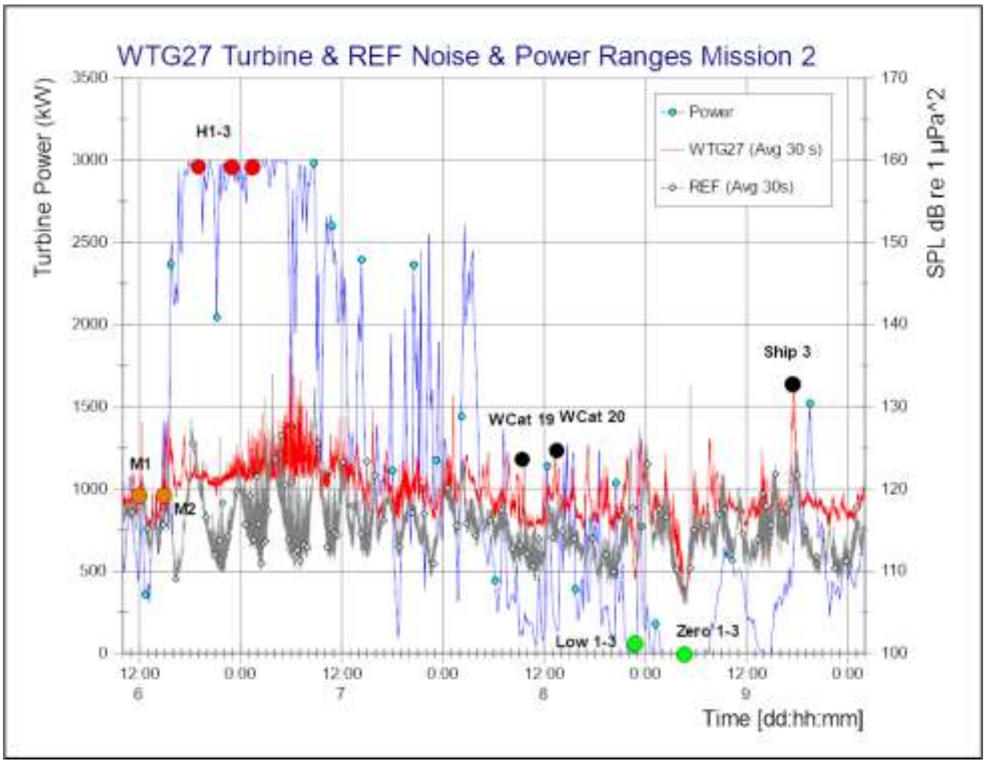


Figure 58 Broad-band noise levels (average 30s) against turbine power and the marked power ranges where frequency analysis was applied.

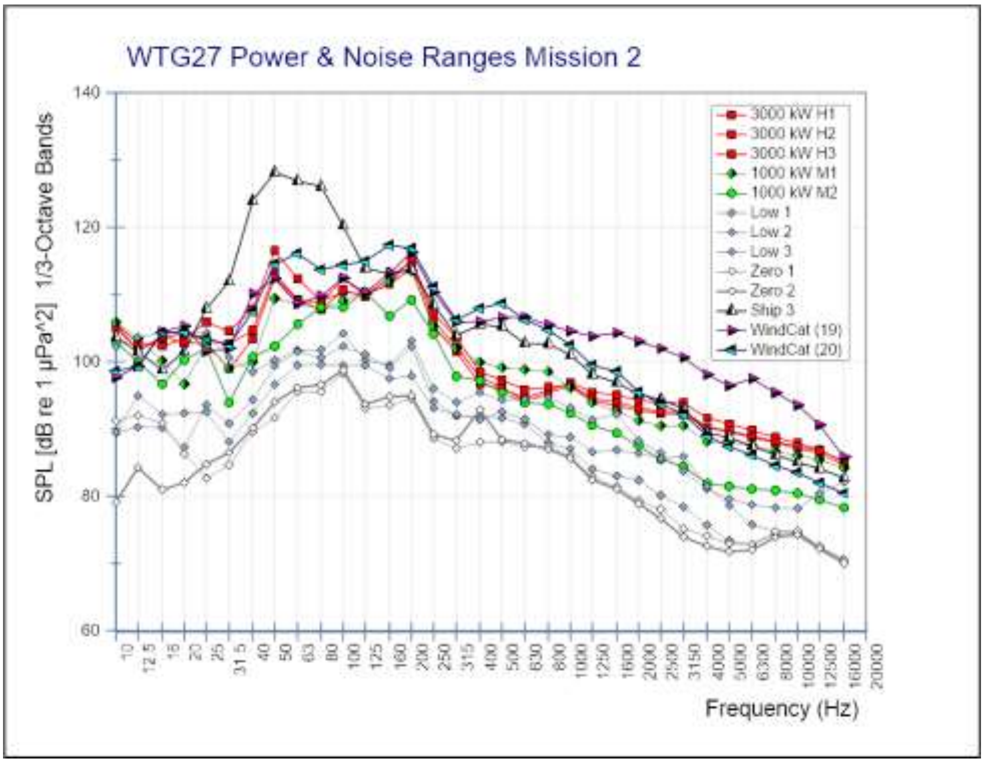


Figure 59 Noise levels filtered in Third-Octave bands (60 s linear averaged 1 s samples) of idle, low, medium and maximum turbine power ranges, marked in Figure 58, including the noise spectra of 3 ship noise events, WindCat noise case 19 & 20 (Appendix C, Table 10) and the passage of a larger vessel not related to wind farm operation (Ship 3).

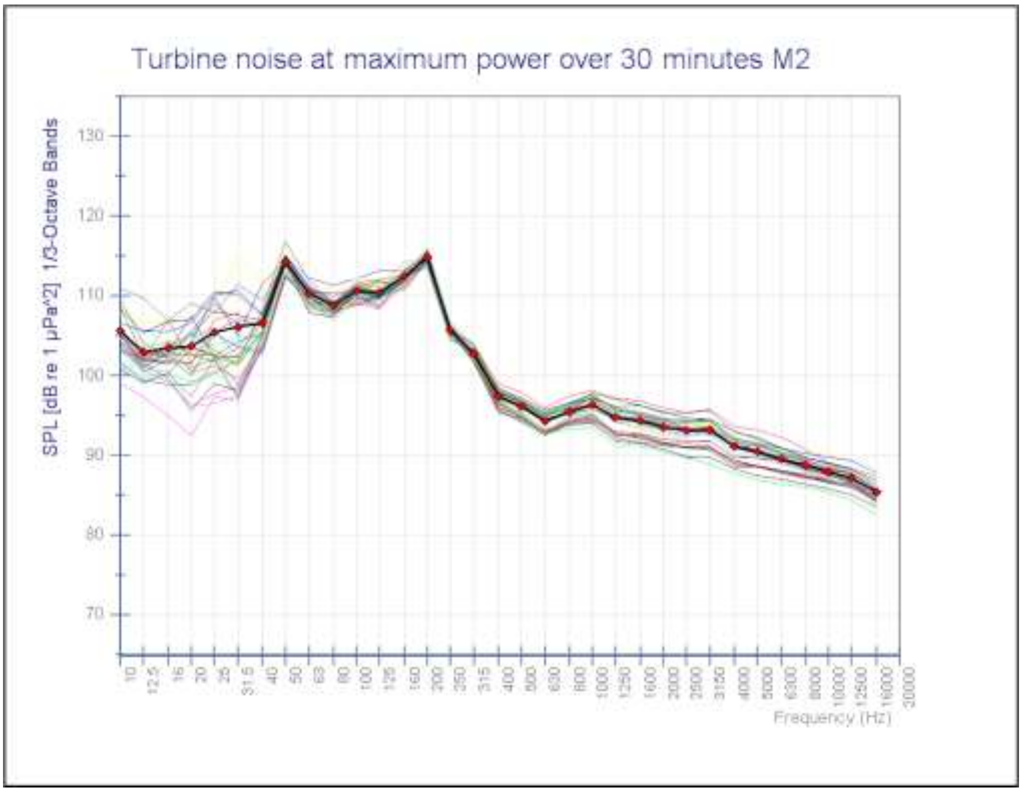


Figure 60 Third-Octave spectra at maximum turbine power condition on 7 February 2013 sampled with 1 minute-intervals between 00:21 and 00:51. In this period there was no contribution of ship-noise. The marked track is the calculated average. The contours of the turbine noise are mainly in the 50 Hz- and 200 Hz. Compared to the results of the first period the energy in the 100 Hz-band shifted to the 50 Hz-band (Figure 44).

Third-Octave band (Hz)	Average (dB re 1 µPa^2)	Max Average (dB re 1 µPa^2)	Min Average (dB re 1 µPa^2)
50	114.2	116.8	112.3
100	110.6	112.2	108.8
200	114.8	116.0	113.4

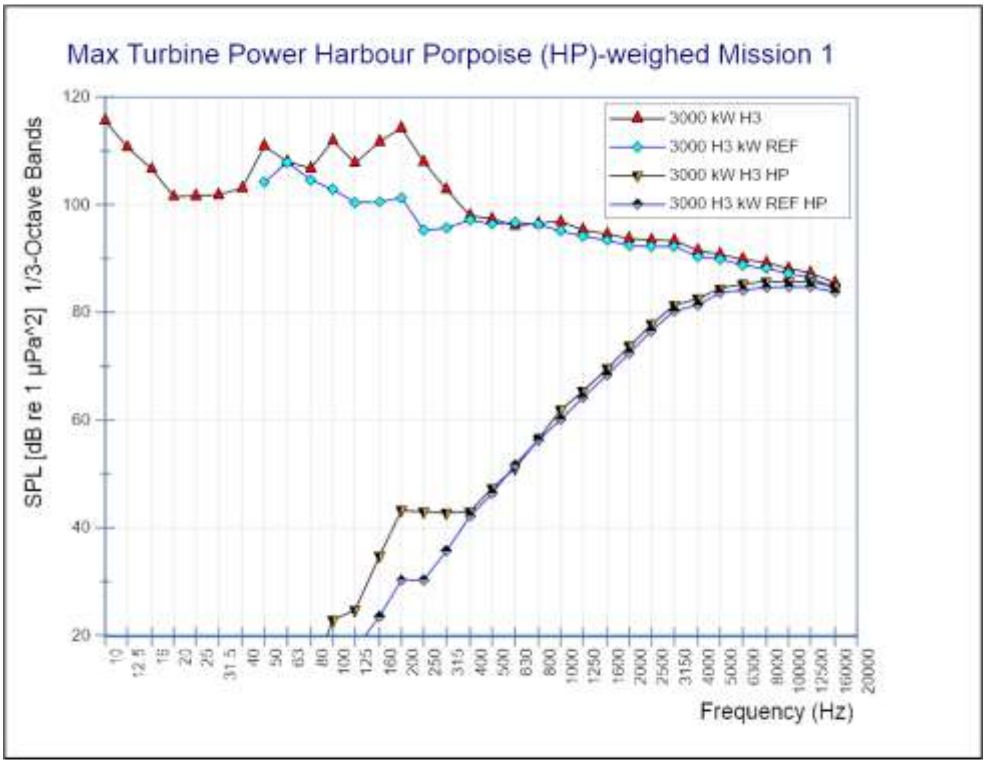


Figure 61 Turbine noise spectrum measured at maximum power condition weighed against the hearing curve of harbour porpoise. The graph shows that a very low part of the energy remains above the reference level at frequency bands < 315 Hz where this species is not a specialist.

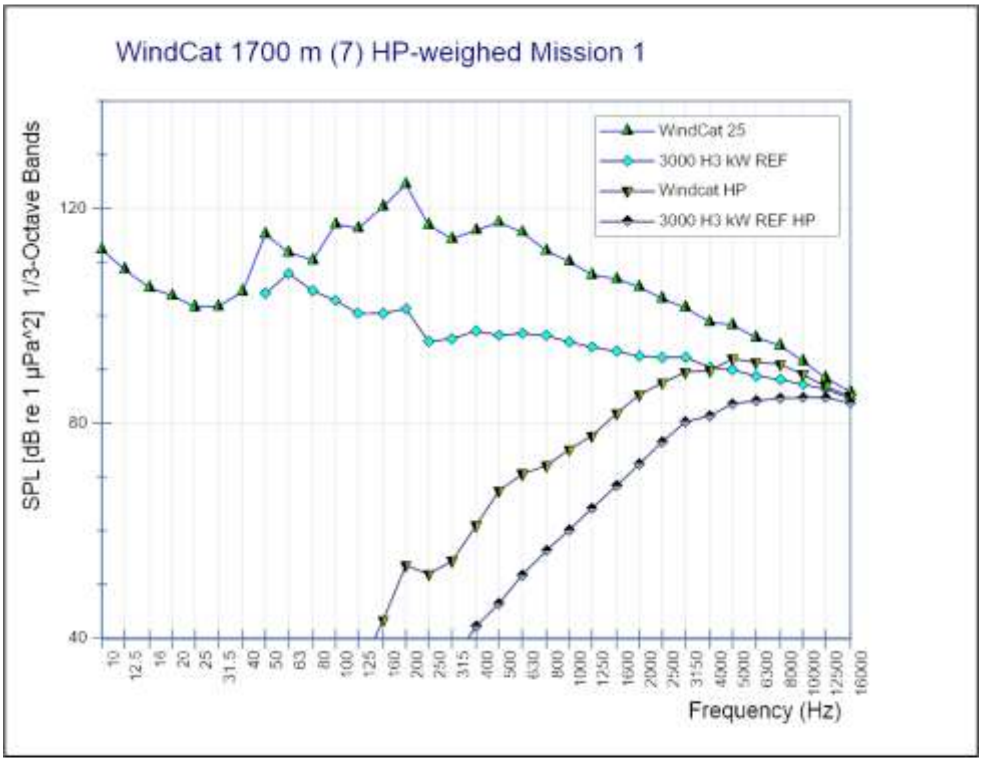


Figure 62 WindCat noise spectrum measured at 1722 m (WTG21-case 7) filtered against the hearing curve of harbour porpoise. The filtered result is well above the weighed reference spectrum

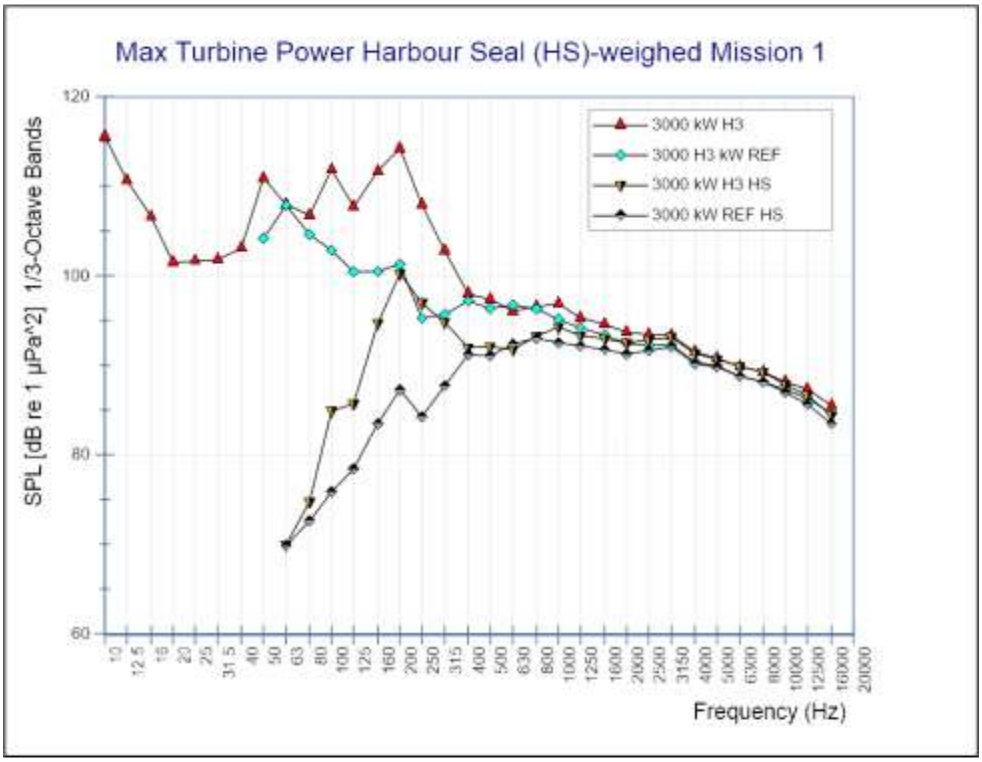


Figure 63 Turbine noise spectrum measured at maximum power condition weighed against the hearing curve of harbour seal. The graph shows that a significant part of the weighed energy <400 Hz remains above the weighed reference level and demonstrates that this animal has the hearing ability to detect the noise in the measured position.

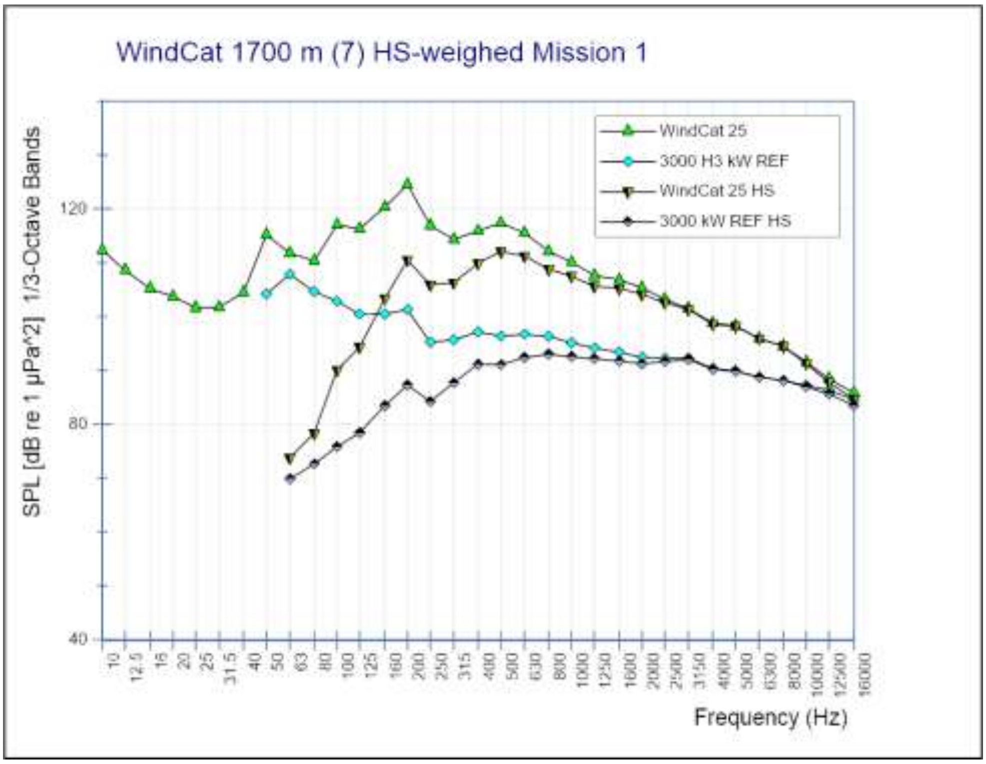


Figure 64 WindCat noise weighed against the auditory thresholds of harbour seal show that this type of noise remains detectable on almost the full range of the spectrum. At the peak of the noise (200 Hz) the weighed result is 25 dB above the weighed ambient noise level measured in the reference position.

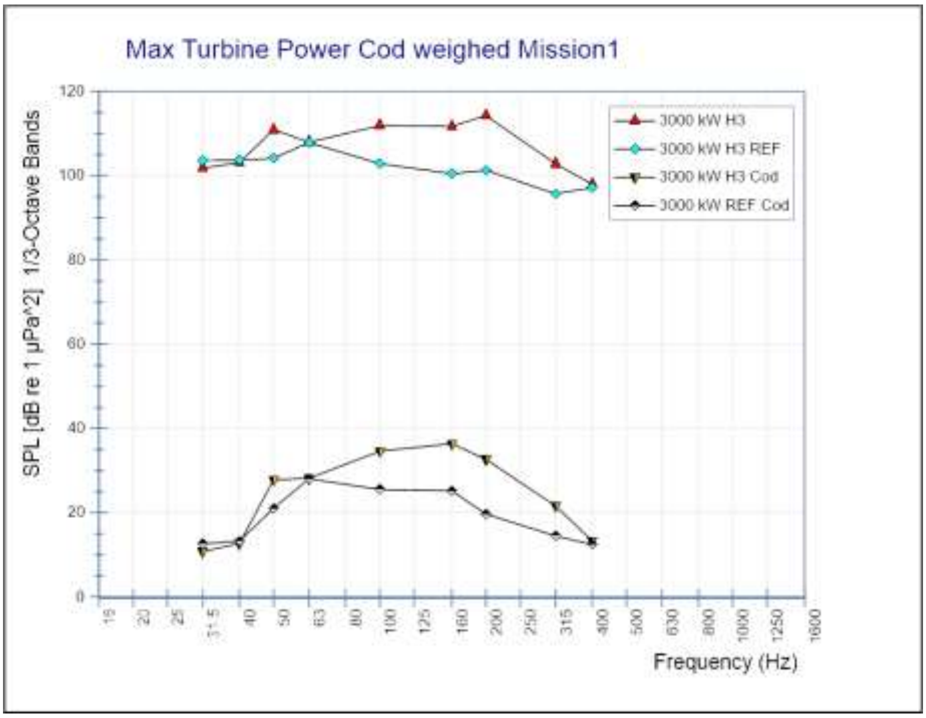


Figure 65 Turbine noise spectrum at maximum power condition weighed against the auditory thresholds of Atlantic cod (Gadus morhua) according the study of Hawkins et al., 1973. The weighed results show that cod is sensitive over the full unmasked spectrum of turbine noise in the received position to a maximum of 10 dB above the background noise at 160 and 200 Hz.

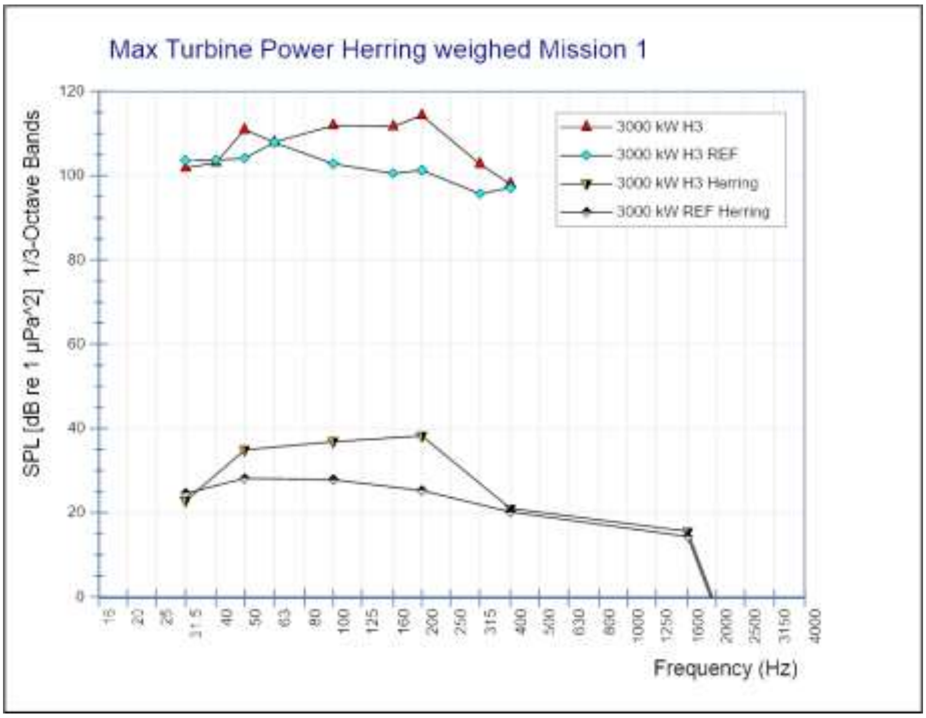


Figure 66 Turbine noise spectrum at maximum power condition weighed against the auditory threshold of Atlantic herring (Clupea harengus), according the study of Enger, 1967. The results after weighing show that a small part of the energy is filtered and that this species is sensitive in the full unmasked spectrum to a maximum of 10 dB at 200 Hz.

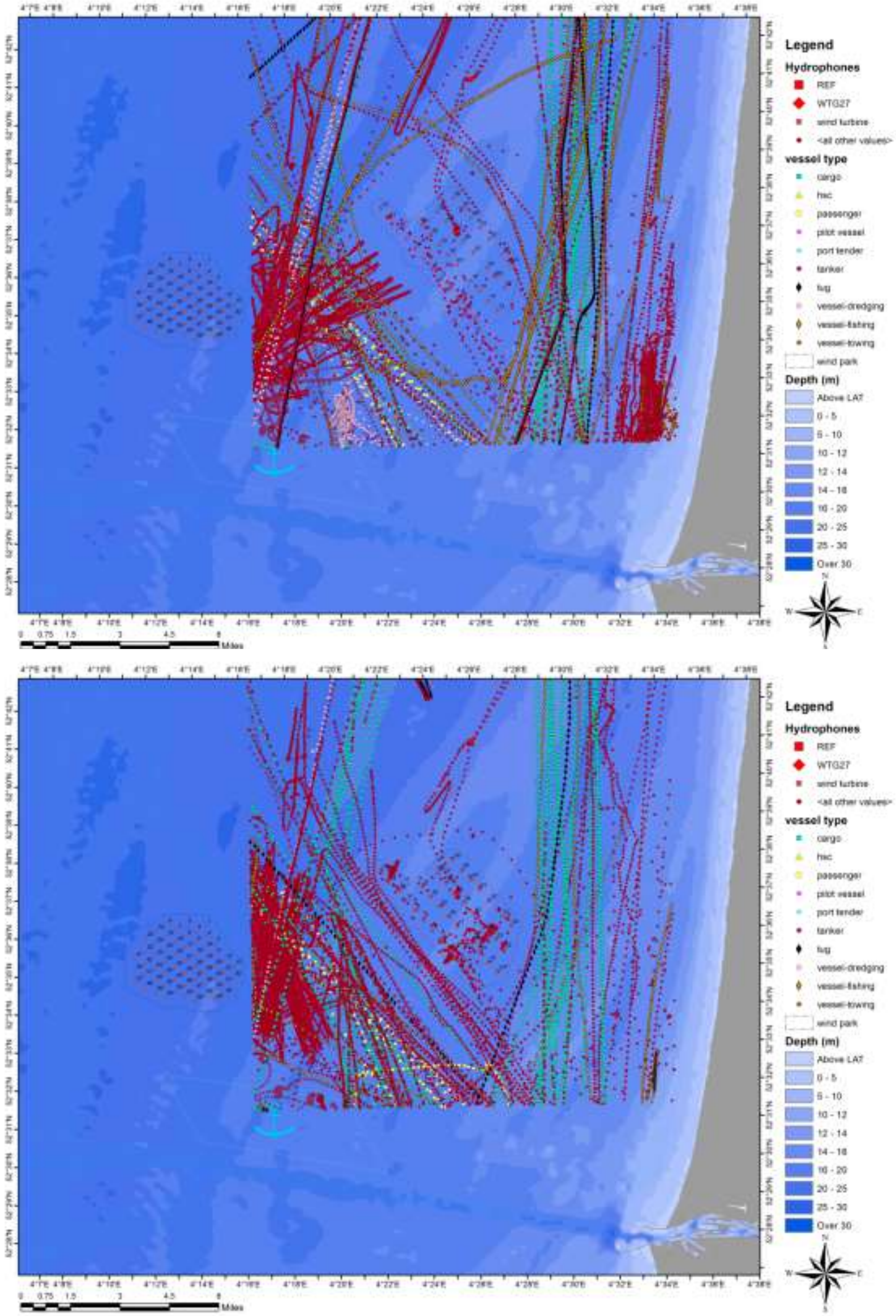


Figure 67 a and b Overview of shipping activity in Mission 1 & 2 based on the AIS records of the Dutch coastguard, provided by Marin, Wageningen, NL.

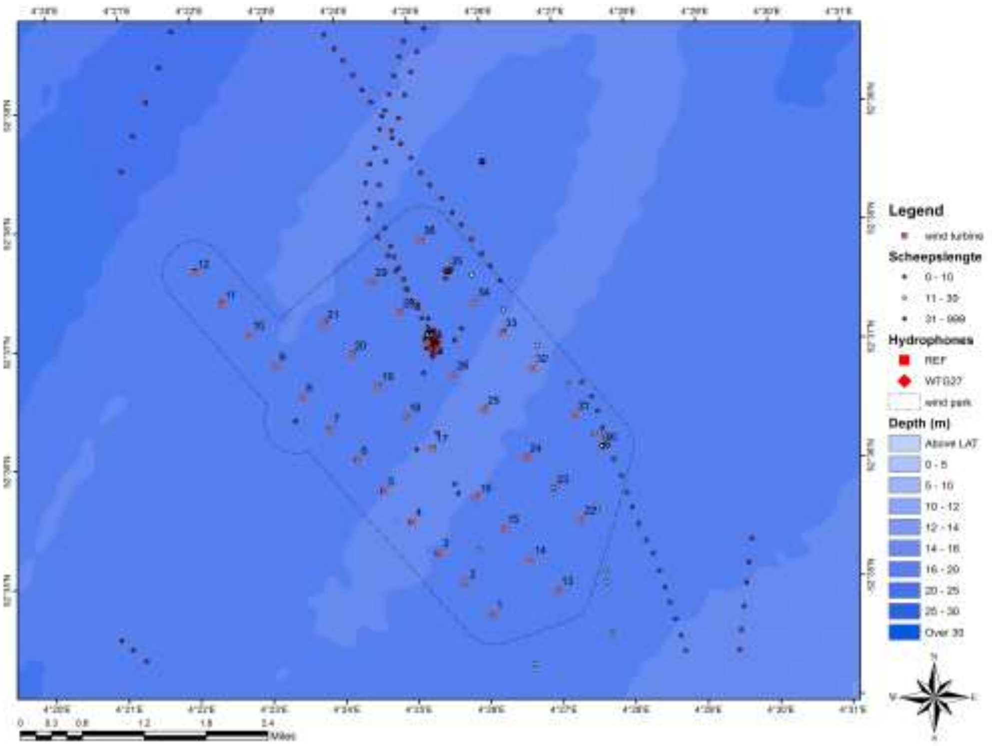


Figure 68 Shipping Activity on 16 January 2013 from 06:00 to 17:00 with MS "Terschelling" at WTG27 on the moment of the deployment of the equipment and a fishing vessel sailing at the east side of OWEZ.

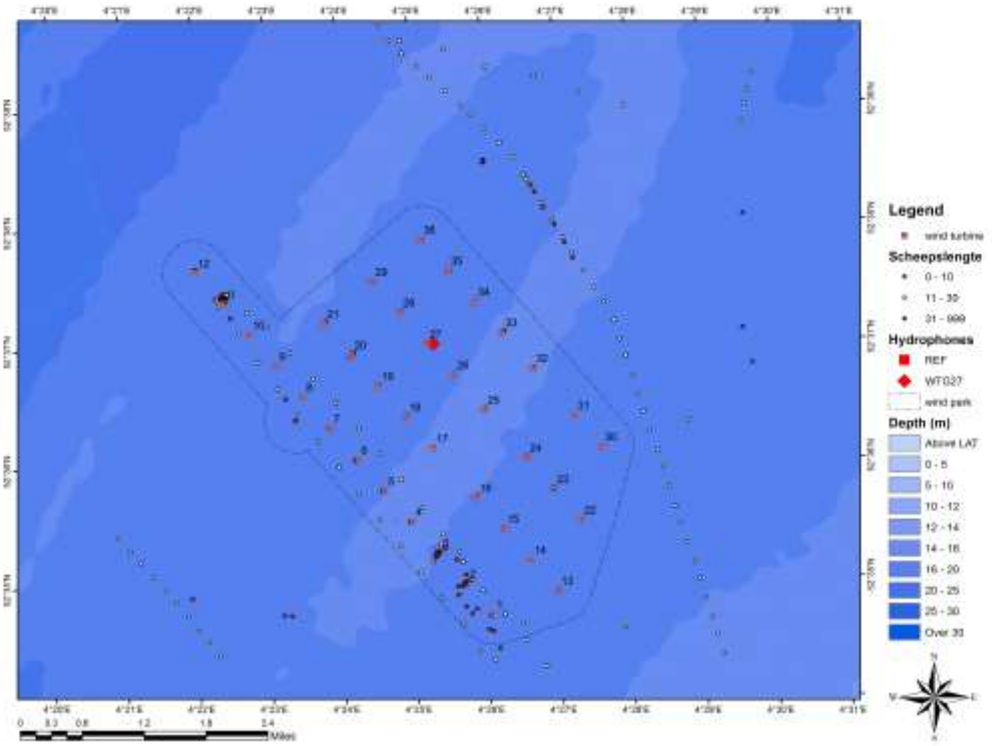


Figure 69 Shipping Activity on 17 January 2013 (06:00 to 17:00) with WindCat type of vessels at WTG11, 02 and 03 and a fishing vessel sailing at the east side of OWEZ.

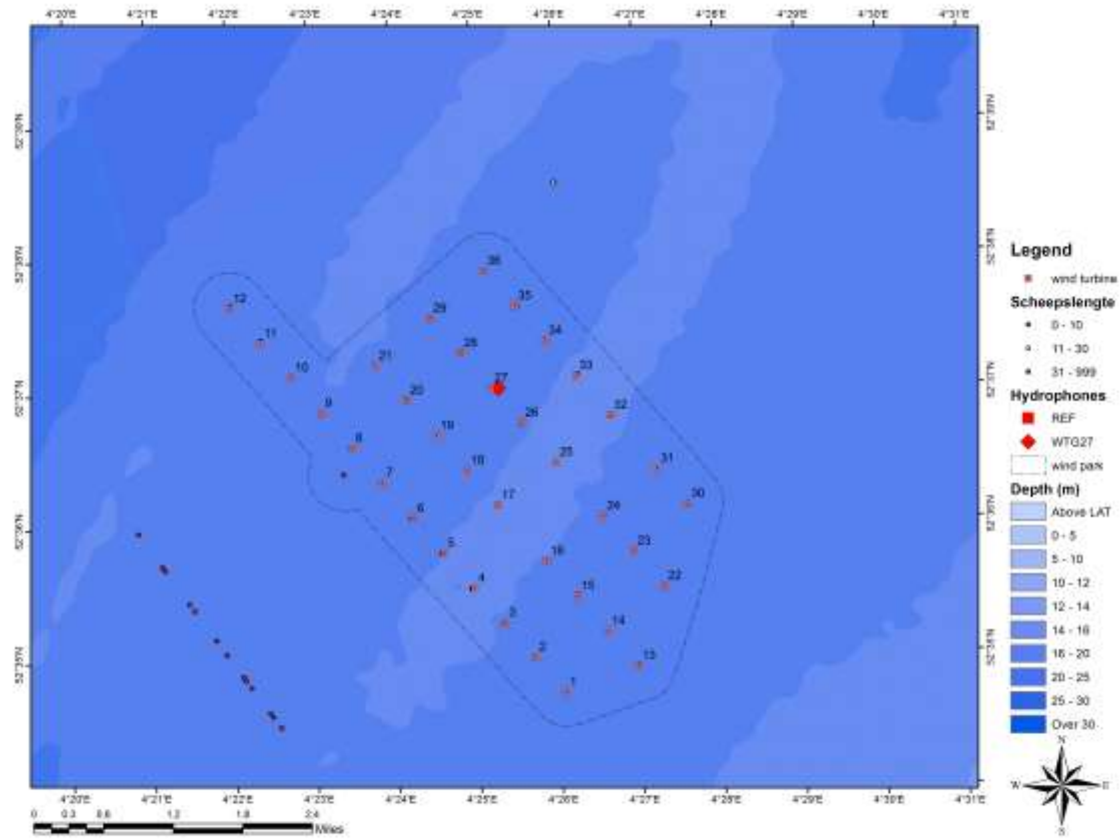


Figure 70 AIS detected track of a cargo vessel (163 m length, 6.1 m depth) passing OWEZ on 18 January between 21:00 and 22:00. The speed of the vessel was 20 knots. The acoustic detection is the highest measured peak of Mission 1 illustrated in Figure 48 and 49.

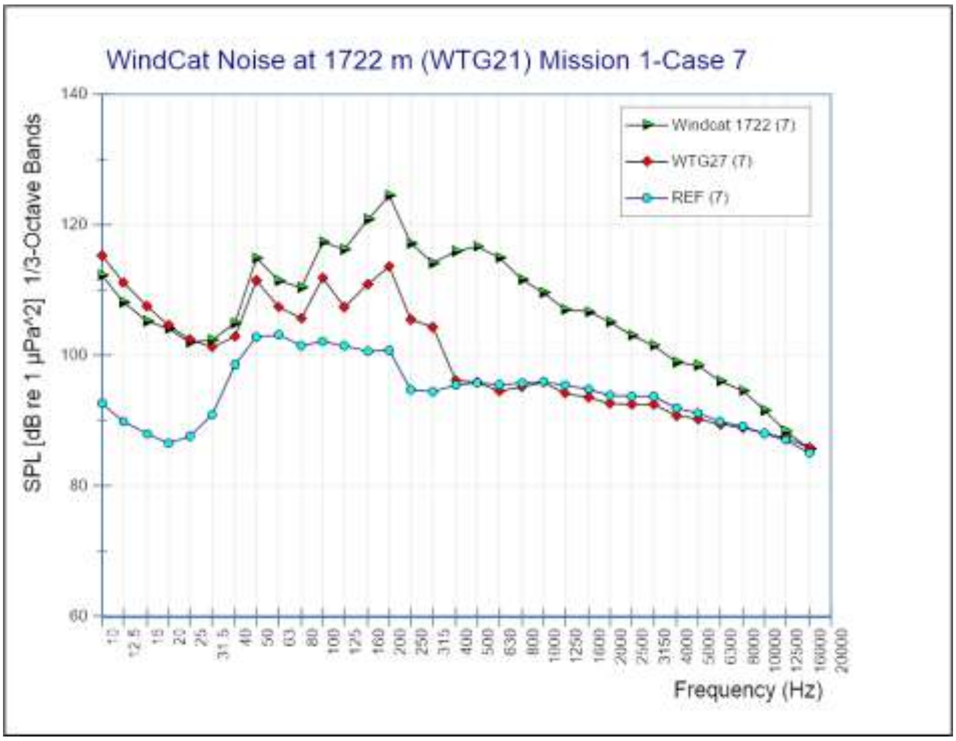


Figure 71 WindCat noise developed on landing at WTG21 (distance of 1722 m, Case 7) against the turbine noise spectra of turbine noise (WTG27) and noise at the reference position (7400 m to the north of OWEZ) both taken 6 minutes after the WindCat noise distinguished. The turbine power was 2562 kW at a wind speed of 11.8 m.s^{-1} and a rotor speed of 16 RPM.

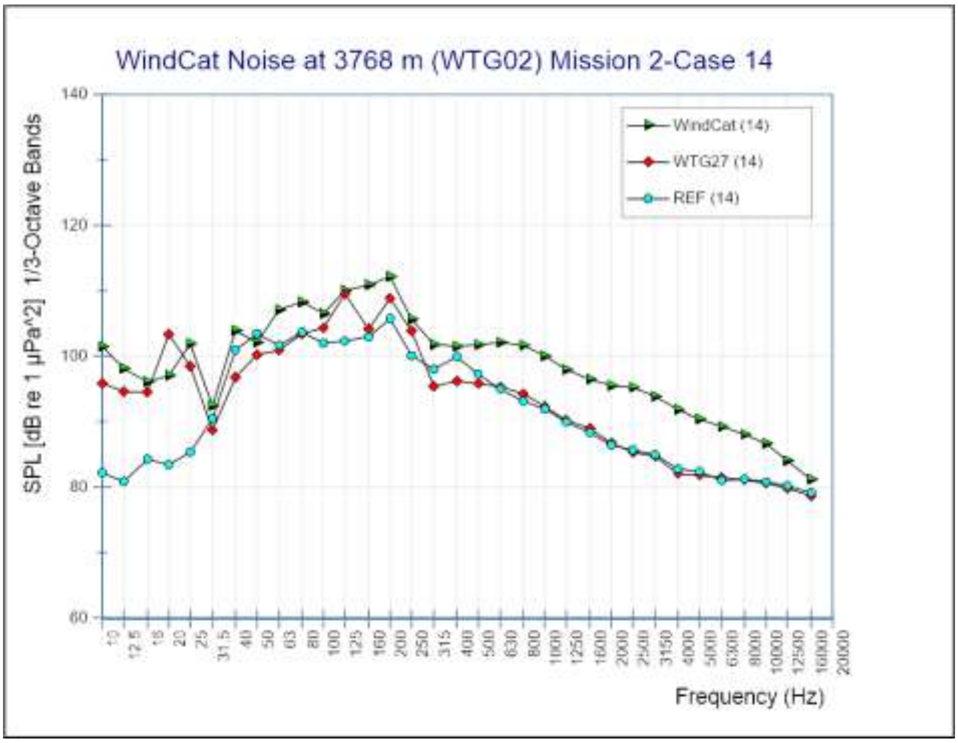


Figure 72 WindCat noise developed at the highest measured distance of 3768 m, while landing at WTG02 against the turbine noise spectrum and the reference noise (7400 m north of OWEZ) both taken 6 minutes before the arrival. The turbine produced 753 kW at a wind speed of 7.4 m.s^{-1} and a rotor speed of 13.4 RPM.

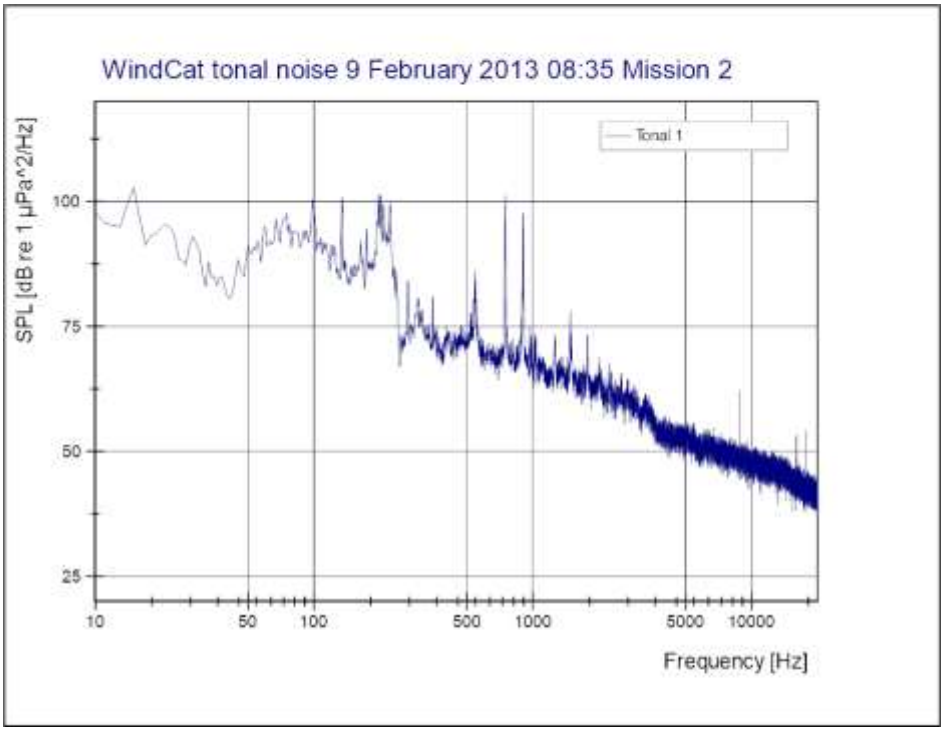


Figure 73 Narrow-band analysis of tonal type of noise on 9 February 2013 08:35:52 (FFT 10 s average length, 1 s block, 50 % overlap). The noise appeared as soon as the WTG propulsion was lowered after landing at WTG11 and is probably attributed to noise of main engines in idling/low power mode.

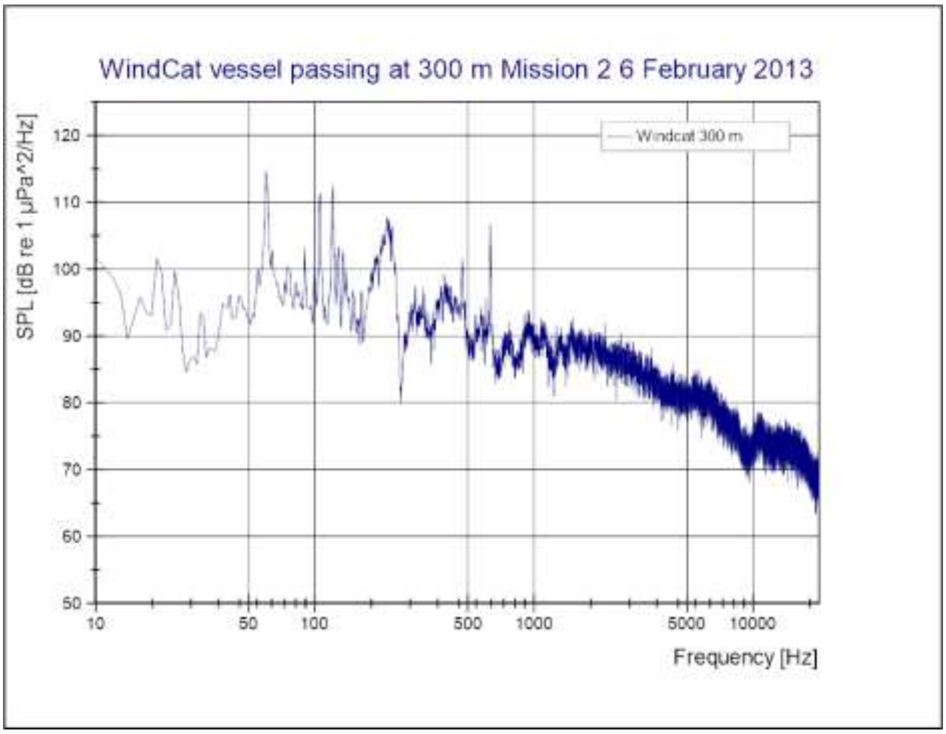


Figure 74 Narrow-band analysis of WindCat vessel noise on 6 February 2013 12:16:14 (FFT 10 s average length, 1 s block, 50 % overlap). The vessel passed the hydrophone at 300 m.

Appendix B Overview of turbine noise as a function of produced energy

Lists of first period M1

Table 5 Turbine Noise as a function of Turbine Power.

Measurement label	Date	Time	Power WTG27 (kW)	Wind Speed ($m.s^{-1}$)	Rotor Speed (RPM)	Rotor Blade Angle (°)	SPL (WTG27) 1/3-Octave bands dB re 1 μPa^2
Zero 1	17/01	16:10:59	-11.1	2.1	1	20	93.8
Zero 2		16:13:22	-11.1	2.1	1	20	93.6
Zero 3		16:14:17	-11.1	2.1	1	20	92.6
Low 1		17:21:43	30.5	3.2	10	0.6	98.1
Low 2		17:22:15	30.5	3.2	10	0.6	98.4
Low 3		17:23:00	30.5	3.2	10	0.6	98.2
1000 M1	18/01	04:30:00	956	7.6	13.8	-2.5	103.5
1000 M2		06:40:00	986	7.8	14.1	-2.5	104.9
1500 M3	18/01	07:35:01	1479	9	15.7	-2.6	106.1
1500 M4		16:10:30	1516	9.1	15.5	-2.5	105.0
2000 M5		15:10:00	1986	10.1	16	-2.5	107.2
2000 M6		16:49:59	1984	10.2	15.8	-2.3	105.7
3000 H1	19/01	17:23:56	2930	13.7	16	3.1	105.9
3000 H2		17:17:02	2930	13.7	16	3.1	106.4
3000 H3		17:06:00	2932	13.4	16	1.9	106.8

Table 6 Turbine Noise Levels during the starting from idle mode on 17 January Mission 1

Measurement label	Date	Time	Power WTG27 (kW)	Wind Speed ($m.s^{-1}$)	Rotor Speed (RPM)	Rotor Blade Angle (°)	Yawing Activity (s/10 min)	SPL (WTG27) 1/3-Octave bands dB re 1 μPa^2 (10s-1s)
Pre 1	17/01	15:49:57	-11.1	1.8	0	20	0	94.5
Pre 2		16:00:05	-11.2	2.3	0	20	0	95.4
Pre 3		16:24:57	-11.1	2.1	0	20	0	92.6
Pre 4		16:29:07	-13.2	2.9	0.9	0.6	95	94.0
Rattle 1		16:01:56	-11.2	2.3	1	20	0	95.8
Started		16:36:02	35.2	3.5	8.3	4.2	87	102.2

Lists of second period Mission 2.

Table 7 Turbine Noise as a function of Turbine Power & Ship Noise events. On the maximum power condition the turbine control, adjusted the rotor pitch to limit the power range. Conditions of WindCat noise Case 19 and 20 are also listed in Table 10 WindCat Noise period M1 & M2

Measurement label	Date	Time	Power WTG27 (kW)	Wind Speed ($m.s^{-1}$)	Rotor Speed (RPM)	Rotor Blade Angle (°)	SPL (WTG27) 1/3-Octave bands dB re 1 μPa^2
Zero 1	09/02	04:29:47	-11.6	2.8	0	20	90.0
Zero 2		04:49:06	-11.4	2.6	0	20	90.3
Low 1	09/02	14:51:55	-10.9	1.6	0	20	99.1
Low 2	08/02	22:35:09	-12.3	2.9	3	19.3	95.2
Low 3	08/02	22:41:06	-12.3	2.9	3	19.3	93.6
1000 M1	06/02	12:09:58	1007	8	14.1	-2.5	104.8
1000 M2	06/02	14:30:58	980	8.1	14.4	-2.5	102.2
2000 M5	08/02	02:39:36	1997	10.5	15.9	-2.3	106.9
2000 M6	08/02	03:40:01	2006	10.3	15.9	-2.8	105.3
3000 H1	07/02	17:23:56	3004	16.4	16	8.9	106.9
3000 H2	07/02	23:05:20	2929	13.8	16	2.5	106.0
3000 H3	06/02	17:06:00	2998	14.6	16	4.1	106.1
Ship 3	09/02	17:37:37	748	7	12.7	-1.8	117.9
WindCat 19	08/02	09:36:34	250	5.1	10.1	-2.0	120.9
WindCat 20	08/02	13:15:04	178	4.4	10	-1.1	123.3

Appendix C Shipping activity during the measurements

Table 8 WindCat reports Vestas Mission 1 & 2. The original reported times were adjusted to UTC

Date	Time	Destination	Action
18/01/2013	06:48	WTG30	Pushed onto WTG30
	06:56		Pulled of
	06:57		Idle at WTG30
	07:25		Engines off
	08:25		Engines on
	09:20		Pushed onto WTG30
	09:25		Depart from WTG30
	09:30	WTG3	Pushed onto WTG3
	09:38		Depart from WTG3
	09:46	WTG11	Pushed onto WTG11
	09:58		Pushed onto WTG04
	10:00	WTG04	Idle at WTG04
	10:10		Engines off
	11:50		Engines on
	12:10		Depart from WTG04
	12:17	WTG03	Pushed onto WTG03
	12:35		Departure heading IJm
19/01/2013	12:50	WTG01	Entry at WTG01
	13:00	WTG21	Pushed onto WTG21
	13:08		Engines idle
	13:25		Engines off
	14:55		Engines on
	15:33	WTG21	Pushed onto WTG21
	15:40		Departure heading IJm
Mission 2			
06/02/2013	08:50	WTG16	Drifting with engines on
	09:00		Pushed onto WTG16
	09:35		Engines off
	09:40	WTG02	Engines on, heading to WTG02
	09:45		Pushed onto WTG02
	09:50	WTG04	Heading to WTG04
	09:55		Pushed onto WTG04
	10:00	WTG16	Heading to WTG16
	10:05		Pushed onto WTG16
	10:10		Engines off
	11:30		Engine on
	11:35	WTG01	Heading to WTG01
	11:35	String 1	Sailing along string 1 to WTG12
	11:50	String 2	Sailing along string 2 (WTG13/21)
	12:10	String 3	From string 2 to 3 (WTG22/29)
	12:20	String 4	From string 3 to 4 (WTG30/36)
	12:40	WTG24	Drifting near WTG24 engines on
	13:30	WTG16	Pushed to WTG16
	13:35		Engines off

Date	Time	Destination	Action
	13:50	WTG02	Engines on heading to WTG02
	13:55		Pushed onto WTG2
	14:00	WTG16	Return to WTG16
	14:05		Engines off
	14:35	WTG04	Engines on heading to WTG04
	14:50	WTG25	Heading to WTG25
	15:00	WTG24	Heading to WTG24
	15:10	WTG25	Heading to WTG25
	15:30		Departure IJM harbour
	15:35		Leaving OWEZ boundaries
08/02/2013	08:35	WTG04	Entering OWEZ heading for WTG04
	08:40		Pushed onto WTG04
	09:00	WTG05	Moved from WTG04 to WTG05
	09:20		Engines off
	09:25		Engines on and moved to WTG04
	09:30	WTG04	Pushed onto WTG04
	09:35	WTG05	Back to WTG05
	09:50		Engines off
	11:50		Engines on
	12:35		Engines off
	13:10		Engines on, heading to WTG04/05
	13:15	WTG04	Pushed onto WTG04
	13:20	WTG05/11	Moved from WTG05 to WTG11
	13:40		Pushed onto WTG11
			Drifting between WTG11 &WTG12
	15:15	WTG11	Pushed onto WTG11
	15:25		Depart to IJm harbour
	15:35		Leaving OWEZ
09/02/2013	08:10	WTG04	Entering OWEZ heading for WTG04
	08:15		Pushed onto WTG04
	08:35		Drifting between WTG03 and 04
	09:15	WTG03	Pushed onto WTG03
	09:25		Engines off
	11:20		Engines on
	12:25		Engines off
	13:35		Engines on
	14:15		Moved from WTG03 to WTG04
	14:20	WTG04	Pushed onto WTG04
	14:25		Depart to IJm harbour
	15:30		Leaving OWEZ
10/02/2013	06:55	WTG04	Entering OWEZ heading for WTG04
	07:00		Pushed onto WTG04
	07:10		Drifting near WTG04 engines on
	07:35	WTG04	Pushed onto WTG04
	08:10		Engines off
	09:45		Engines on
	10:10		Engines off

Date	Time	Destination	Action
	11:45		Engines on
	13:10	WTG04	Pushed onto WTG04
	13:20		Depart to IJm harbour
	13:25		Leaving OWEZ

Table 9 Overview of all underwater shipping noise received at the WTG27 hydrophone. The Case numbers are linked to the analysed cases of WindCat noise in Table 10.

Case (nr)	Date	Detection Intervals	OWEZ related Vessel (WindCats)			Other Ships
			Interval (hh:mm)	Distance (m)	WTG (nr)	Interval (hh:mm)
	16/01	18:50-19:10				00:20
		19:12-19:20				00:08
		19:26-20:40				01:14
		22:13-23:11				00:58
	17/01	01:10-01:25				00:15
		02:14-02:20				00:06
		03:24-03:40				00:16
		04:28-04:38				00:10
		05:15-05:26				00:11
		05:35-05:40				00:05
		05:44-05:49				00:05
		06:44-06:47				00:03
		06:50-07:20				00:30
		07:30-07:50				00:20
		09:51-09:57				00:06
		10:02-10:13				00:11
		10:26-10:47				00:21
		10:56-11:43				00:47
		12:05-12:50				00:45
		13:13-15:54				02:41
		18:15-18:20				00:05
		18:32-18:37				00:05
		19:40-19:50				00:10
		20:42-21:00				00:18
		21:51-21:56				00:05
	18/01	00:00-00:17				00:17
		01:02-01:17				00:15
		02:04-02:37				00:33
		03:03-04:07				01:04
		04:27-04:40				00:13
1		06:38-07:01	00:23	3073	30	
		07:34-08:29				00:55
2/5		09:20-10:05	00:45	3073	30/03/11/04	
		11:30-11:45				00:15
6		12:17-12:51	00:34	3260	03	
		12:51-13:40				00:49
		16:43-17:36				00:53

Case (nr)	Date	Detection Intervals	OWEZ related Vessel (WindCats)			Other Ships
			Interval (hh:mm)	Distance (m)	WTG (nr)	Interval (hh:mm)
		18:34-19:27				00:53
		21:20-22:00				00:40
		22:37-24:00				01:23
	19/01	00:00-00:25				00:25
		02:09-02:16				00:07
		02:21-04:46				02:25
		08:09-08:18				00:09
7		12:47-13:06	00:19	1722	21	
8		15:32-15:42	00:10	1722	21	
	20/01	02:41-03:12				00:31
9	06/02	08:56-09:06	00:10	2492	16	
10/12		09:42-10:07	00:25	3768	02/04/16	
		11:32-11:41	00:09		04	
		11:51-12:07	00:16		16	
		12:07-12:46	00:39		Sailing	
13		13:24-13:49	00:25	2492	Sailing 27	
14/15		13:50-15:21	01:31	3768	Sailing 30/36/16	
		15:25-16:21				00:56
		17:02-17:42				00:40
	07/02	13:27-14:01				00:34
		17:00-17:33				00:33
	08/02	00:57-01:20				00:23
		02:35-03:05				00:30
		04:30-04:49				00:19
		04:51-05:54				01:03
		07:30-08:02	00:32			
16		08:02-08:55	00:53	2792	02	
17		09:00-09:09	00:09	2408	25	
18		09:24-09:42	00:18	2792	04	
19		09:32-09:38	00:06	2408	05	
		11:48-11:58				00:10
		12:04-13:09				01:05
20/21		13:09-13:46	00:37	2792	04/05	
		13:46-15:03				01:17
22		15:03-15:52	00:49	3346	04	
		16:44-17:44				01:00
		18:19-19:11				00:52
		19:28-19:32				00:04
		20:15-20:50				00:35
		22:55-24:00				01:05
	09/02	00:00-00:45				00:45
		02:50-03:08				00:18
		03:15-03:42				00:27
		05:10-06:50				01:40

Case (nr)	Date	Detection Intervals	OWEZ related Vessel (WindCats)			Other Ships
			Interval (hh:mm)	Distance (m)	WTG (nr)	Interval (hh:mm)
23		07:25-08:34	01:09	2792	11	
24		09:15-09:19	00:04	3260	11	
25		14:19-14:28	00:09	2792	04	
		17:08-18:20				01:12
		21:54-22:17				00:23
		22:59-23:30				00:31
		Total Mission 1 Total Mission 2	02:11 08:21			22:02 16:22

Table 10 Underwater WindCat Noise on landing at the WTG terminal received at the WTG27 hydrophone and turbine conditions.

Case (nr)	Date	Detection Intervals	Distance (m)	WTG (nr)	SPL Pre/Post dB re 1 μPa²/Hz	SPL WindCat dB re 1 μPa²/Hz	Delta SPL 1/3 Octave bands dB re 1 μPa²	Wind Speed ($m.s^{-1}$)_	Power WTG27 (kW)	Rotor Speed (RPM)
1	18/01	06:48-06:56	3073	30	120.3	121.9	19.7	8.4	1238	15.1
2		09:20-09:23	3073	30	121.0	121.4	19.3	8.6	1377	15.2
3		09:36-09:39	3260	03	121.1	122.8	17.8	9.5	1635	15.9
4		09:47-09:59	3346	11	121.0	123.2	20.3	9.5	1721	15.8
5		09:58-10:05	2792	04	120.8	121.4	18.4	9.3	1582	15.7
6		12:27-12:30	3260	03	120.7	122.1	17.1	10.6	2028	16
7	19/01	13:01-13:06	1722	21	122.6	128.8	27.5	11.8	2562	16
8		15:34-15:37	1722	21	122.7	126.9	22.8	12.8	2756	16
9	06/02	08:59-09:01	2492	16	117.5	121.0	21.1	6.3	490	11.5
10		09:46-09:50	3768	02	117.1	119.6	30.4	7.4	755	13.4
11		09:53-10:01	2792	04	118.8	120.5	22.0	6.7	597	12.6
12		10:05-10:07	2492	16	118.8	120.0	19.8	6.5	491	12.2
13		13:28-13:29	2492	16	116.0	119.1	23.1	7.5	740	13.5
14		13:55-13:58	3768	02	115.8	118.9	21.4	7.4	753	13.4
15		14:41-14:48	1301	25	117.2	121.1	24.3	9.3	1421	15.9
16	08/02	08:39-08:54	2792	04	116.0	121.3	30.4	5.9	383	10.9
17		09:04-09:08	2408	05	116.0	120.2	28.5	3.9	105	10
18		09:27-09:32	2792	04	115.6	119.7	29.0	4.1	115	10
19		09:34-09:38	2408	05	116.3	120.9	31.4	5.1	251	10.1
20		13:12-13:21	2792	04	118.7	123.3	20.3	4.4	178	10
21		13:38-13:46	3346	11	119.5	122.0	23.9	7.1	727	13.2
22		15:17-15:24	3346	11	117.5	121.9	22.1	8.4	1200	15
23	09/02	08:17-08:34	2792	04	118.1	121.6	24.6	5.5	338	10.3
24		09:18-09:19	3260	03	119.2	120.7	19.8	6.9	646	12.9
25		14:21-14:24	2792	04	115.9	120.8	24.3	2.5	-12.1	1.8

Lists of Noise of category Other Ships

Table 11 Underwater noise Levels in both measured positions on the passage of a cargo vessel 18 January 2013.

Range (nr)	Date	Time	Power WTG27 (kW)	Wind Speed ($m.s^{-1}$)	Rotor Speed (RPM)	Rotor Blade Angle (°)	SPL WTG27 1/3 Octave bands dB re 1 μPa^2 (10s-1s)	SPL REF 1/3 Octave bands dB re 1 μPa^2 (10s-1s)
Pre Noise	18/01	21:06:17	2218	10.9	16	-2.1	122.3	123.2
Start		21:22:05	2217	10.9	16	-2.1	125.0	118.4
Piek		21:38:50	2084	10.5	16	-2.3	136.5	120.2
Stop		21:57:45	2469	11.4	16	-1.5	125.1	126.3

Appendix D Hydrophone specifications and calibration certificates

Certificate Sound Level meter, type B&K 2239 sn 2449130

Sensitivity curve RESON Hydrophone TC4032 sn 1009004
Sensitivity curve RESON Hydrophone TC4032 sn 3209020

Brüel & Kjær

The Calibration Laboratory
Skodsborgvej 307, DK-2850 Nærum, Denmark

ilac-MRA | DANAK CAL Reg.nr. 307

KALIBRATIE-CERTIFICAAT

No: C1207959 Pagina 1 van 26

GEKALIBREERDE APPARATUUR

Geluidsniveaumeter:	Brüel & Kjær Type 2239	No: 2449130 Id: -
Microfoon:	Brüel & Kjær Type 4188	No: 2462009

AANVRAGER

Wageningen IMARIS
Haringkade 1
1976 CP IJmuiden
Netherlands

OMGEVINGSCONDITIES

Voorconditionering:	4 uur op 23°C
Omgevings condities:	Luchtdruk: 101,3kPa ± 3kPa. Rel. vochtigheid: 50% RH ± 25% RH. Temperatuur: 23°C ± 3°C.

KALIBRATIE SPECIFICATIES

De Geluidsniveaumeter Brüel & Kjær Type 2239 getoetst aan de eisen, zoals gespecificeerd in IEC 60651 en IEC 60804 Type 1. Een lijst van de uitgevoerde (sub)testen is vermeld op pagina 2 van dit certificaat.

WIJZE VAN ONDERZOEK

De metingen zijn uitgevoerd met behulp van het Brüel & Kjær Geluidsniveaumeter Kalibratie Systeem 3630 met applicatie software: type 7763 (versie 4.7 - DB: 4.70) en kalibratie procedure 2239A-B-4188.

RESULTAAT

Kalibratie Manier: Kalibratie als ontvangen.

De gerapporteerde onzekerheid is gebaseerd op de standaard-meetonzekerheid vermenigvuldigd met een dekkingsfactor $k = 2$, wat resulteert in een dekkingswaarschijnlijkheid van 95 %. Bepaling van de meetonzekerheid is uitgevoerd in overeenstemming met EA-4/02 met gebruik van elementen afkomstig van gebruikte standaarden, kalibratie-methode, effect van omgevingscondities en elke kort durende bijdrage van het te kalibreren instrument.

Kalibratie Datum: 2012-10-24

Steen Vodstrup Andersen
Kalibratie Technicus

Certificaat uitgegeven: 2012-10-24

Morten Høngård Hansen
Tekeningsbevoegde

Brüel & Kjær Sound & Vibration A/S The Calibration Laboratory Skodsborgvej 307, DK-2850 Nærum Tel.: DK +45 45 80 05 00 info@bksv.com	DANAK is één van de ondertekenaars van de multilaterale verklaring van de European Cooperation for Accreditation (EA) en van de ILAC Mutual Recognition Arrangements (MRA) voor de wederzijdse acceptatie van kalibratiecertificaten.	Reproductie van het volledige certificaat is toegestaan. Gedeelten van het certificaat mogen slechts worden gereproduceerd na verkregen schriftelijke toestemming van het laboratorium van afgifte.

Brüel & Kjær

The Calibration Laboratory
Skodsborgvej 307, DK-2850 Nærum, Denmark

1. Commentaar

n/a

2. Summary

4.1. Visual inspection	Passed
4.2. Absolute Acoustical Sensitivity Level	Passed
4.3. Frequency Response Measured in Acoustic Coupler, FW A	Passed
4.4. Frequency Response Measured in Acoustic Coupler, FW C	Passed
4.5. Electrical Inherent Noise Level, FW A	Passed
4.6. Electrical Inherent Noise Level, FW C	Passed
4.7. Determining Electrical Level for LRef @1kHz	Passed
4.8. Frequency Response measured with Electrical Signal, FW A	Passed
4.9. Frequency Response measured with Electrical Signal, FW C	Passed
4.10. Level Range Control, 1000 Hz	Passed
4.11. Linearity Range, IEC60651, 1000 Hz, SPL 1 dB steps	Passed
4.12. Linearity Range, IEC60651, 4000 Hz, SPL 10 dB steps	Passed
4.13. Linearity Range, IEC60804, Leq	Passed
4.14. Time Weighting, Difference in Reference Level Indication	Passed
4.15. Time Weighting, Response to Single Burst, 200 ms, F	Passed
4.16. Time Weighting, Response to Single Burst, 500 ms, S	Passed
4.17. Time Weighting, Response to Single Burst, 20 ms, I	Passed
4.18. Time Weighting, Response to Single Burst, 5 ms, I	Passed
4.19. Time Weighting, Response to Single Burst, 2 ms, I	Passed
4.20. Time Weighting, Response to a Continuous Sequence of Bursts, 100 Hz	Passed
4.21. Time Weighting, Response to a Continuous Sequence of Bursts, 20 Hz	Passed
4.22. Time Weighting, Response to a Continuous Sequence of Bursts, 2 Hz	Passed
4.23. Time Weighting, Peak	Passed
4.24. RMS Detector, Sine Burst, CF3	Passed
4.25. RMS Detector, Sine Burst, CF5	Passed
4.26. RMS Detector, Sine Burst, CF10	Passed
4.27. Time Averaging, Leq	Passed
4.28. Pulse Range, Leq	Passed
4.29. Overload Indication, Sine Signals, Inverse A	Passed

"Passed" Betekent dat het resultaat van de (sub)test valt binnen de gestelde toleranties van de gespecificeerde norm/normen.

"Failed" Betekent dat het resultaat van de (sub)test valt buiten de gestelde toleranties van de gespecificeerde norm/normen.

"Near Limit" Betekent dat het niet mogelijk is een uitspraak te doen. Het resultaat valt binnen de gestelde toleranties van de gespecificeerde norm/normen. Maar rekening houdend met de meetonzekerheid is de kans op een goed resultaat kleiner dan 95%.

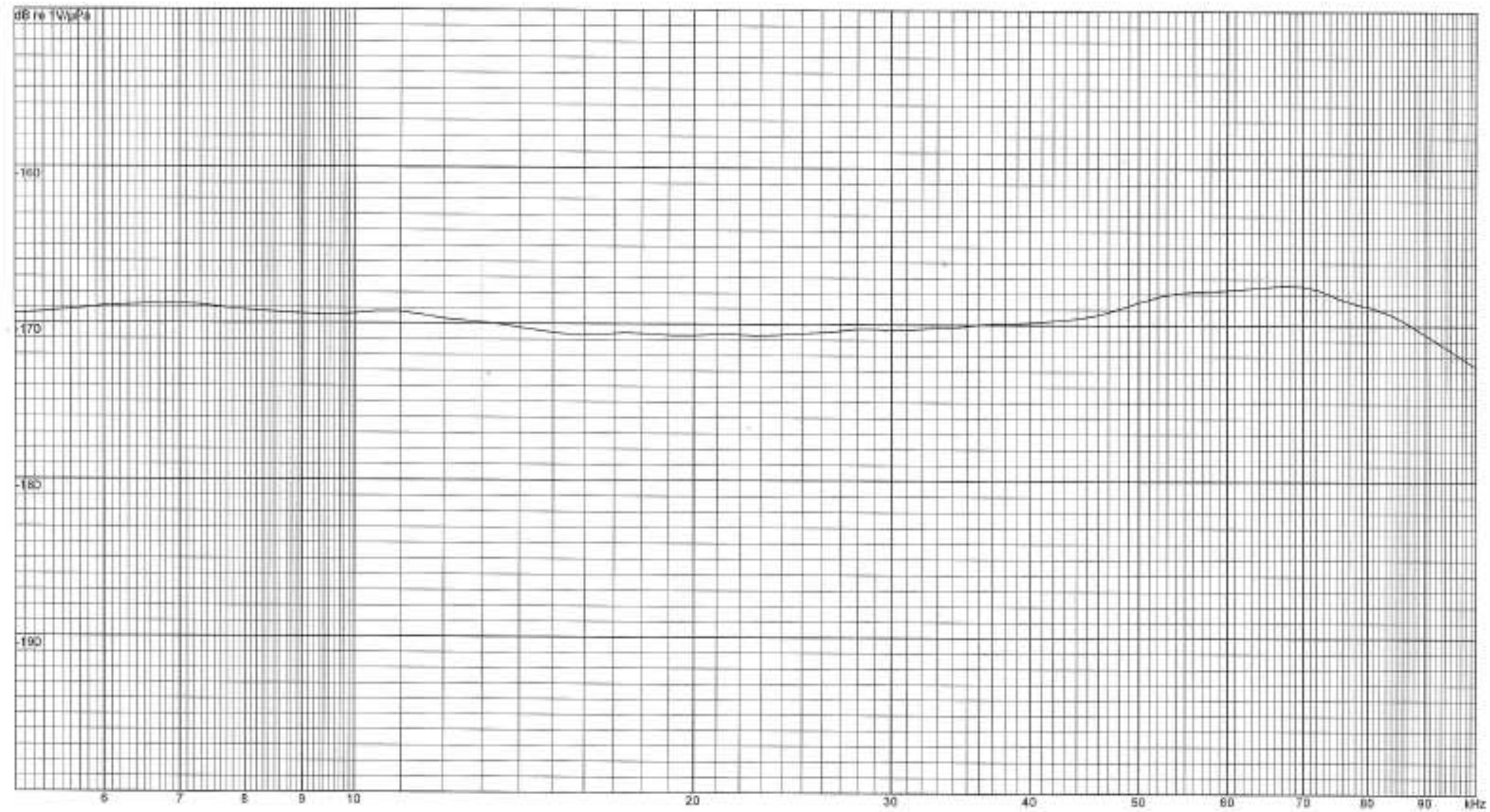
"!" Wordt gebruikt om het meetresultaat te waarmerken, wanneer deze aan de "Near Limit" voorwaarde voldoet.

"^" Betekent deze metingen zijn buiten de scope van onze DANAK accreditatie.

RESON

HYDROPHONE SENSITIVITY

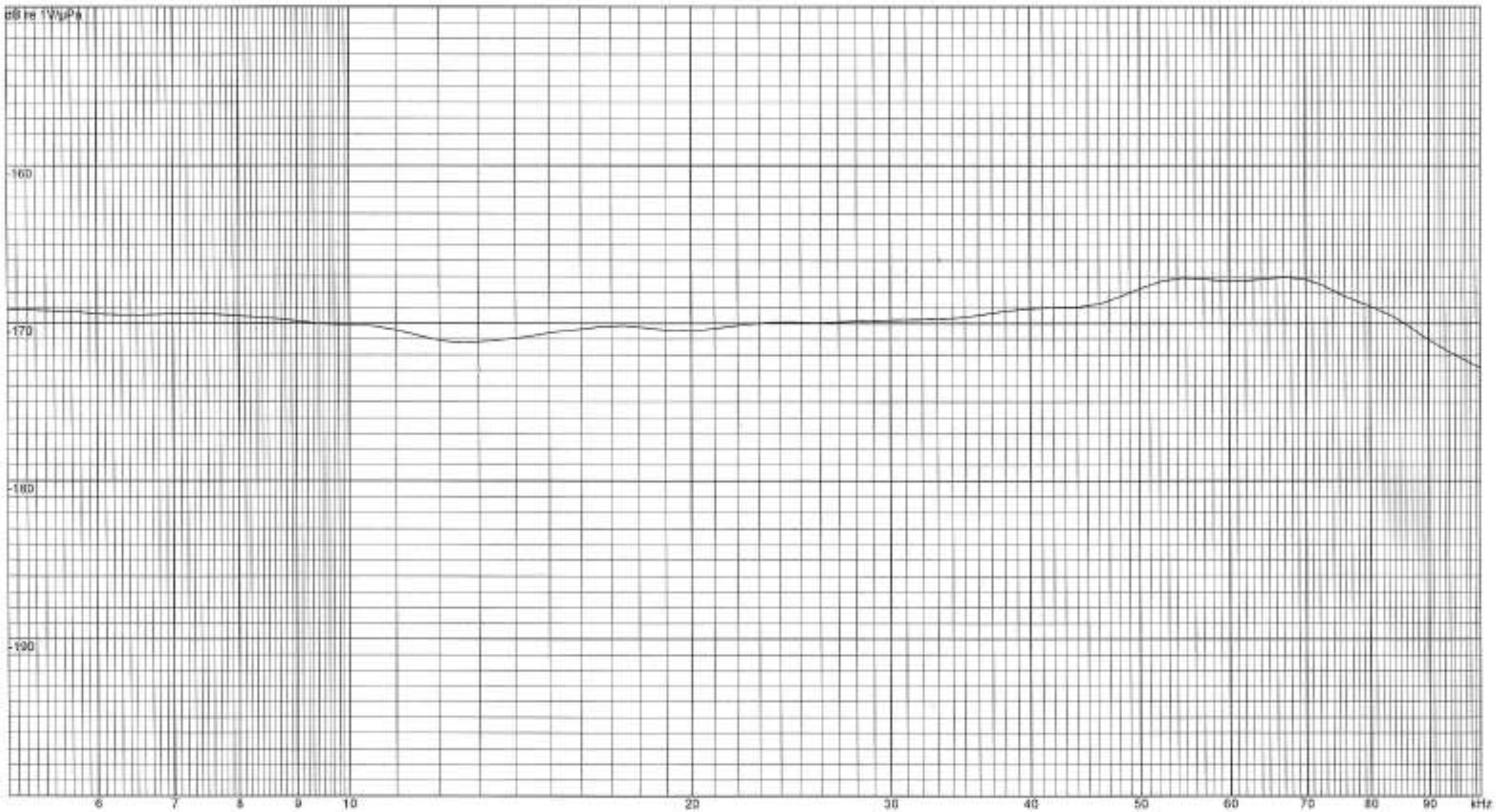
Under Test:	TC4032-1	Amplitude:	10.0 Vrms	Temperature:	21.60°C
S/N:	1009004	Pulse Width:	214.3 µs	Depth:	1.2 m
Reference:	TC4033	Rep Rate:	50.0 ms	Distance:	0.60 m
Date:	2009-09-16	Averages:	8	Tested by:	HHP 090916
Session, Run:	10526, 19				
Comment:	PHO @ 250Hz: -169.2dB.				



HYDROPHONE SENSITIVITY

RESON

Under Test:	TC4032-1	Amplitude:	10.0 Vrms	Temperature:	21.38°C
S/N:	3209020	Pulse Width:	214.3 µs	Depth:	1.2 m
Reference:	TC4033	Rep Rate:	50.0 ms	Distance:	0.60 m
Date:	2009-09-15	Averages:	8	Tested by:	HHP
Session, Run:	10525, 12				
Comment:	PHO @ 250Hz: -169.7dB.				



Appendix E Validation of Results

Reference measurements TNO, The Hague, NL 2013-04-16

Overview of main results concerning the hydrophones used in the reported experiments of January and February 2013 exposed to a “pink noise” type of signal in the range of 20 Hz to 20 kHz and compared to TNO reference equipment.

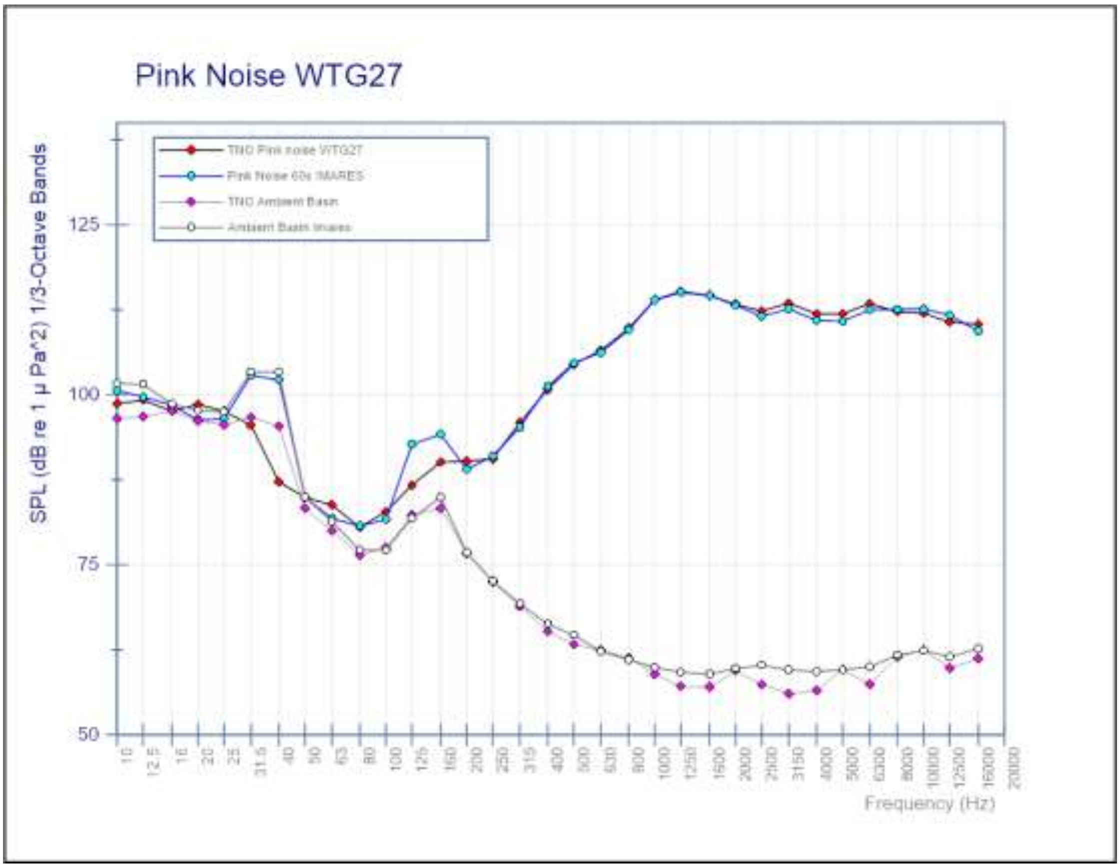


Figure 75 Hydrophone and conditioning hardware exposed to a pink noise type of signal and compared to a equivalent TNO reference hydrophone. The results are similar with some deviation in the LF range in the 100 to 160 Hz bands and are attributed to minor changes in the hydrophone positions in relation to the wavelength limitation in relation to the basin dimension.

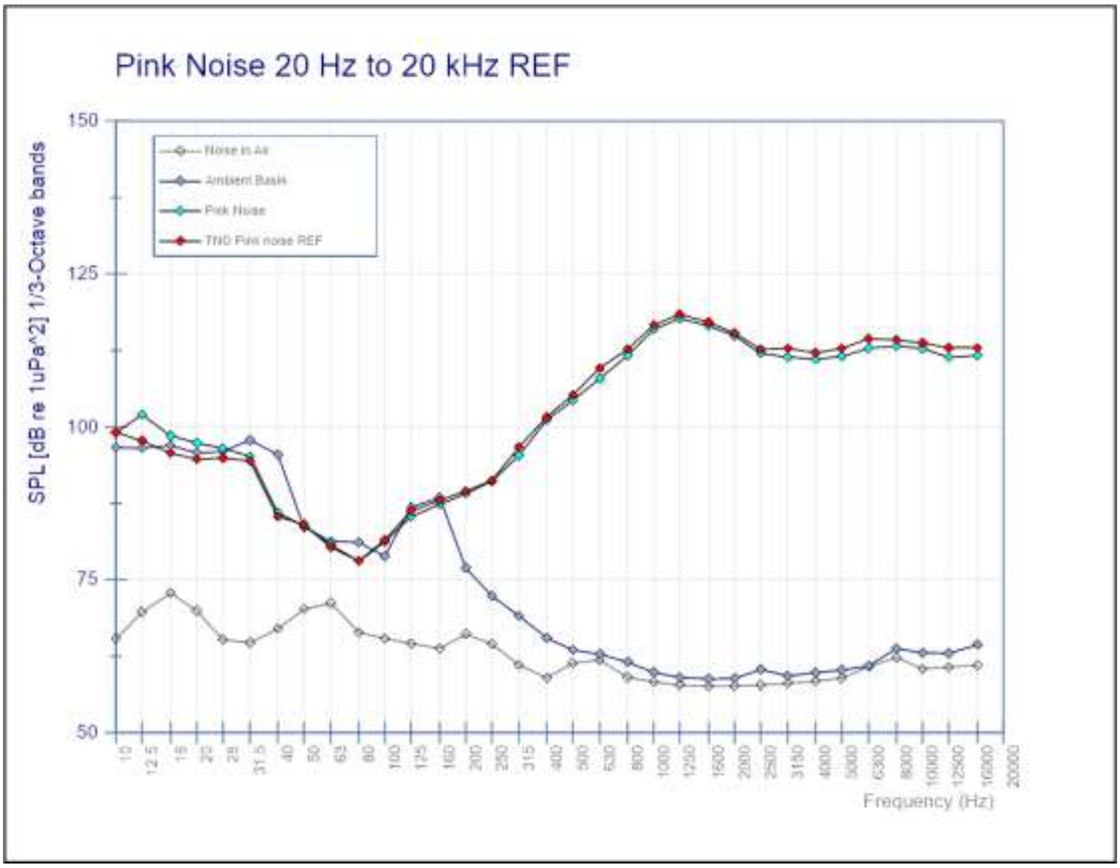


Figure 76 Hydrophone and conditioning hardware used in the refrence position exposed to a "pink noise" type of signal and compared to a equivalent TNO reference hydrophone. The results are similar with some deviation in the LF range in the 100 to 160 hz bands and are attributed to minor changes in the hydrophone positions in relation to the wavelength limitation in relation to the basin dimension.

From this outcome the hydrophone sensitivity reported in the sheets of Appendix D was adjusted according the overview of Table 12.

Table 12 Adjusted hydrophone sensitivity according the calibration references executed with the pistonphone calibrations.

		Reson TC-4032 #	dB re 1 V/uPa
Sensitivity	Reference	3209020	-173.8
	WTG27	1009004	-173.1

Appendix F First measurements 2007

Between 1 June and 29 August 2007 three measurement sessions were conducted at several distances from the south-western and eastern outer turbine rows. The results were published as first results in a progress report (de Haan et al., 2008).

There are a number of motives to review these measurements and add this as a supplementary outcome:

- Other measurement locations and hydrophone positions were applied:
    - They were executed at the south-western side of the OWEZ area in slightly deeper water (+ 2 to 3 m compared to the position of WTG27);
    - The measurements were executed at symmetrical distances from WTG09 and WTG10 and not opposite a single turbine position (WTG27) as in the present set-up;
- They follow the TNO-recommendation of measuring at multiple locations (de Jong et al., 2011);
- The results represent the condition before the filling of the monopiles with concrete in 2010;
- They were executed at distance of around 500 m, which is presently estimated to be the threshold distance where turbine noise becomes masked in the background noise;
- A clear detection was captured at 1100 m of noise attributed to the yawing of a turbine, which was not observed in the present results in a much closer range (100 m);
- The present acoustic analysis technique further improved and the analysis procedures reported in the progress report published in 2008 did not follow the present acoustic convention/metrics.

As the methods of the first measurements differed from the present method and represent short intervals of 29 s per record the results are proposed as indicators.

Summary

The analysis of noise measured at a symmetrical distance range 481 to 567 m from WTG09 and 10 showed that only at 481 m a minor contribution of turbine noise can be observed in the 100 Hz Third-Octave band. These earliest results indicate that turbine noise becomes masked by background noise at a distance < 600 m.
Although the results were influenced by heave noise < 40 Hz stronger low-frequency components of turbine noise could not be detected. The engine noise exposed during the yawing of WTG11 received at 1100 m, however was clearly detected and had contributions in the 80-125 Hz and 500 to 8000 Hz bands and peaked in the 1600 Hz Third-Octave band to 113 dB re 1 μPa^2, which is 13 dB above the level recorded when the turbine was running after the yawing noise extinguished. The narrow-band FFT-analysis showed that the yawing noise consisted of three major sharp peaks at 282, 766 and broader around 1500 Hz. At that time of yawing the wind speed measured on WTG10 was 10.6 m.s^{-1} and this turbine produced 1650 kW.

Methods

Each session involved a single day-time period and measurement files were relatively short and maximised to 29 s. Although the applied equipment differs from the set-up of 2013 and the noise spectra contain contribution of heave-noise below 40 Hz the outcome is valuable to compare to the current results.
On the first session in June 2007 hydraulic engine-noise related to the yawing of WTG11 was captured with the hydrophone at a distance of 1102 m. The hydrophone was positioned on the center axis between WTG09 and 10, perpendicular to the southwestern outer turbine string (Figure 77).

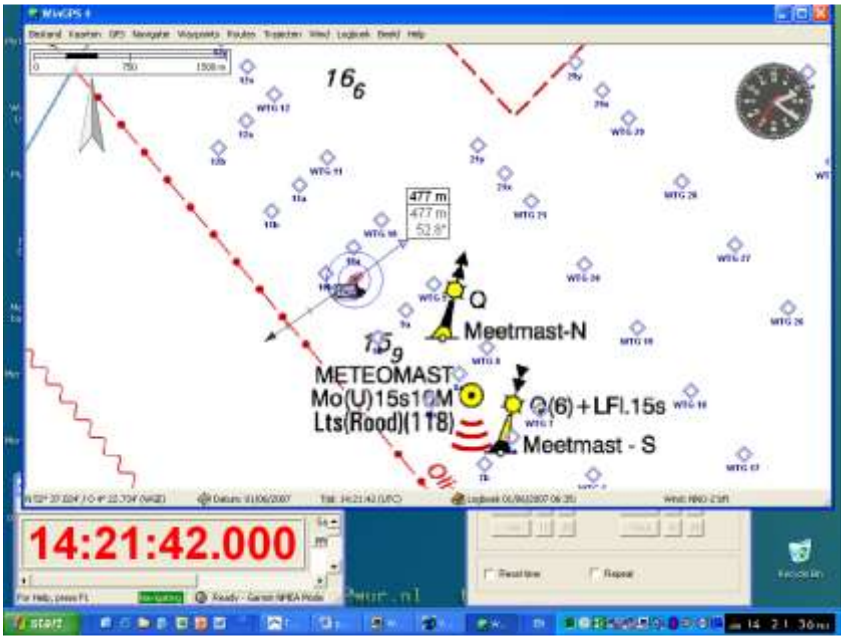


Figure 77 Received position of yawing noise 600 m from WTG09 and 10 applied on the records of file 9 to 12 (Table 13). The plot contains marked positions 300 and 600 m from the outer turbines.

Based on the file properties of an additional audio recording the yawing event took at least 8 minutes. The WindCat support vessel was positioned at WTG12 and left the area at 14:06, which is 6 minutes after WTG11 started running (Table 13, file 10). Such a yawing event was not detected in close range (100 m) of WTG27 although the OWEZ-records of 2013 include multiple yawing events. This raises the question if the propagation of noise along the structure-borne path was affected by the filling of the monopiles in 2010. Since 2007 the IMARES measurement system and analysis tools were further developed and the acoustic data recorded in 2007 was re-processed using the methods of 2013.

Description of measurement equipment and conditions

The measurement equipment consisted a RESON, TC 4032 (S/N 2005017) with 30 m extension cable. The TC 4032 hydrophone was connected to a RESON EC 6073 interconnection module for signal transfer and powering. The TC 4032 hydrophone was powered by a 12.6 V battery (PBQ 17 12.6 V/17Ah). The hydrophone output signal was connected to a battery powered amplifier (ETEC A1101) with an adjustable gain of 0-50 dB in 10 dB steps. The measurements were executed with a gain setting of 10-20 dB. The amplifier's high-pass filter was set to 1 Hz to reduce the sea wave and heave noise off the hydrophone cable on the rolling action of the ship. As the gain characteristics are flat to 1 MHz, a passive low-pass filter was used on the output of the amplifier to filter the HF noise above 150 kHz with 12 dB/octave. The output of the filter was connected via a BNC 2110 coaxial input module to a 16 bit data acquisition card (National Instruments type PCI 6281M) on which the analogue signals were digitized with a sample rate of 512 kHz (data rate of 0.5 Msamples/s). Of each data sample the SPL (Sound Pressure Level) was computed using the SPL/voltage relation of a pistonphone (G.R.A.S., model 42AC) reference source. This reference level was measured at the side gate of the hydrophone coupler using a B&K 2239 sound level meter with the hydrophone coupled into the pistonphone. The reference level measured was 156.32 dB re 1 μPa^2.

The record containing the yawing noise (file 9) was also recorded in WAV-format for audio play-back.

The computer equipped with the PCI type of DAQ card was powered by an Uninterruptible Power Supply (UPS), type APC 1400, which supported AC mains supply when all ship engines were switched off. Two additional batteries (24 V/24 Ah (2xPBQ 24-12 in series) were connected to the UPS battery to extend the buffering capacity from standard 20 to 120 minutes. Highest noise immunity was obtained when the ground reference of the amplifier/BNC chassis was referred to seawater using a brass reference terminal suspended at equal depth in close to the deployed hydrophone position.

Hydrophone position and distance

The hydrophone was suspended at a depth of 4 m without using a dead weight at the hydrophone end to avoid strumming cable noises. The distance from the hydrophone to the acoustic source was calculated using the GPS NMEA–records of the ship's GPS-receiver (WAAS type FURUNO GP-32). The positioning information was also used to navigate and position the ship to measurement locations. The satellite NMEA-0183 data string of the module was coupled to the RS 232 communication port of a laptop computer with Visual GPS software to log the data. Positioning data was updated every second and started on arriving at the OWEZ wind farm. WIN GPS 4+ software was used to navigate and plot the NMEA data on a DKW 2005 North Sea map (Stentec software, NL) as background map. With this utility the measurement and WTG-coordinates were imported. The WINGPS 4+ software supported a log function to store the closest position and distance from the target.

All three sessions were conducted using the 12 m long MS "Het Sop", Texel, earlier used to measure the of piling noise on the construction of the OWEZ wind farm in 2006 (de Haan et al., 2007b).

Wind and turbine conditions

All times are reported in UTC, the OWEZ time reference was Dutch wintertime (+1 hour UTC) and was corrected to UTC. The acoustic measurements were conducted between 12:20 and 15:36. In this period the wind direction was north-northwest with a wind speed peaking at 12:00 of 11 $m.s^{-1}$. At the time of the background noise measurements the wind speed was 9 $m.s^{-1}$ (Table 13).

The wind speed conditions during the measurements are illustrated in Figure 78 and shows that the MET01 sensor mounted on the OWEZ Meteo mast did not follow the trend of the sensors on the WTG nacelles. The yawing moment can also be observed in the readings of the WTG11 wind speed sensor, which are raising around 13:30.

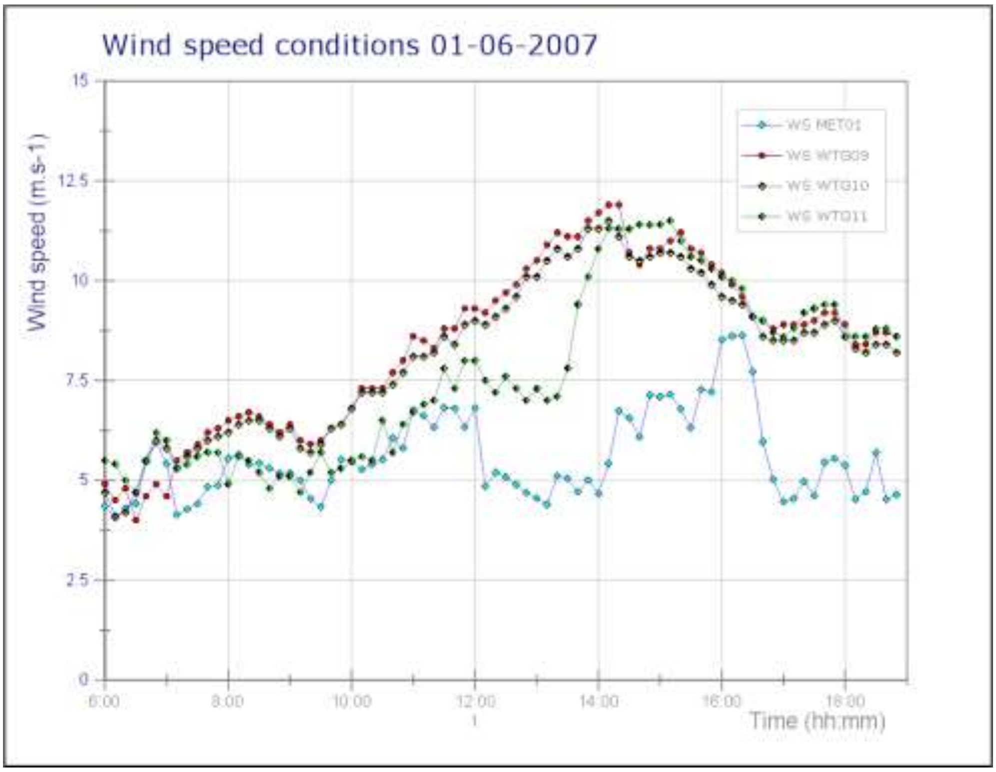


Figure 78 Wind speed conditions during the measurements taken from the OWEZ Meteo mast sensor "Met_01 South" and the wind speed sensors on the nacelles of WTG09, 10 and 11.

The wind condition and turbine power production data are listed in Table 13. The wind speed reference was taken from the sensor on the nacelle of WTG10.

Procedures and sequence of operations

The hydrophone was positioned along a symmetrical axis between WTG 09 and 10 perpendicular to the outer western row of turbine in a distance range of 500 to 3200 m. The measurements were conducted either in a fixed anchored position (file 9 and 10) or while drifting in a reference position or at distances < 500 m. Turbine noise contribution at distances < 500 m was not found and is not given in the overview. Background noise measurements was used as reference to the turbine noise results and were carried out 7.5 km to the north of the OWEZ wind farm in position 52.38 N and 004.45 E. These measurements were carried out approximately 2 hours before the measurements of the start of WTG11. The calibration of the hydrophone with the G.R.A.S. pistonphone took place after the background measurements.
As a standard test procedure for acoustic measurements (de Haan et al., 2007a&b) the equipment was also tested using a Ducane 1000 pinger sound source deployed at a distance of 1.8 m from the hydrophone and both at a depth of 2 m. These results matched other references and were left out the reports.

Table 13 Overview of data files and wind speed and turbine power conditions

Session 1 2007-06-01					Turbine conditions WTG10		
File (nr)	File Start Time	Hydrophone distance (m)			Wind speed ($m.s^{-1}$)	Turbine Power (kW)	Rotor Speed (RPM)
		WTG09	WTG10	WTG11			
REF 1	12:25:24			7541	9.3	1221	15.6
REF 2	12:26:19			7511	9.3	1221	15.6
9	13:24:10	570	606	1102	10.6	1650	15.6
10	14:00:39	568	567	1059	11.3	1871	15.6
11	14:17:49	598	552	1028	11.1	1817	15.6
12	14:19:51	600	518	992	11.9	1817	15.6
19	15:35:22	495	514	1045	10.2	1475	15.6
20	15:36:16	487	481	1018	10.7	1475	15.5

Analysis procedures

The acoustic records were filtered in Third-Octave bands and represent a linear averaged period of 20 blocks of 1 s. Narrow-band FFT-analysis was applied to observe the energy peaks of the noise in detail and to determine harmonic contributions. FFT-analysis was applied over 20 s of 1 s time blocks with 50 % overlap. As 1 s time blocks were applied the results expressed the spectral levels.

Results

The noise developed on the activation of WTG11 after maintenance (Figure 79) shows the auxiliary engine noise contribution on yawing the turbine. The received distance of the noise was 1102 m. The yawing noise contribution is observed in the range of 500 to 8000 Hz with a peak in the 1600 Hz Third-Octave band, 12.9 dB above the turbine noise level measured 30 seconds later when the yawing was completed. The equipment was not conditioned to filter the hydrophone noise affected by heave actions (high-pass filter set at 1 Hz), therefor the results < 40 Hz are disqualified.

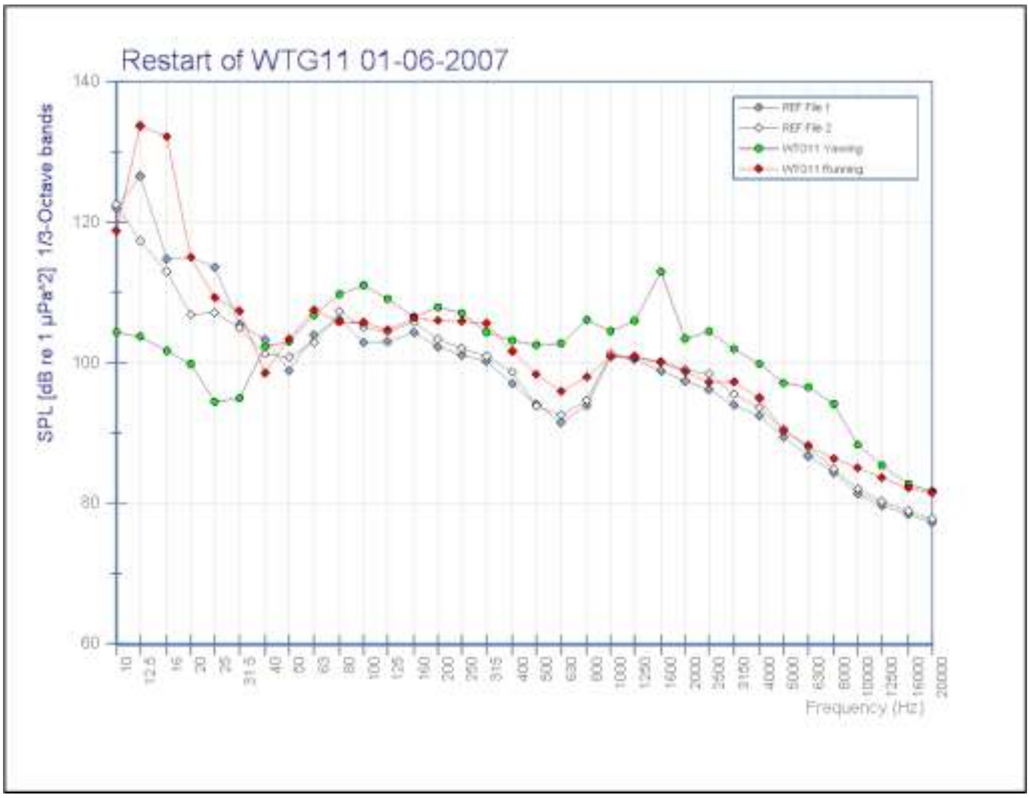


Figure 79 Restart of WTG11 with the contribution of engine noise peaking in the 1600 Third-Octave band.

The narrow-band FFT result shows that the noise consists of three major strong energy peaks around 282, 766 and broader around 1500 Hz (Figure 80).

The analysis of noise measured at a symmetrical distance range 481 to 567 m from WTG09 and 10 showed that only at 481 m a minor contribution of turbine noise can be observed in the 100 Hz Third-Octave band.

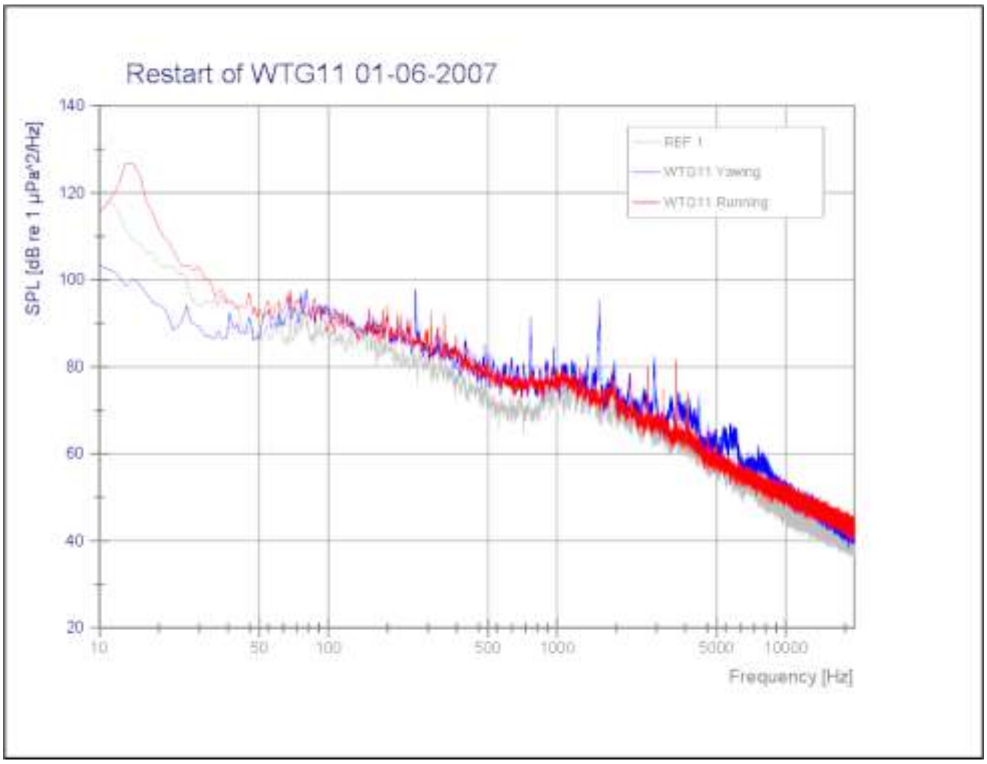


Figure 80 Narrow-band FFT-analysis of the yawing noise of WTG11 against the running mode shortly after completion of the operation showing some sharp peaks at 282, 766 and broader around 1500 Hz (FFT 20 s average length, 1 s block, 50 % overlap).

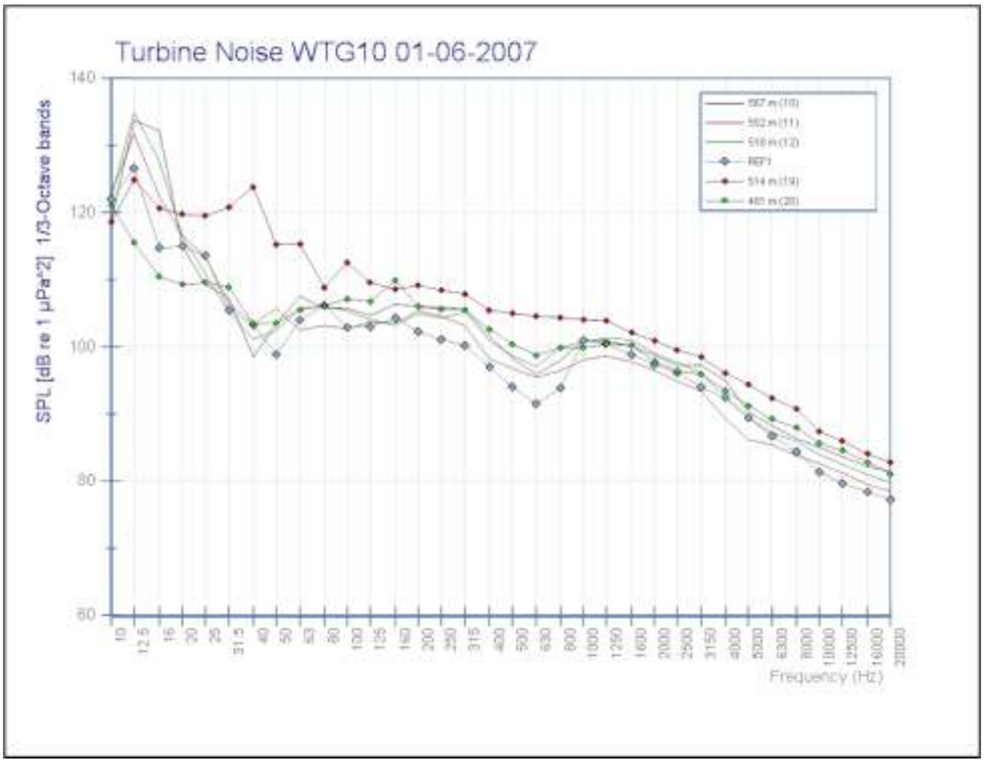


Figure 81 Noise filtered in Third-Octave bands measured in a symmetrical distance range of 480 to 567 m from WTG09 and 10. A minor contribution of turbine noise can be observed in the 100 Hz Third-Octave band received at 481 m.