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

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Summary

The demand for renewable energy has led to a significant growth of offshore wind farms in European waters. According 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 30 in 2030. Turbine dimensions increased from 2 MW in 2006 to 5 MW at present.

In Holland the first two offshore wind farms, the Offshore Wind Farm Egmond aan Zee (OWEZ) and “Prinses Amalia” 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 construction to the environment. The construction was licenced to NoordZeeWind, a consortium of Shell and NUON, and completed in August 2006 and involved 36 turbines of 3 MW each. To demonstrate the impact an extensive Monitoring and Evaluation Program (MEP) was developed to evaluate the effects on benthic organisms, fish, birds and marine mammals. One of the tasks was to measure the underwater noise characteristics before and during the construction and with turbines in operation and to estimate the effects.

Turbine 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 and a second measured position 7.4 km to the north of the WTG27 location used as background noise reference not exposed to wind farm noise. The measured periods involved 83 hours in January and 88 hours in February 2013. Both periods involved the maximum power production condition.

Turbine noise raised above the background noise level as soon as the turbine is activated and produced power ≥ 100 kW. At a wind speed of 15 $m.s^{-1}$ the turbine broad-band spectral noise level, averaged over 10 minutes was 123 dB re 1 $\mu Pa^2/Hz$. Under this condition the reference noise level was 6 dB lower at a wave height of 3 m and 9 dB lower when the wind was from the east with only 0.8 m wave height. Based on the highest difference of 9 dB and the assumption transmission losses are according an intermediate between a 20 Log R (spherical spreading) and 10 log R (cylindrical spreading) (Thomsen et al., 2006), we estimated that turbine noise will by masked by the background noise level at 500 m from the turbine position.

Turbine noise peaked in the 50, 100 and 200 Hz Third-Octave bands and equalled the background noise level in the bands ≥ 315 Hz. When not masked by shipping noise, turbine noise has the strongest contribution in the 200 Hz band (115 dB re 1 μPa^2 $^+/_-$ 1.2 dB). Turbine noise levels in the range 16 Hz could not propagate at the local water depth of 18 m and were only observed incidentally at the highest tide condition of the measurement period.
The turbine noise was detected at low wind speed conditions ranging between 6 to 8 $m.s^{-1}$ and reached the maximum level between 500 to 2000 kW, above 2000 kW the turbine noise level hardly increased. No other significant noise sources related to the wind turbine structure were found. Wind farm related propulsion 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 a factor 7 times the estimated distance (500 m) where turbine noise is masked by the background noise. WindCat propulsion noise masked turbine noise for a total period of 10 hours (5.9 % of the total measured period). The contribution of all shipping noise detections (including WindCats) was rather high 28.4 %. 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, while the passing ship masked the turbine noise for a period of 40 minutes and a sailed distance of 20 km.

Noise from turbines and shipping was analysed against the hearing capabilities of marine mammals, harbour porpoise (*Phocoena phocoena*), harbour seal (*Phoca vitulina*) and two fish species Atlantic cod (*Gadus morhua*) and Atlantic herring (*Clupea harengus*). This outcome showed that for harbour seal turbine noise measured at 100 m from the source is 30 dB above the background at 200 Hz and levels to the background noise at 400 Hz. For harbour porpoise this difference is 12 dB. The weighed results for both fish species show 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 by marine animals, in particular on the relation between signal and noise in fish. The results showed that harbour seals can detect the noise over the full unmasked range and that the perception of harbour porpoise is limited in range. 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.

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. The expectations for the dimensions of the wind turbine capacity are an increase from 3 at present to 5 MW in the near future. 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 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 is estimated to at least 20 years. With respect to this aim 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.
The expected growth of wind power production is expressed in the new licenced wind farms (Figure 1) planned in the Dutch sector of the North Sea taken from the "RWS Noordzee" chart (NZWS 2011-0060) with the existing (blue), new licenced (green) and rejected licences (brown) locations.

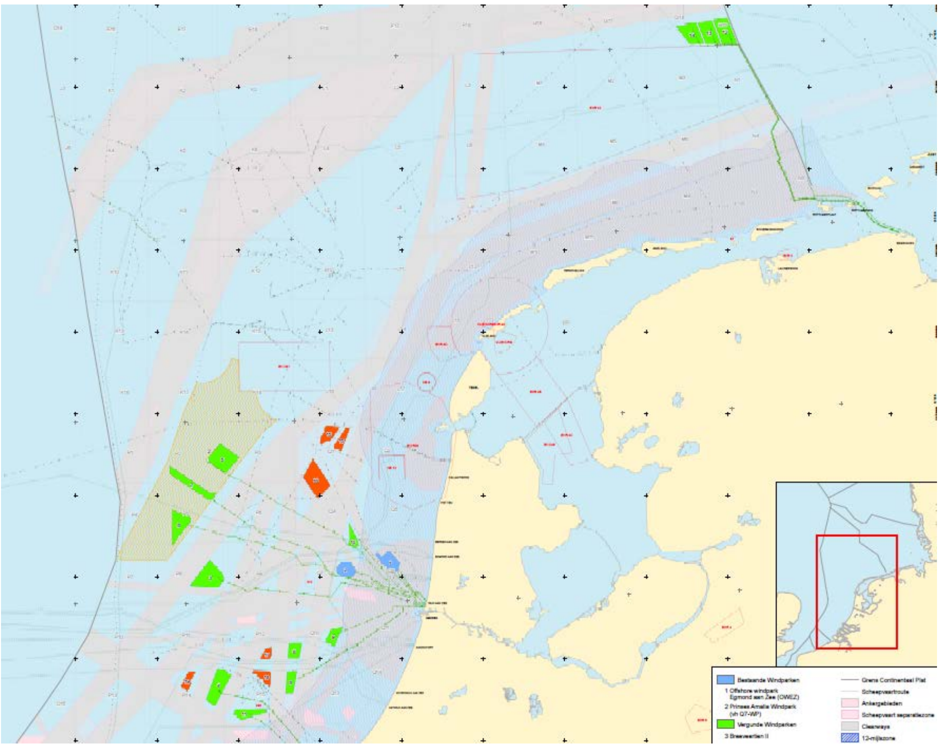

Figure 1 Overview of existing and expected future wind farm location in the Dutch NorthSea zone

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).

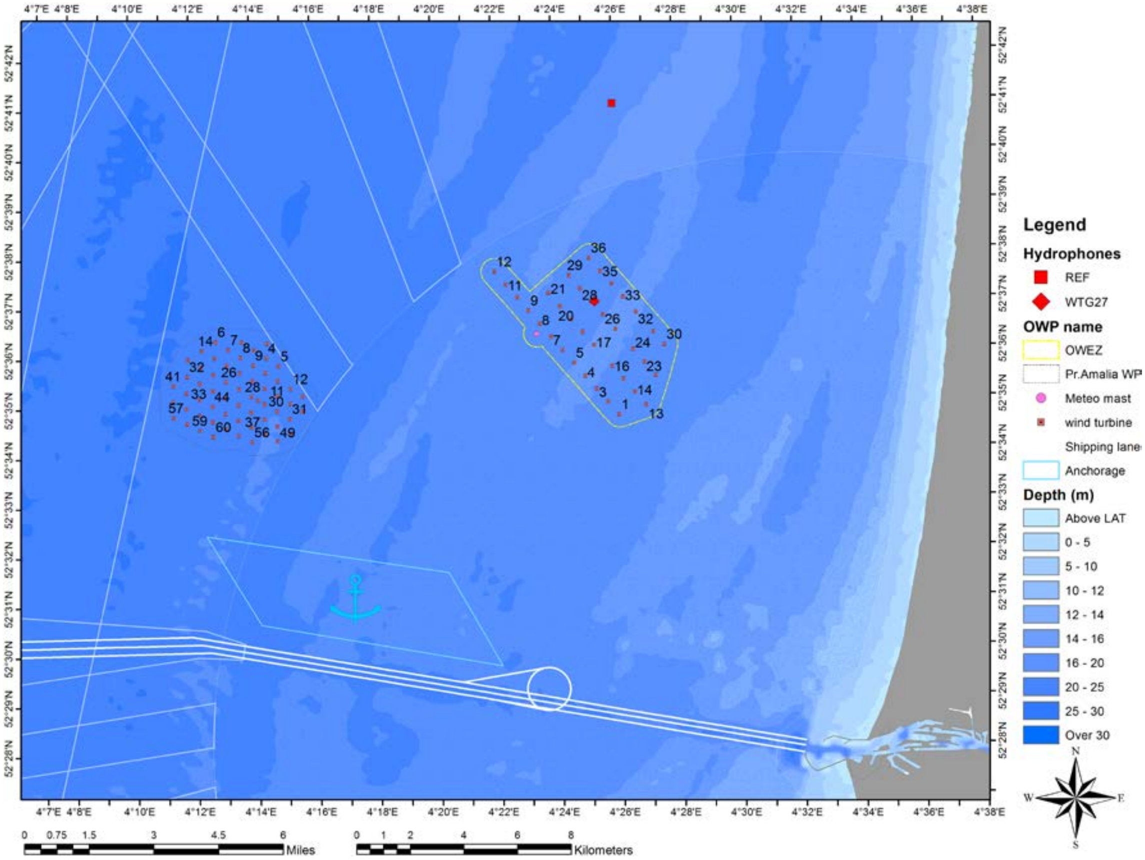

Figure 2 Location of the OWEZ wind farm with at the west "Prinses Amalia" wind farm and coastal shipping lanes. To the west of the OWEZ site the sub lanes towards the main shipping route. The map marks the measuring position of the hydrophone 100 m east of Wind Turbine Generator 27 (WTG27) (red diamond) 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) by 2896 m (maximum width). The other wind farm of similar scale, "Prinses Amalia" (Q7) 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. 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 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.

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

1.3 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 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 $m.s^{-1}$).

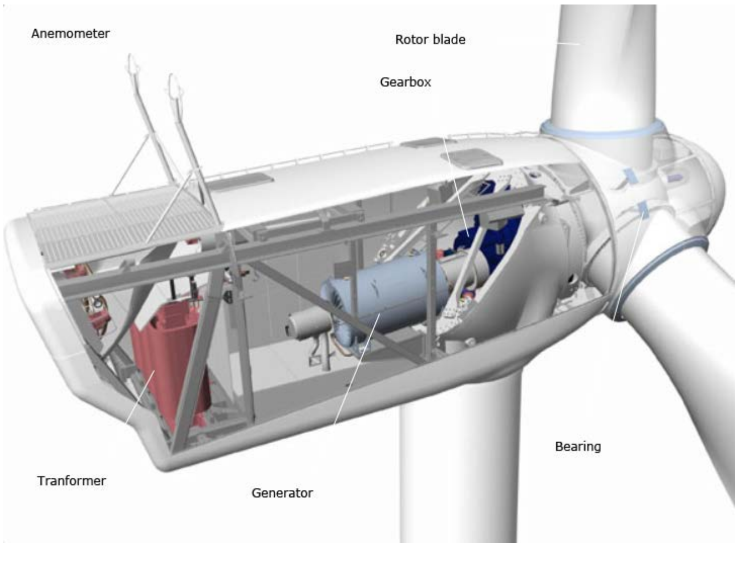

Figure 4 Overview of the Wind turbine construction (nacelle) with main parts of the construction.

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.

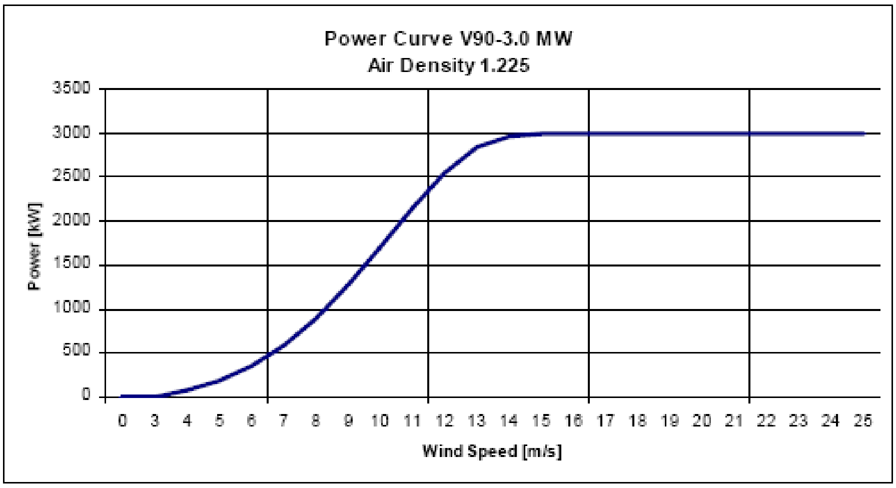

Figure 5 Power curve of the Vestas V90 wind turbine as a function of wind speed

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.

1.4 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 methods of measuring and analysing the results follow the guidelines of a national discussion on standardizing the acoustic metric units. The measurement and analysis procedures are summarised in a TNO-report by de Jong et al., 2011. The overview of published results and reviews on wind farm noise of similar scale showed that wind turbine noise is mainly developed in low frequency ranges < 500 Hz with levels too low to cause hearing loss or impairment (Madsen et al., 2006).

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 (Figure 6).

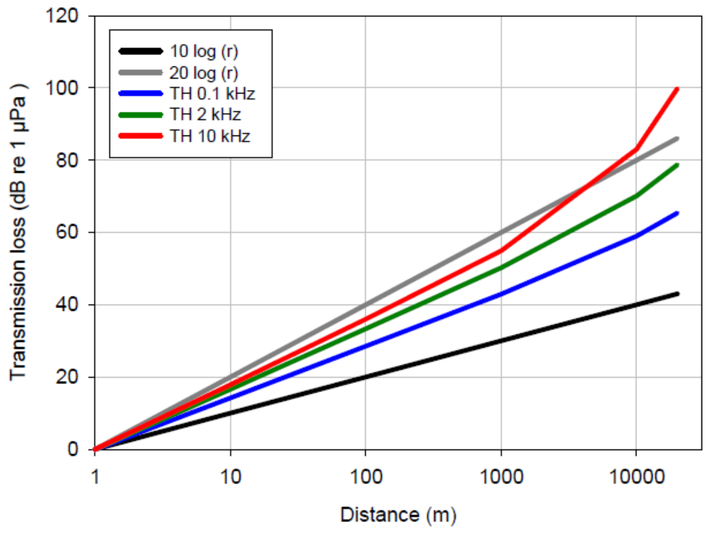

Figure 6 Transmission loss models according spherical (20 log R) and cylindrical spreading (10 log R) and the models according Thieme (2002) for 0.1 and 2 kHz.

According model of Thieme the transmission loss is intermediate between spherical and cylindrical spreading for 100 Hz and at this frequency the model estimates 4.5 dB loss at double distance. When turbine noise would be mainly based on 100 Hz the transmission loss would be 9 dB at 500 m from the turbine.

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.

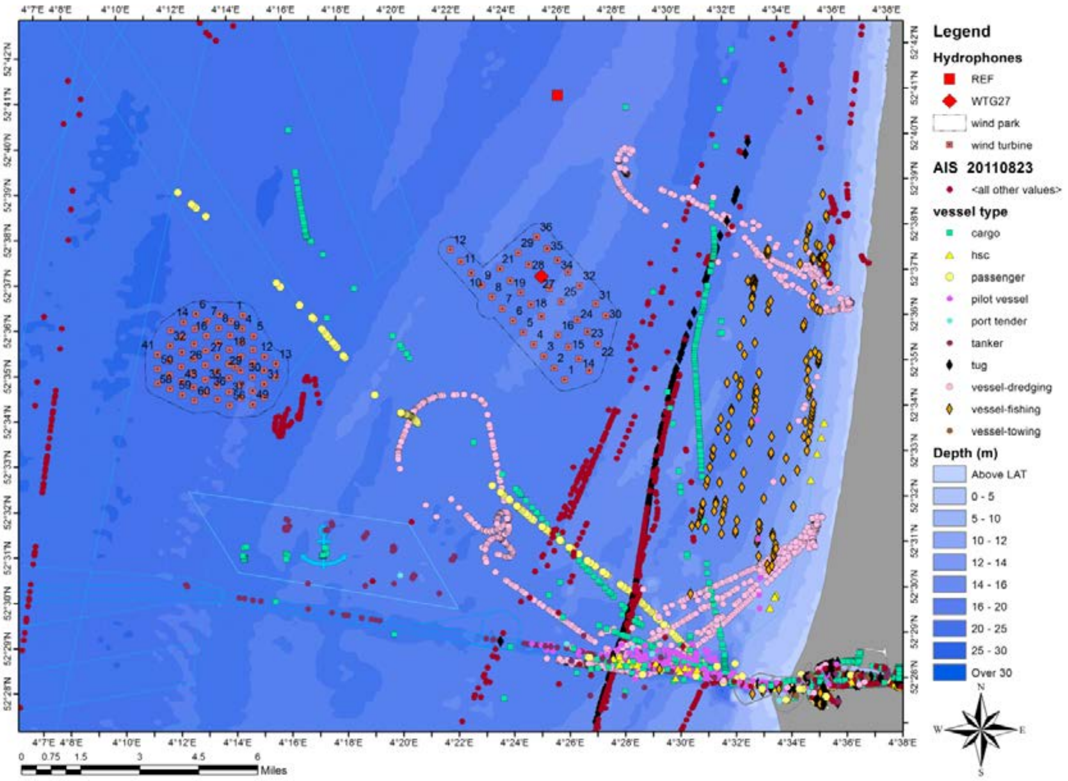

Figure 7 A randomly selected AIS-record with the shipping activity over 24 hours on 24 August 2011 around the OWEZ wind farm area.

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).

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).

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

1.6 Reference data of turbine noise and the effects on marine animals

Knowledge on the sound emission of offshore wind farms at the scale similar to OWEZ is 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). Their conclusion was that the reported noise levels from operating wind farms were low and that measurements at 100 m from a turbine will not exceed 120 dB re 1 µPa^2 (RMS). The main part of the energy is low frequency in the range of 60-200 Hz, with some sharp peaks at 60 and 180 Hz indicating tonal type of contributions.
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).

1.6.1 Marine mammals

Madsen et al., 2006 concluded that it is unlikely that turbine noise will impair the hearing capabilities of marine mammals, but that the noise will be audible to them in particular to the species more sensitive in the lower frequency range, like pinnipeds. Figure 9 and 10 show the auditory thresholds of the most relevant species, on which the effects of the measured turbine noise were applied, harbour porpoise (*Phocoena phocoena*) and harbour seal (*Phoca vitulina)*.

These curves (Figure 9 and 10) are based on 50 % detection levels derived from the study of Kastelein 2010a (harbour porpoise) and Kastelein et al., 2009 (harbour seal).

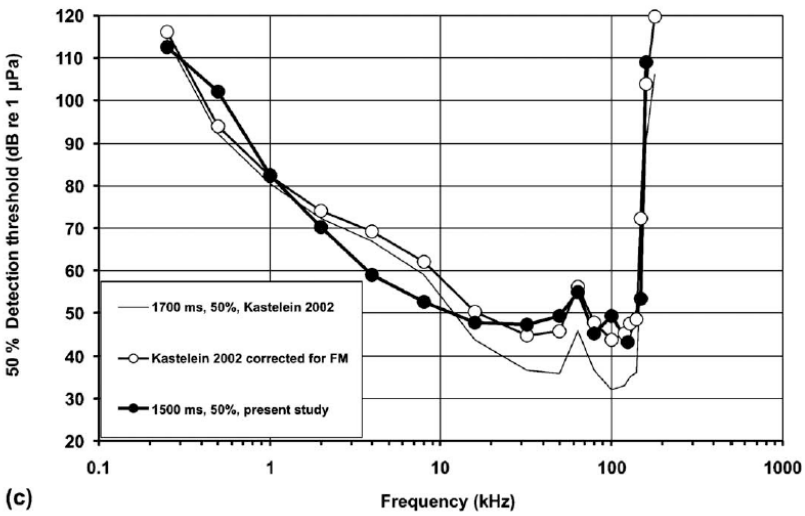

Figure 9 Overview of detection thresholds for harbour porpoise (Phocoena phocoena) with frequency-modulated tonal signals (Kastelein et al., 2002) and was corrected to match the study with various signal duration (Kastelein et al., 2010a).

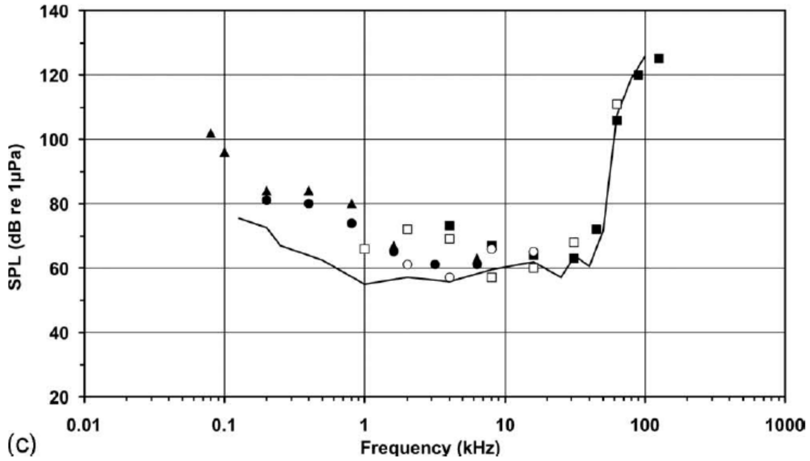

Figure 10 The average detection thresholds for harbour seal based on two animals (Kastelein et al., 2009a and b) and pure tones and 900 ms narrow-band FM displayed the outcome of other studies Møhl, 1968 (■); Terhune, 1988 (□); Turnbull and Terhune, 1993 (o); Kastak & Schustermann, 1998 (▲), Southall et al., 2005 (◯).

The sensitivity curves show that harbour porpoise has the highest sensitivity between 20 and 100 kHz. In this range the sensitivity is 70 dB higher than in the band where turbine noise is expected (200 Hz). Harbour seal is most sensitive between 1 and 75 kHz. In the frequency range of turbine noise the sensitivity of harbour seal is 20 dB lower than in the highest sensitivity range. Other important criteria in the perception of sound in noisy environments are the relation/ratio between sound to be detected and the background noise level (critical ratio) and the frequency relation between the target sound and dominant frequencies in the background noise spectrum (critical bandwidth). For harbour seals these aspects were studied by Southall et al., 2000 in a low frequency range between 0.1 and 2.5 kHz and Turnbull and Terhune, 1990 between 4 and 32 kHz. Little is known on critical ratio in harbour porpoise. 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.

Since the publication of Madsen et al., 2006 the effects of high impulsive noise levels from the hammering of turbine pile foundations (“pile driving”) into the substrate have been a common issue, in particular if these exposures cause hearing injury in marine animals. Studies on the auditory effects focus on the threshold range where the hearing sensitivity is temporarily reduced (Temporarily Threshold Shift ≈TTS). However, this type of studies introduces a number of variables/factors that all play their role in the origin of TTS. These factors are the type of sound/noise to which the animal is exposed, the Sound Exposure Level (SEL), which is a composition of the Sound Pressure Level (SPL) and the duration of the exposure, the interval time between the exposures, which is the period the hearing sense requires to resettle to its original sensitivity level. 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 presence of wind. This raises the question if this type of low frequency noise/tonal can affect TTS over a longer period of time in marine mammals. Another motive to investigate long term exposures is the expected growth of offshore wind production (100 times the present offshore wind power production) and the spreading of wind farms over a wider area of the North Sea. With the review of Southall et al., 2007 toothed whales were divided in classes relative to their hearing and sonar capabilities. Secondly the application of a weighing filter (M-weighing filter) was recommended to negotiate the difference of hearing sensitivity among cetacean species. The application of this type of filter, where only the very low/high parts of the spectrum are filtered, was a common debate, in particular when the sensitivity of a HF specialist, like harbour porpoise, has to be weighed against low-frequency type of sounds such as turbine noise. In this example the weighing against the hearing curve is proposed as a more appropriate approach (Verboom et al., 2012). This weighing filter model for harbour porpoise and harbour seal is based on the hearing curves determined by Kastelein et al., 2010a and b. These two filter curves were used to estimate the effects of turbine noise rather than the less progressive method of the M-weighing model proposed by Southall et al., 2007 (Figure 11).

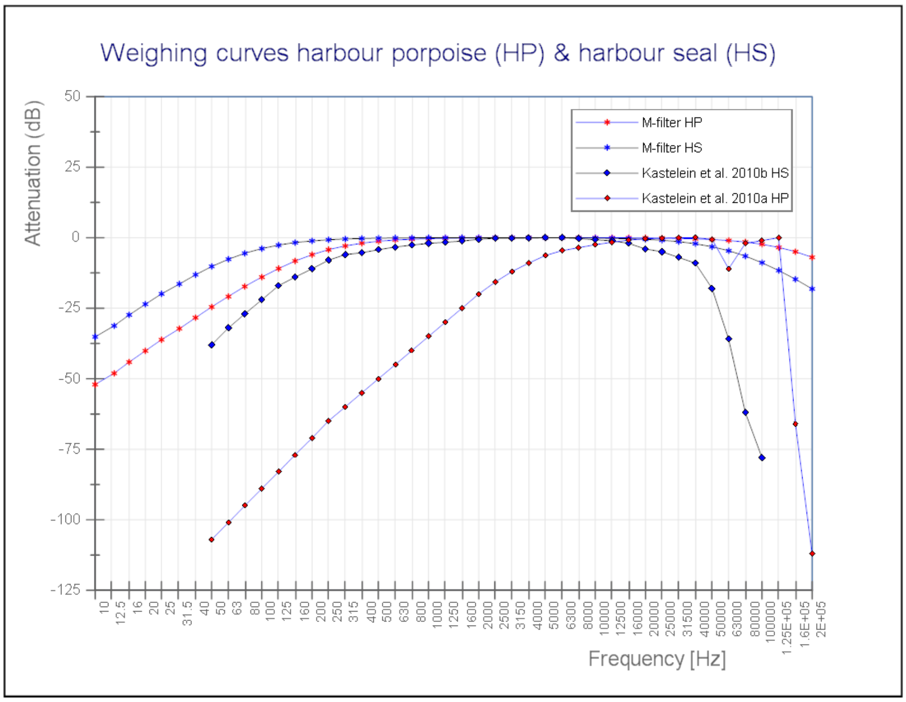

Figure 11 Weighing models for harbour porpoise and harbour seal according Southall et al., 2007 (M-filter) and Kastelein et al 2010a and b, proposed by Verboom et al. 2012.

The proposal of Verboom et al., 2012 of applying the auditory weighing technique is not internationally widespread accepted and there is a lack of knowledge on the effects in the frequencies < 4 kHz.
The TTS-study on bottlenose dolphins of Finneran et al., 2010 involved a 3 kHz fatiguing sound as lowest of a range of tested frequencies. The outcome shows that the amount of TTS reduced at 3 kHz and that the results have a relation with the hearing curve. This trend could also be valid for other toothed whales like, harbour porpoise. In 2012 Finneran and Jenkins published new weighing filter models and proposals for exposure criteria per functional hearing group of marine mammals.

1.6.2 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 mechanosensory 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 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 have the ability to enhance sound reception. 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.

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.

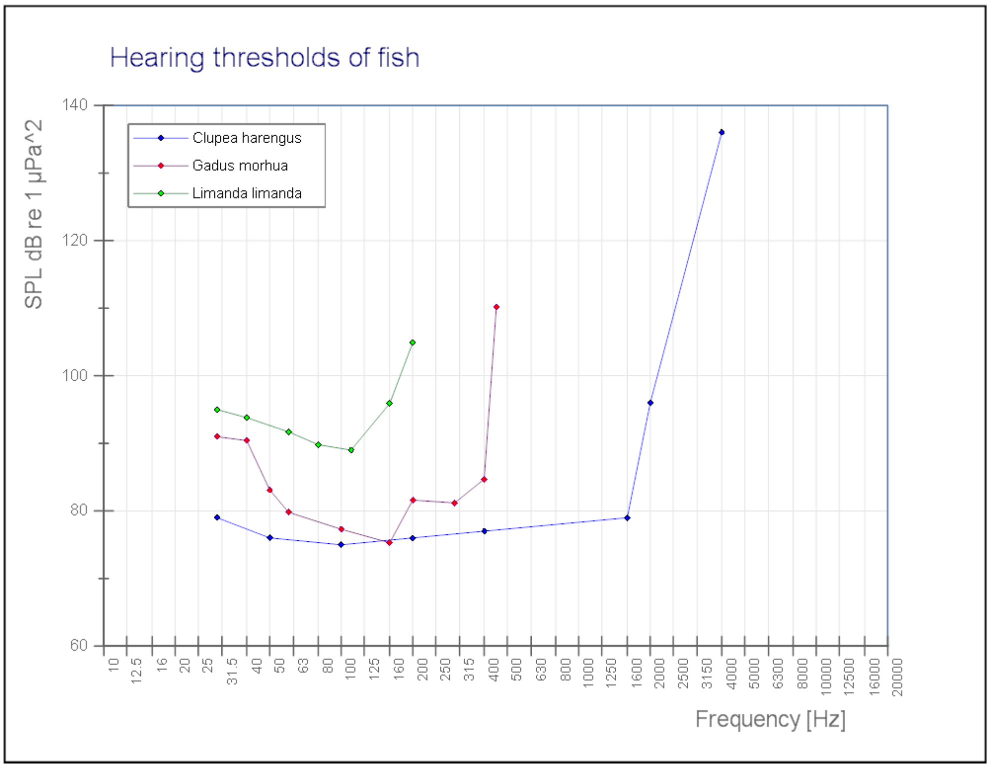

Figure 12 Auditory thresholds of three fish species, Atlantic Cod (Gadus Morhua) produced by Chapman and Hawkins, 1973, dab (Limanda limanda) produced by Sand and Enger, 1973, and Atlantic herring (Clupea harengus) published by Enger, 1967.

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 on 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 the published 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. There were three short-term sessions 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 a 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 is 541 m for 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 conditionally 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 second 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 and developed, but not available before the start of the measurements in close range of a wind turbine 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. From the VMS (Vessel Monitoring System-records of 2010 (van Hal et al., 2012) we observed that fishing vessels fished very close along the western boundary of the OWEZ wind farm. With these data 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 effort needed for this particular assessment has to be considered against the importance of this answer against the present results. An additional limitation of the data is that the outcome cannot be referred to a reference background noise level.

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 (Figure 2). The water depth in this position is 18 m. The second measured position was used as background noise reference not exposed to wind farm noise in a position 7.4 km to the north of the WTG27 location. The measurement location near WTG27 enabled the highest flexibility of manoeuvring on the deployment/recovery operations in the wind farm, the lowest risk of damage to the turbine moored power cables in this section. The WTG27 measurement location also provided shelter against fishing vessels, which appear to fish closely along the boundaries of the wind farm (VMS-records). 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. The position of the hydrophone frame 100 m east of WTG27 was 52°37.012200'N and 004°25.289700'E. The reference hydrophone system was moored to the north at a distance of 7.4 km from the WTG27 hydrophone, in position 052°41.00'N and 004°26.00'E (Figure 2).
The eastern boundary of the sub-lane towards the main shipping lane (Figure 2) lies 4.4 km west from the WTG27 hydrophone location and 7.24 km from the hydrophone deployed in a reference position (REF). The shortest distance from the WTG27 hydrophone to the main shipping lane is 15.5 km.

2.2 Description of measurement equipment and deployment

A functional diagram of the deployed recording system is given in Figure 13. It 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. 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.

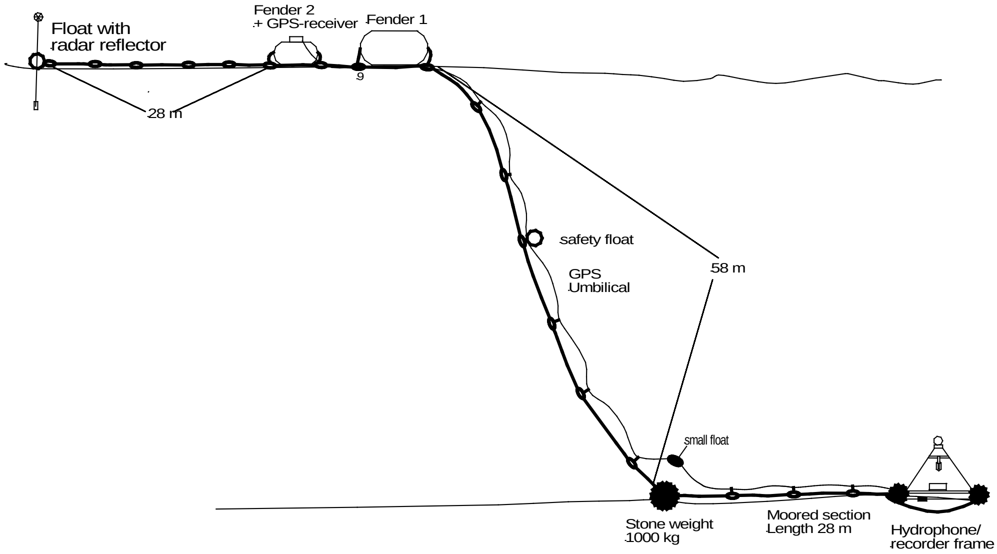

Figure 13 Overview of the rigging of the measurement system with the anchoring and floatation sections.

The equipment was deployed using MS “Terschelling”, which is equipped with a Dynamic Positioning Class 2 System, DPS-2, enabling safe operation on the heavier sea state conditions as well as the accuracy of deployment.

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 (The 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. The mini PC was powered by a 70 Ah NImH-battery, the analogue circuits were separately powered by an additional 4.5 Ah NImH-battery. The internal clock of the mini PC was synchronised to UPC by use of a GPS-receiver mounted on the surface flotation. The GPS-receiver was connected to the moored system by a RS232 serial connection as part of a 10 mm underwater cable. A brainbox US-257 USB to serial RS 232 module was used to adapt the RS232 connection to the USB-gate of the mini PC. The UPC time was synchronised on deviations > 1000 ms using TAC 32 software.

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).

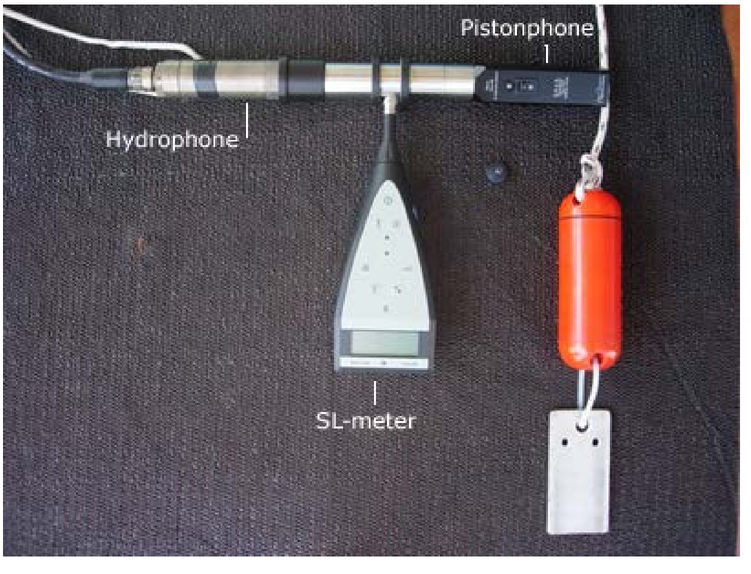

Figure 15 Hydrophone calibration set-up with a Reson hydrophone TC4032 coupled onto the G.R.A.S. 42 AC pistonphone and the sound level meter type B&K 2239 coupled onto the side gate of the coupler. On the right side a 10 kHz Ducane NetMark 1000 pinger occasionally used as reference source on acoustic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

An overview of the measured levels of reference data (including a 10 dB gain setting) per mission is listed in Table 1.

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 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.

2.3.2 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 data was taken of the sensor mounted on the meteo mast at the south side at 70 m altitude, identified as “MET01-South”, as the wind direction sensor of WTG27 was not referred to an absolute compass angle.

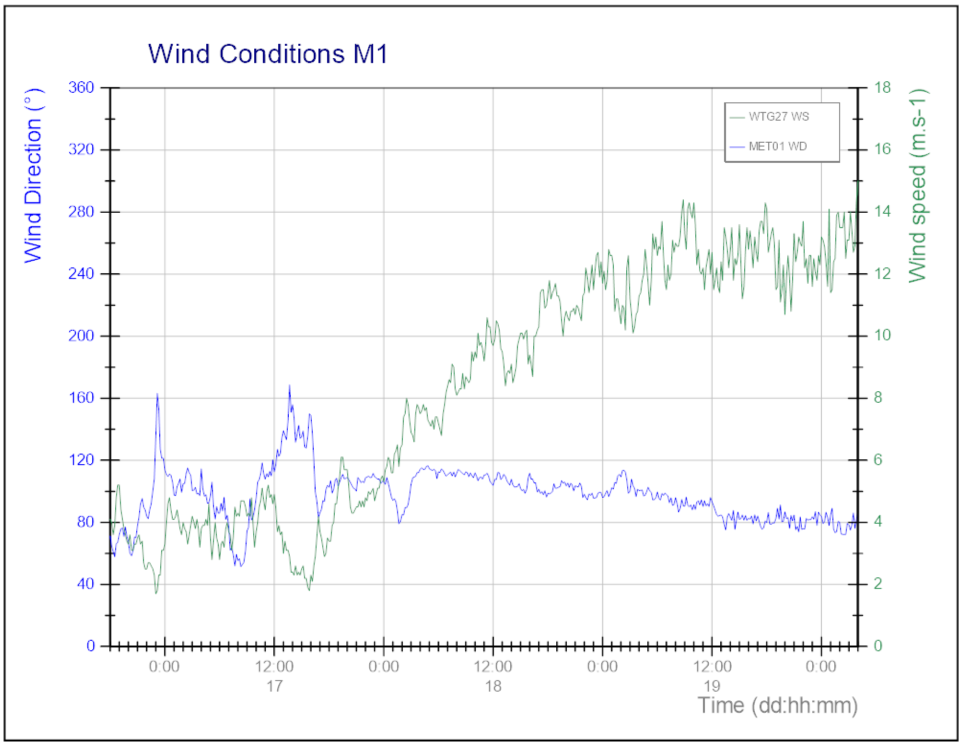

Figure 16 Wind conditions during the first measurement period (Mission 1).

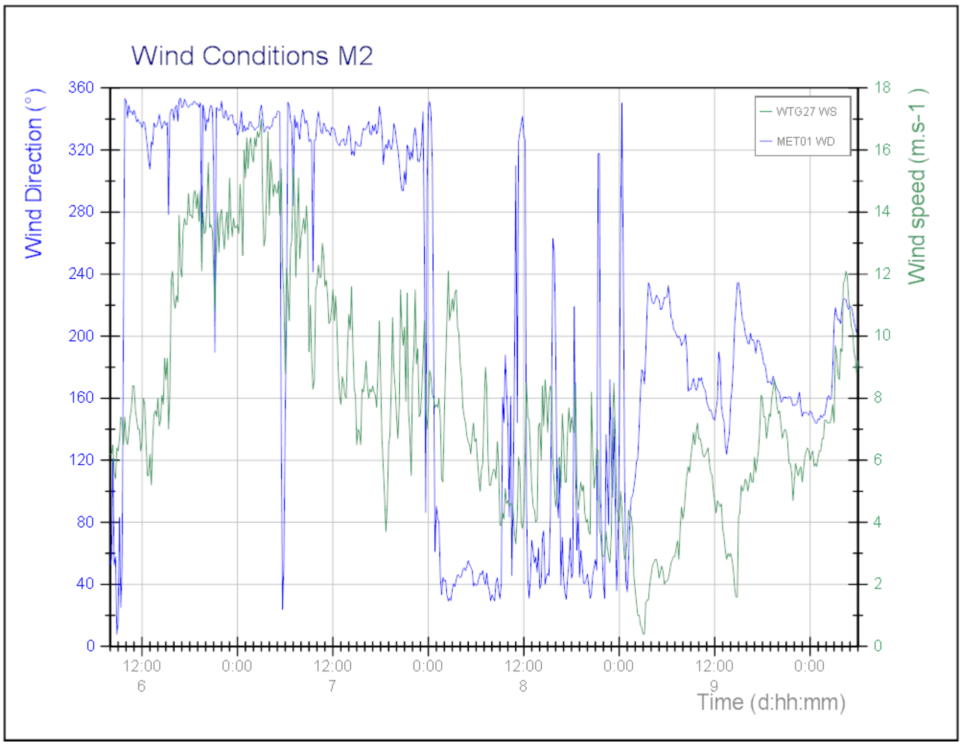

Figure 17 Wind conditions during the second measurement period (Mission 2)

2.3.3 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.

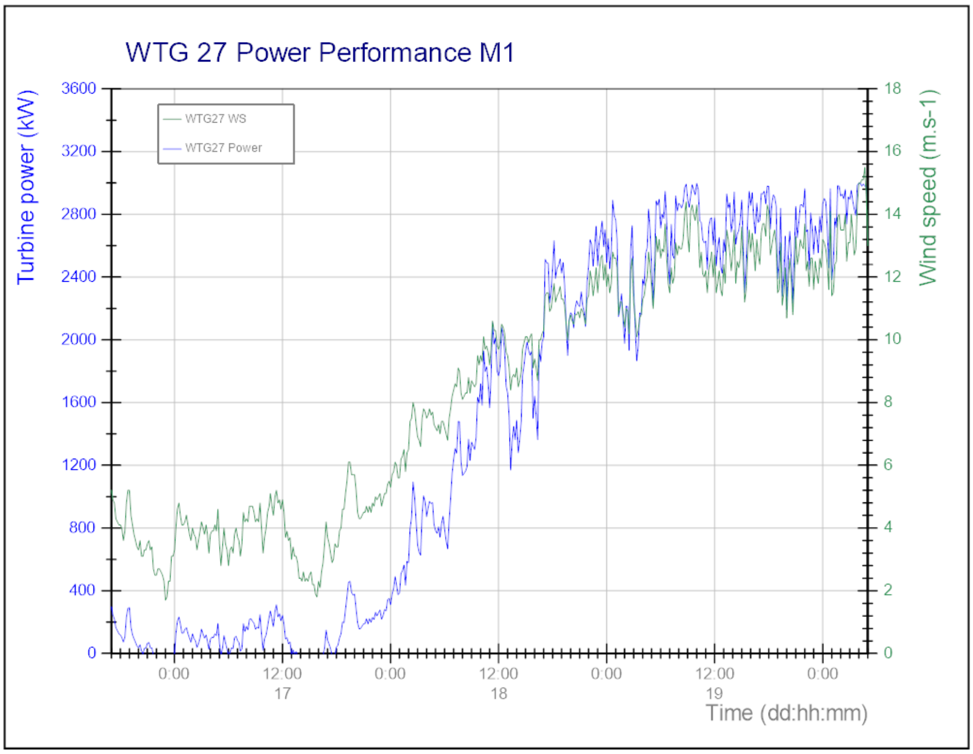

Figure 18 WTG27 turbine power and wind speed (WTG27 WS) on Mission 1.

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).

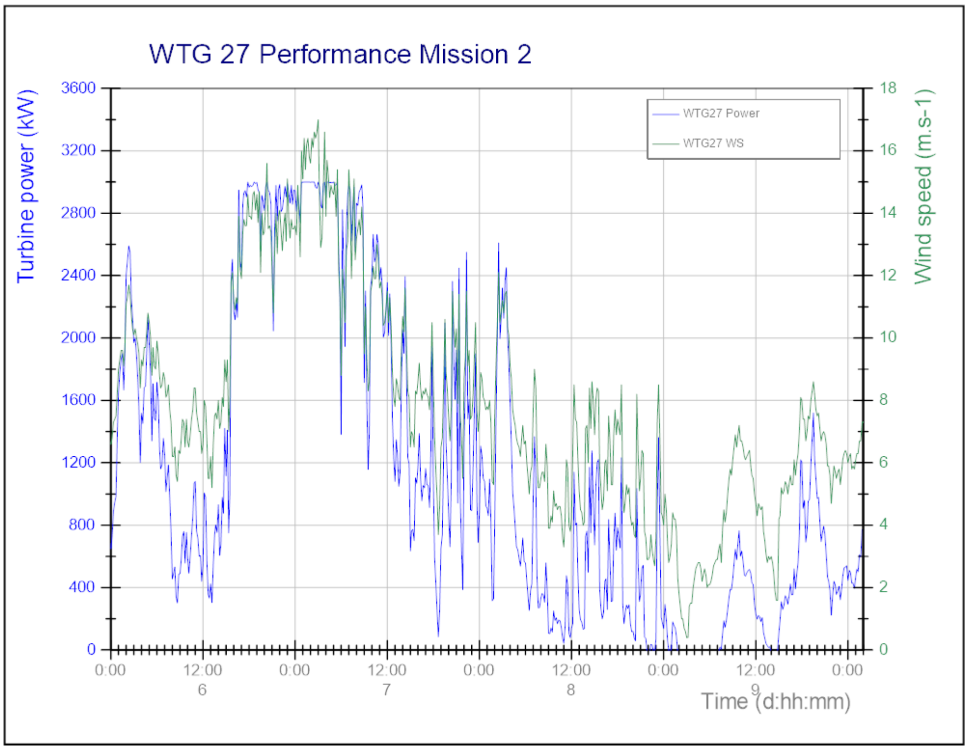

Figure 19 WTG27 turbine power and wind speed (WTG27 WS) on Mission 2.

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).

2.3.4 *Wind speed versus power production*

The data from the wind sensor mounted on the 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.

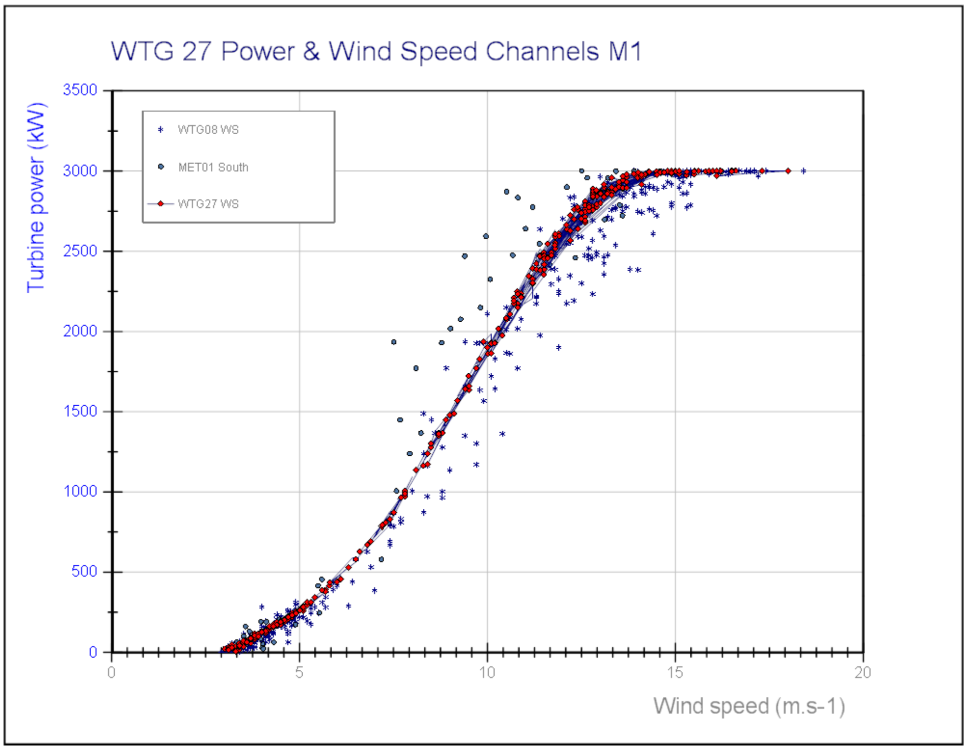

Figure 20 Turbine power as a function of wind speed channels on the first period (Mission 1).

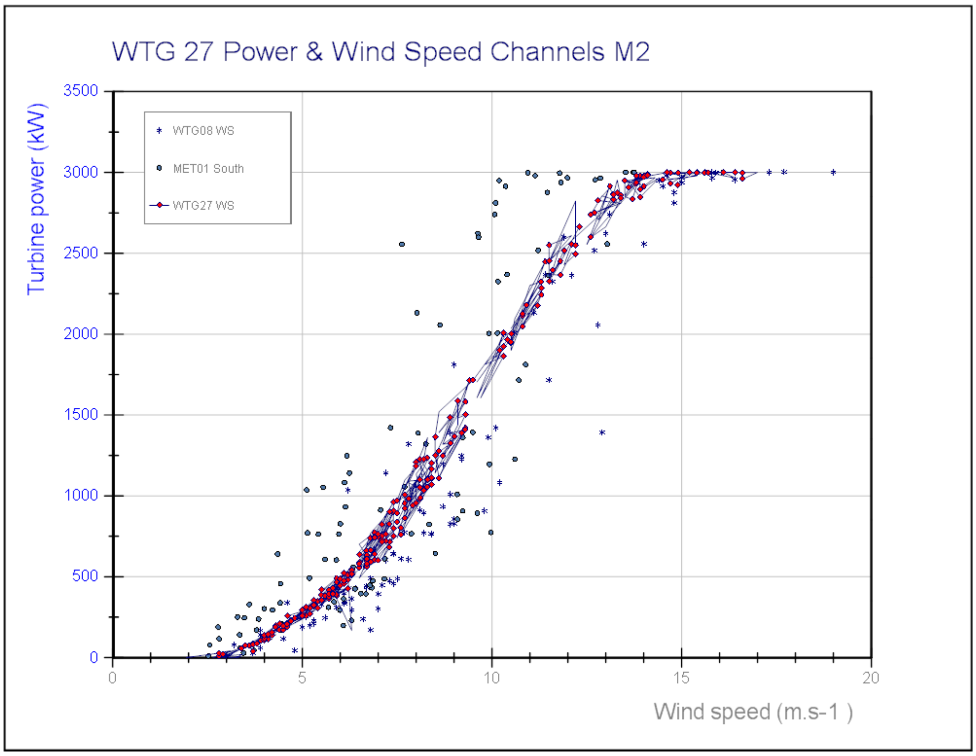

Figure 21 Turbine power as a function of wind speed channels on the first period (Mission 2).

The overview showed that the turbine wind sensor had the strongest relation with the turbine power as indicated in Figure 20 for Mission 1 and Figure 21 for Mission 2.

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.

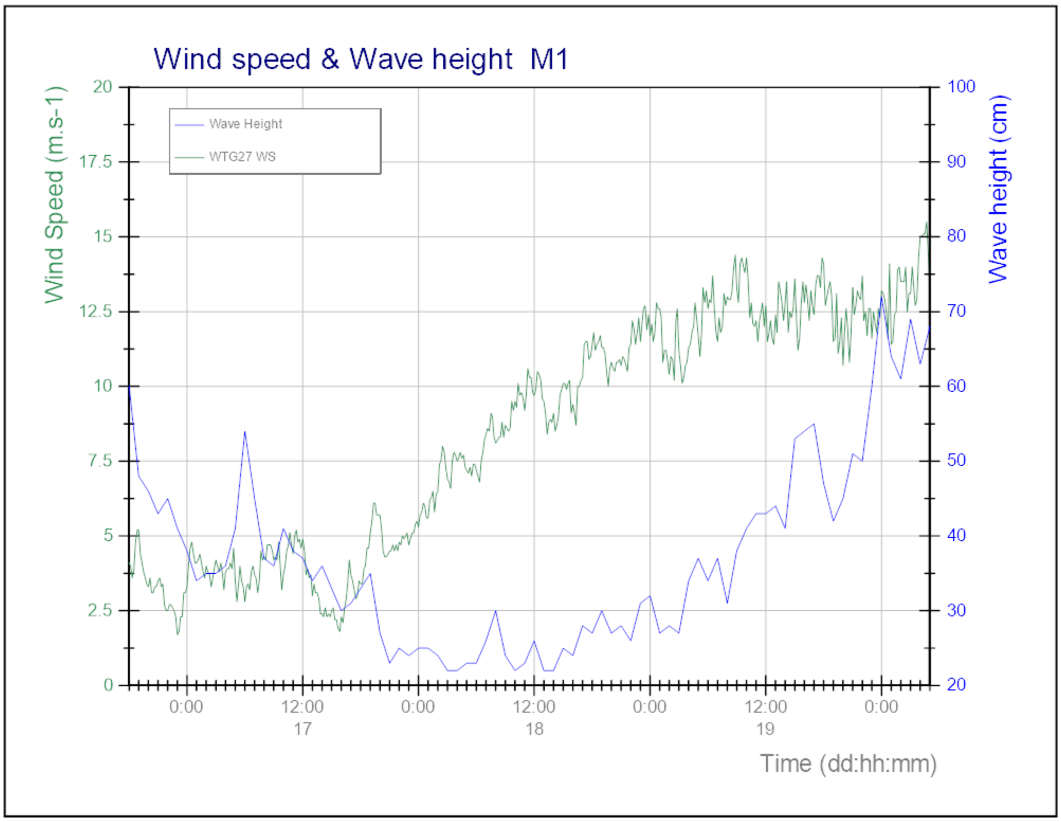

Figure 22 Wave height as a function of wind speed (RWS IJmond station) Mission 1

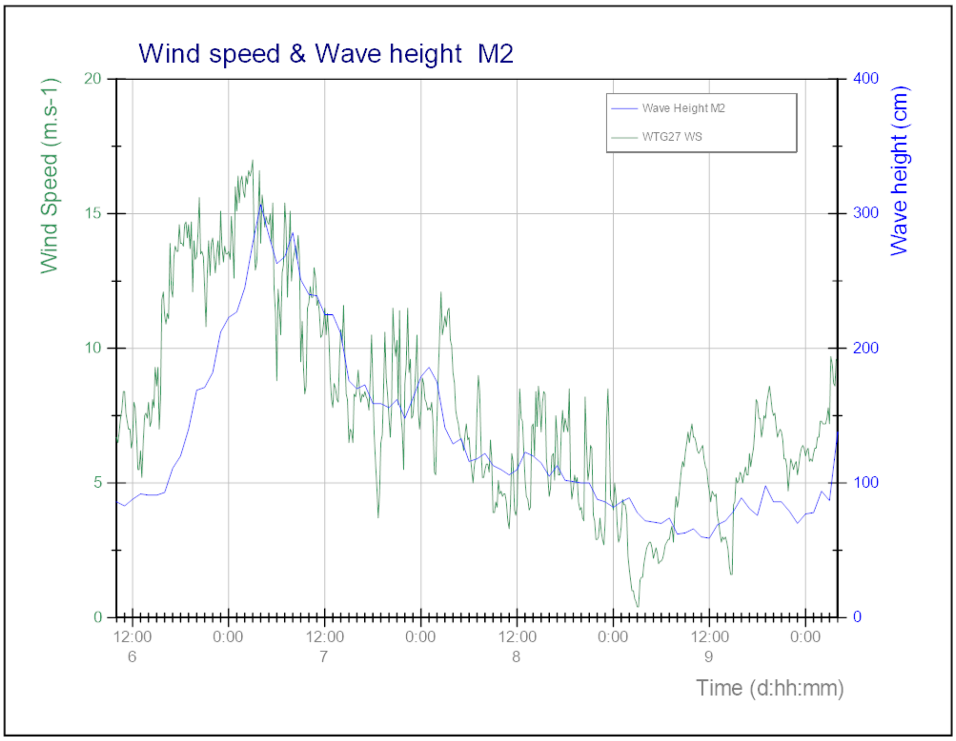

Figure 23 Wave height and tidal current (RWS IJmond station) Mission 2

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.

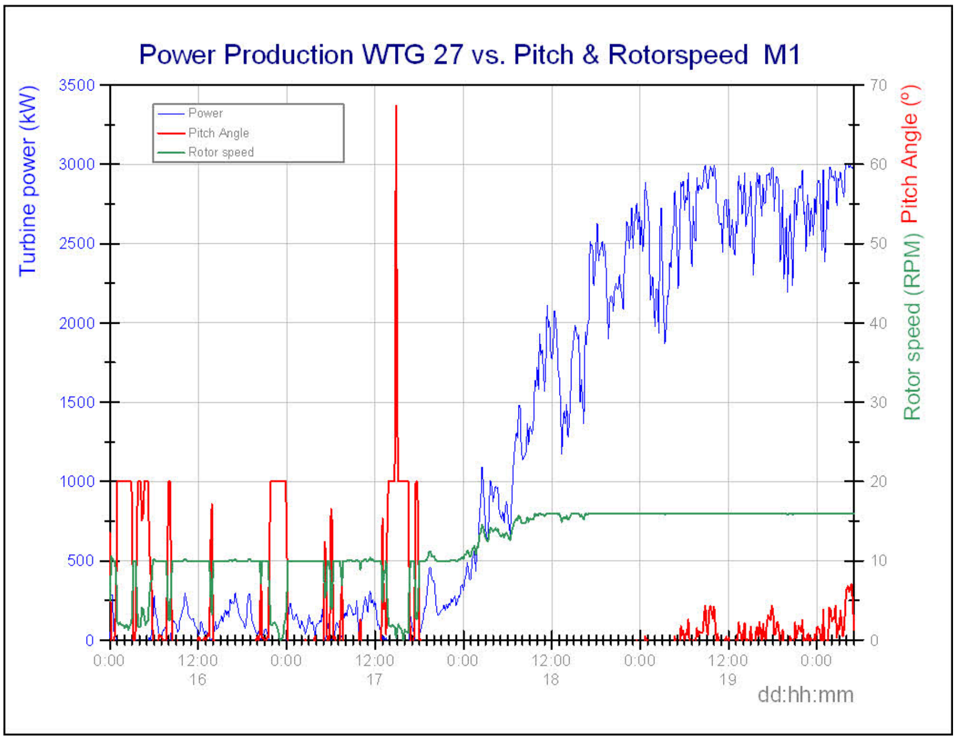

Figure 24 Rotor blade angle operations on the first period (M1)

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.

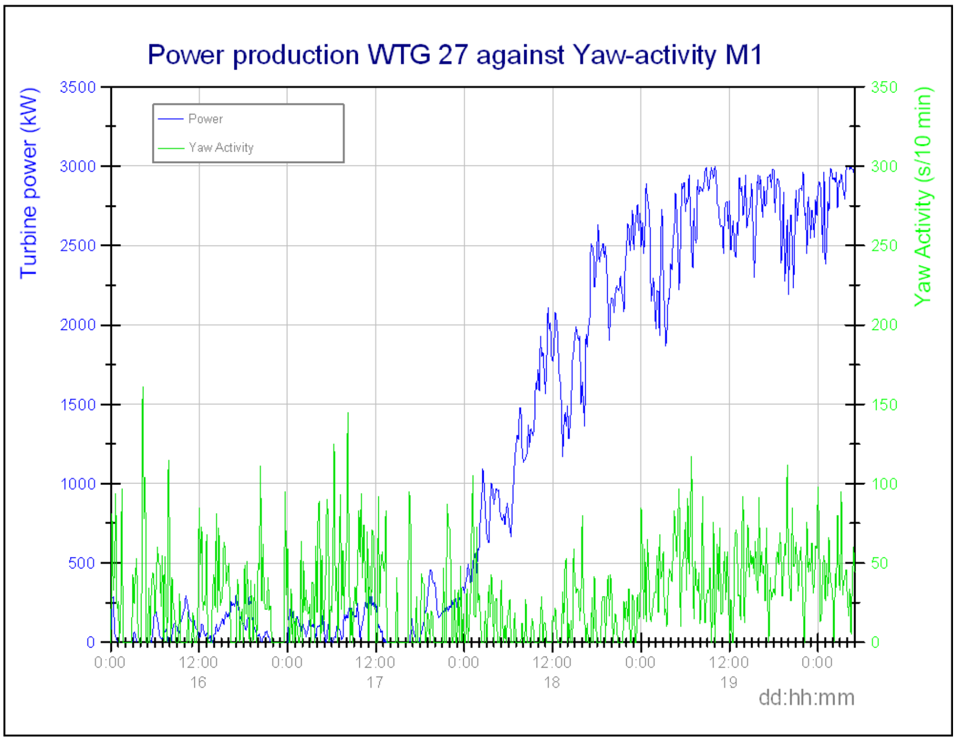

Figure 25 Yawing activity on the first period expressed in seconds per 10 minute time period.

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 propulsed 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 9 and 10). 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 9 (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 noise in terms of the level and as percentage of the total logged time (Appendix C, Table 7). On the 16^{th} of January between 07:00 and 09:00 a WindCat vessel manoeuvered around the outer northern string between WTG 30 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. On 17 January a WindCat vessel entered the OWEZ area at 08:00 and a second vessel, MS "Tender Express" entered at 07:00 and headed for WTG11. These gaps were completed from data from AIS & radar records of shipping traffic and estimated at 1 hour per day. 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 the Dutch institute Marin, Wageningen. 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:

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

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.

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.

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 9). 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

To determine the effects of the turbine noise on marine animals the Third-Octave results were filtered (weighed) according 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. 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 74 and 75). 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 11).

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 measurement periods is that the noise curves include a high number of incidental high peaks, most of them identified as ship noise. 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 was recognized in the Third-Octave bands < 315 Hz, while ship noise contribute in all Third-Octave bands. Another aid for identification was that the shipping noise peaks were sequentially received in both measurement positions and slowly increased over time. The peak of the noise occurred when the ship was at the shortest distance from the measured location. This time was used to correlate the acoustic events to the AIS-records.

3.1 Mission 1

3.1.1 Turbine Noise Broad-band levels

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 28 and 31 as well as the details of a shorter 20 hours interval in the first Mission (Figure 29). 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 level is mainly developed in the range of 500 to 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 4) illustrates that the biggest effect is found when the turbine power increased from "low" (30 kW) to 1000 kW. An increase from 1000 to 3000 kW did only add a few dB's to the total summed noise level of developed noise. 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 broad-band spectral noise levels sorted per 10 min wind speed (Figure 30) shows that turbine noise is ramping up in the wind speed range of 6 and 12 $m.s^{-1}$. This observation confirms the result of Figure 28, that turbine noise is mainly developed in the 500 to 2000 kW power range.

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 33 to 39). Low-frequency contribution in the 16 Hz Third-Octave band was only observed on the first 24 hours of the Mission 1 at a very low power production (Figure 33 and 34) the noise is already emphasized. Also the contribution of ship noise is significant in all cases with some very strong masking events. The contribution of ship noise is described in section 3.3. The turbine noise spectra taken at a range of power conditions (Figure 40 and 41) 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 4. As soon as the turbine starts to operate (power production increased from 30 to 950 kW, Table 4) the levels in the lower frequency bands < 63 Hz increase with approximately 8-12 dB (Figure 39). 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 42) showed energy peaks of contribution from the transmission link between 40 and 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 43).

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 (M1) 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 44, 45 and 46). 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 5). The incidental rattling noise contribution is marginal and caused some higher frequency components around 3 kHz (Figure 44 and 45). The noise of the auxiliary engines driving the rotor blade pitch control and “yawing” system could not be detected.

3.2 Mission 2

The broad-band noise levels measured at 100 m from WTG27 started to rise on 6 February 15:00, 7 hours after deployment (Figure 31). 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 57 and 58). 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 49 to 56). 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 overview of power ranges filtered in Third-Octave Bands (Figure 58) 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 59). 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 (M2) 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 43) 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 32) 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 6). Also in this period there were incidental noises related to propulsion noise of ships (Figure 57). The Third-Octave analysis of turbine noise at several power ranges (Figure 58) 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

An overview of the shipping activity based on AIS- and radar logs is illustrated per Mission in Figure 66a 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. On demand of the Dutch coastguard authorities the vessel id's were anonymised by Marin and detailed information of the ship's identification other than description with overall length, depth and main category of the detected vessels was taken out the data records. As not all vessels operating in the Dutch coastal zone are detectable by AIS and AIS-transponders on vessels can be switched off radar detected logs of the Dutch coastguard were provided additionally to include vessels that were not detected by AIS and to achieve a full coverage of shipping activities.

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.
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 67 and 68. On 16 January the tracks of MS "Terschelling" is shown as well as a WindCat vessel. The WindCat vessel operated on 16 January at WTG30 and 35 and left the OWEZ area around 15:00. The day after a WindCat vessel landed at WTG02 and 03, while another OWEZ related vessel (according the brief communication of that particular days must have been MS "Tender Express") was heading towards WTG11 and entered the OWEZ area around 07:00. The contribution of WindCat noise on 16 and 17 January was estimated at 1 hour per day. The track of a fishing vessel is shown at the east side of OWEZ wind farm.

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 hydrophone at 100 m from WTG27. The 25 cases of detections with known distances are listed in Appendix C, Table 9. Two examples of how the noise developed while landing the ship at the WTG terminals are shown: case 7 with the vessel at WTG21 at a distance of 1700 m (Figure 70) and at the maximum measured range, WTG02 at a distance of 3768 m distance (Figure 71). Although the turbine power production of 753 kW was below the range where the maximum noise was found (1000-3000 kW), the WindCat noise at maximum measured distance would have also masked the high turbine power conditions.

WindCat activity contributed to the measured noise is listed as broad-band spectral noise levels in Appendix C, Table 9. 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 9). 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 70 and 71. 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. 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 9 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. The Vestas report of that particular event showed that WindCat engines were switched off at 09:25. When this is a miscommunication the 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 72). This contribution was detected in other cases (while passing the hydrophone at short distance (Figure 73) 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 (10, 11 and 12) WTG positions served by the WindCat vessel were in close range of the received position and shipping noise was received continuously over longer period. The free-sailing of the 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 (Case 15). At 12:16:10.5 the highest broad-band level of the series was measured, 130.5 dB re 1 $\mu Pa^2/Hz$ (Figure 73). 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 8).
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 69). 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 47 and 48) and 16 dB above the reference noise level (Appendix C Table 10). 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 47). 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 10.

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 4 and 6) 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. In Table 9 in Appendix C the turbine production conditions on these measurements are listed. The weighed results for harbour seals showed that the filtered turbine noise and a WindCat vessel remain significant and above the background noise reference level at 7400 m from the wind farm (Figure 62 and 63). The weighed results of turbine noise and WindCat to the hearing curve of harbour porpoise (Figure 60 and 61) showed that the weighed turbine noise is at the masking level of the reference spectrum and that the turbine noise 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 64). 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 65).

4 Discussion

The analysis of contribution of shipping activities observed over the total measured period showed that in 35 % of the measured time period shipping noise dominated the noise spectrum, including the noise from WindCat vessels. This share of contribution might be higher than one would have expected, but that noise from shipping was masked already at 100 m from the turbine in 35 % of the measured time is at least just as important to conclude. Wind farm related shipping contributed over a period of 6.2 % of the total measured time (171 hours).

Wind from the east at a wind speed of 15 $m.s^{-1}$ on Mission 1 had a relatively low effect on the wave height and sea state. On this condition the spectral broad-band turbine noise level was 9 dB above the background noise level measured in the reference position 7400 m to the north of the turbine measurement location. When this condition changed and a higher sea state was developed by winds from northern direction this difference reduced to 6 dB. The statistical 95% Confidence Intervals indicated that these results are valid within 2 dB. Turbine noise peaked mainly in the 50, 100 and 200 Hz Third-Octave bands, with energy levels at maximum power condition respectively 113, 114 and 115 dB re 1 μPa^2. With respect to the low-frequency contribution mainly in the 50, 100 and 200 Hz bands, the turbine noise will level the background noise at about 500 m. This estimate is supported by two references, a transmission loss model of Thieme (2002), published in Thomsen et al., 2006, predicting 4.5 dB at double distance as intermediate between spherical (20 log r) and cylindrical spreading (10 log r) and 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 10 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.

This estimate is also confirmed by the outcome of the first measurements of 2007 (Appendix F First measurements). 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 indications confirm the present estimate the masking threshold of 500 m.

Turbine noise filtered in Third-Octave bands (Figure 33-39 and 48-55) show that the contribution of energy in the lower bands (≤ 20 Hz) only occurred on the Mission 1 on the first 24 hours. Two explanations can be found for this observation, either on the low power condition frequencies developed in the transmission link are developed due to that particular torque/revolution condition, but then it cannot become clear why this condition did not occur on the second Mission. On 16 and 17 January the highest tide condition occurred the detections in the 16 Hz-band are most likely attributed to a lower frequency cut-off. Although the low-frequencies ≤ 16 Hz are not propagated, they are likely to contribute to the particle motion spectrum in the water column and the top layer of the sediment. This part of the results shows that the present results are strongly connected to the measurement location and that lower frequency contributions (≤20 Hz) are likely to be developed on wind farms constructed more off-shore as shown in the publication of European Wind Energy Association (EWEA) of January 2013 (Arapogianni et al., 2013).
When filtering of the noise by the audiogram is a valid approach, the audibility of turbine noise to harbour porpoise is that the perception of turbine noise is limited in range to harbour porpoise (Lucke et

al., 2007). 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 $\mu Pa^2 s$. 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 reports of harbour porpoise activity, based on the records of echo-location sonar detections inside the OWEZ wind farm showed the presence had a seasonal relation with a high activity in the winter months and low in the summer. The present results show that the positions of both detector instruments were within the unmasked zone (< 500 m). The longest echolocation duration was 5.5 hours (Scheidat et al, 2012). When the maximum noise level is taken as example the unweighed Third-Octave summed noise is 122 dB re 1 μPa^2. The unweighed TTS threshold for harbour porpoise SEL of 150 dB re 1 $\mu Pa^2 s$ defined by the study of Kastelein et al., 2012a on the exposure of 4 kHz 1-octave band noise, would be reached after 10 minutes in the received position of the noise, 100 m from a turbine. When the noise spectrum is filtered according the hearing threshold defined by Kastelein et al., 2010a the filtered broad-band summed noise would be 94 dB. The weighed SEL threshold reference of 140 dB re 1 $\mu Pa^2 s$ (Kastelein et al., 2012a) would be reached after 9 hours and 20 minutes. The application of this relatively high frequency reference (4 kHz 1-octave pink noise) for low frequency turbine noise might not be valid and the actual period after which TTS will occur might be much longer. Nevertheless, the planned increase of 50 times the present installed offshore wind power in European water requires a careful consideration. 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). Also Kastelein et al, 2012 made a similar conclusion for the TTS-experiments on harbour porpoise. This all means that the duration of the exposure has a more important role in reaching TTS onset.

Negotiating all TTS related factors in marine mammals is a complex matter and with the lack of knowledge on the effects of different sound types extrapolation of results of other species and other type of fatiguing signals is a delicate matter. Not in the last place the approach of weighing according the species audiogram is not widely supported, however, the TTS-studies on bottlenose dolphins of Finneran et al., 2010 underline that the amount of TTS reduces with frequency and that the results have a relation with the hearing curve (Figure 27). The outcome of this study shows a decreasing trend for TTS as a function of frequency up to 3 kHz. Auditory weighting functions derived from the dolphin equal loudness contours (red lines) fit the TTS onset data (red marked symbols). They also follow the trend of the auditory sensitivity curves, and confirm the weighing function according the auditory threshold rather than the M-weighing function (Southall et al. (2007). A decreasing trend found in a mid-frequency categorised toothed whale could also be valid for other species with similar auditory threshold trend, like harbour porpoise. When this is a valid assumption it is unlikely that TTS in harbour porpoise exposed to turbine noise is reached over longer periods (≥ 24 hours). It is unlikely that harbour porpoise will be exposed in this short distance range for long periods. 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 this type of noise on harbour porpoise and harbour seal. New research on TTS in bottlenose dolphin (Finneran et al., 2010) showed that the TTS-results declined at the lower end of tested frequencies, at 3 kHz (Figure 27). This effect could also be valid for other toothed whales like harbour porpoise, which is also not a low frequency hearing specialist.

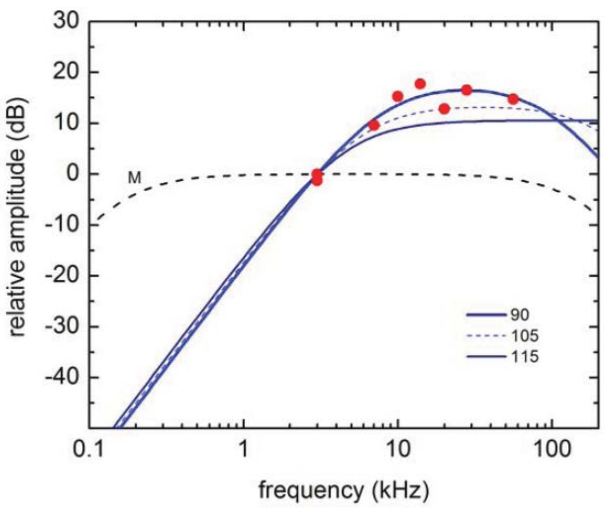

Figure 27 TTS-findings in bottlenose dolphin (Tursiops truncatus) according the study of Finneran et al., 2010, showing the decreasing trend of TTS (red marked symbols) with the highest threshold at a 3 kHz. The trend also seemed to follow the auditory threshold curve.

In that case turbine noise could have a lower effect than the reference used from Kastelein et al., 2012.
At present the development of models for filtering auditory thresholds of cetaceans (Finneran and Jenkins, 2012) is continuing and will evaluate to a more comprehensive reference, hopefully also tested in the lower frequency range (< 3 kHz).

The daily presence of WindCat type of vessels and the noise developed when landing at the WTG terminals masked the turbine noise completely and adds higher frequency components much more audible to marine mammals. The weighed noise levels of these vessels are well above the background noise and could cause avoidance responses in particular from harbour porpoise.
When the stabilizing of a WindCat vessel at WTG-terminals can be carried out without the need of propulsion power, wind farm related noise will be masked beyond 500 m from a turbine position.

The hydraulic engine noise contribution related to the yawing of WTG27 could not be detected in the present results at a distance of 100 m, although the OWEZ records show that multiple events did occur. 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. A possible cause could be that propagation of the noise through the structure-borne path is damped by the concrete fixation of all 36 transient pieces in 2010.

4.1.1 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 is 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 Present results in relation 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 results of harbour porpoise echolocation detections showed that an echolocation activity with intervals < 10 minutes was received over a total period of 5.5 hours of harbour porpoise echolocation signals. These results were obtained using T-pod instruments, which is an autonomous recorder only sensitive in the harbour porpoise frequency range (130 to 150 kHz) provided with electronic filtering techniques to filter out echolocation signals from other noise. These records don't provide information on individuals but show the activity of received harbour porpoise echolocation signals (click trains) as a function of time. 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 system (AT_4) was deployed at 446 m from WTG9 and 257 m from WTG10, while the second system (AT_5) was positioned 297 m from WTG33 and 547 m from WTG34. This means that both detecting instruments were poisoned in the unmasked zone (<500 m) of at least one wind turbine structure. Based on the logged sonar activity this study indicated that harbour porpoise had a mild preference for the impact zone.
The report did not show the recording date of the highest echolocation activity. With this information the detections can be linked to a wind speed condition and so to a turbine noise level. The instrument of the detections does not support a distance range related to the received signals. When the detection range of the instrument is taken into account (≤ 200 m) the received positions of echo-locating harbour porpoises could have been inside the unmasked zone (≤ 500 m).
The report of this study match the conclusion of the present research based on the auditory weighing technique that harbour porpoise can hardly detect the low frequency turbine noise.

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 takes 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 the 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

- The results indicate that turbine noise becomes masked by background noise beyond a distance of 500 m;
- Low-frequency turbine noise < 315 Hz is developed as soon as the turbine starts to produce power ≤ 100 kW. The noise energy becomes substantial in the range of 500 to 2000 kW;
- Turbine noise is a low-frequency type of noise, with sharp energy peaks around 100 and 200 Hz. At frequencies ≥ 400 Hz the turbine noise equalled the background noise level measured in the reference position;
- The contribution of turbine noise in the low frequency range (≤ 20 Hz) was ignorable and is strongly related to the water depth (18 m) at the location. At deeper waters this component will raise to at least the levels measured in the 50 Hz-, 100 Hz- and 200 Hz-bands;
- Wind farm related shipping, contributed with an exposure of 6.1 % of the total measured time (171 hours) by the daily transfer of personnel to WTG's. 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;
- 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). A cargo ship passing along the west side of OWEZ masked the turbine noise for 40 minutes, starting at a distance of 10 km from the received position;
- When turbine noise is weighed against the auditory thresholds of harbour porpoise, harbour seal cod and herring it showed that harbour seal and both fish species will most likely be able to detect the noise. Harbour porpoise can hardly detect turbine noise;
- These results are based on measurements to a frequency range of 20 kHz. Conclusions outside this range are not valid;
- Turbine related noise produced by the auxiliary engines, clearly detected in the pilot of 2007 at a distance of 450 m from WTG11, was not present in this result. 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 observation indicate that such a measure could damp the propagation of structure-borne sound;
- The outcome of the present result confirm the conclusions of other OWEZ related IMARES report, in particular the report of harbour porpoise activity in and outside the wind farm;
- The result underline that the projection strategy of positioning wind farms in close range of heavy ship traffic is the best solution to minimise the sound-induced effects on marine mammals and fish.

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 27 March 2013 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

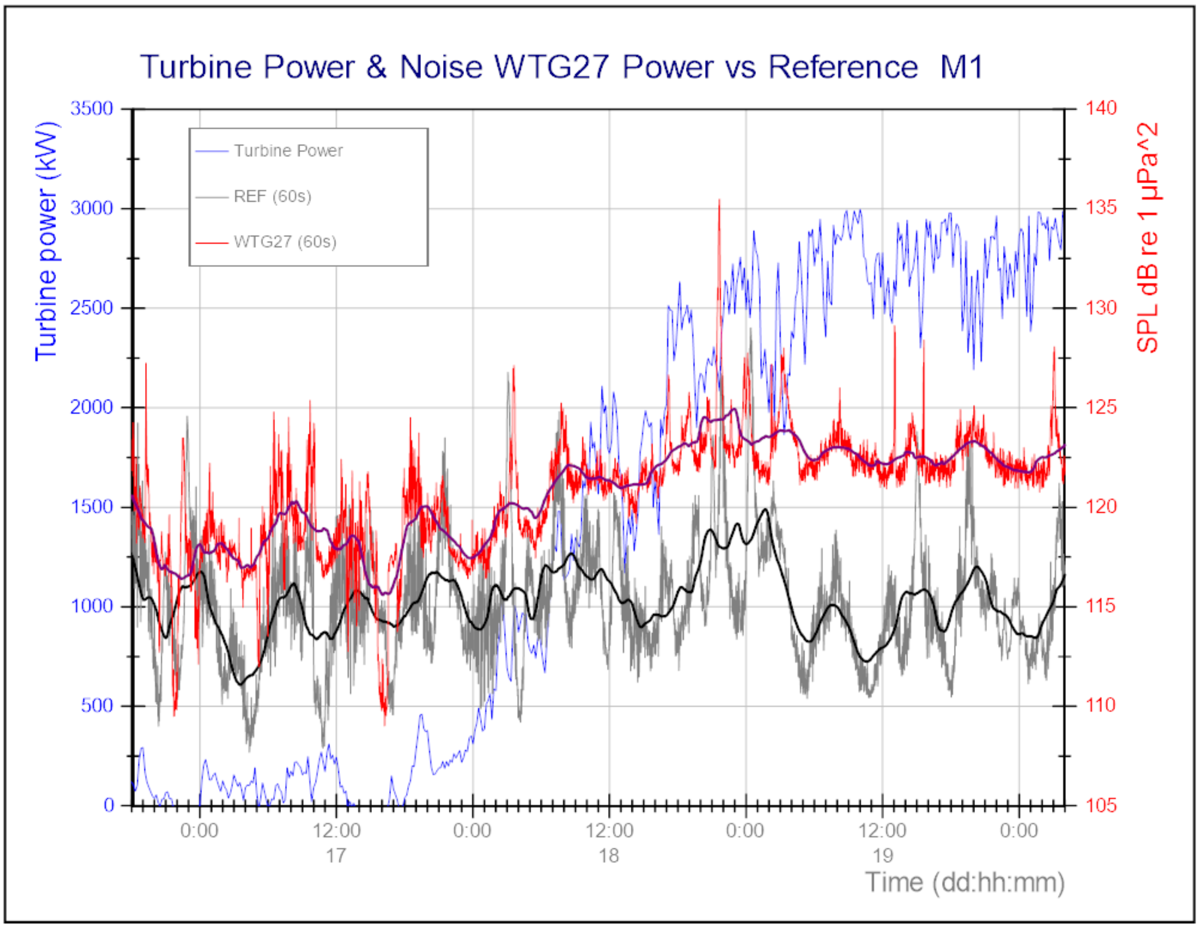


Figure 28 Broad-band Noise levels (averaged over 60 s) measured at 100 m from WTG27 and in a reference position 7.4 km to the north (REF). The main observation of smoothed results is that the turbine noise level is mainly determined in the power range of 500 to 2000 kW. Above this range the noise hardly increased. High incidental peaks were recorded on both positions indicating contribution of ship noise.

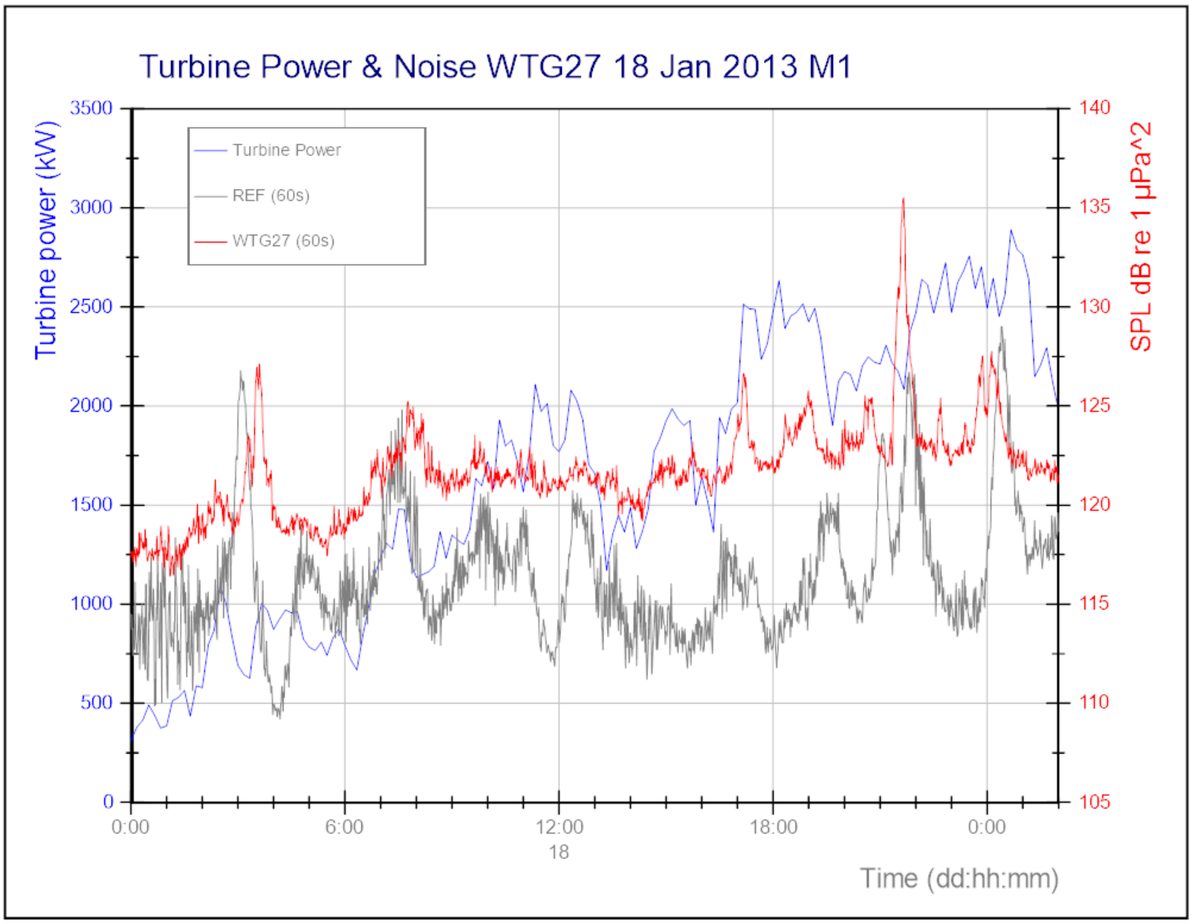


Figure 29 Overview of noise levels of 18 January 2013 (zoom-in of Figure 28) showing two incidental peaks of ship noise not related to wind farm energy production. The first case the ship sailed south with an elapsed time of 32 minutes over 7.4 km. The second case shows more detections expressing multiple ships and/or courses. The detection represented a vessel sailing at the east side in northern direction and passed the WTG27 hydrophone at a distance of 4370 m.

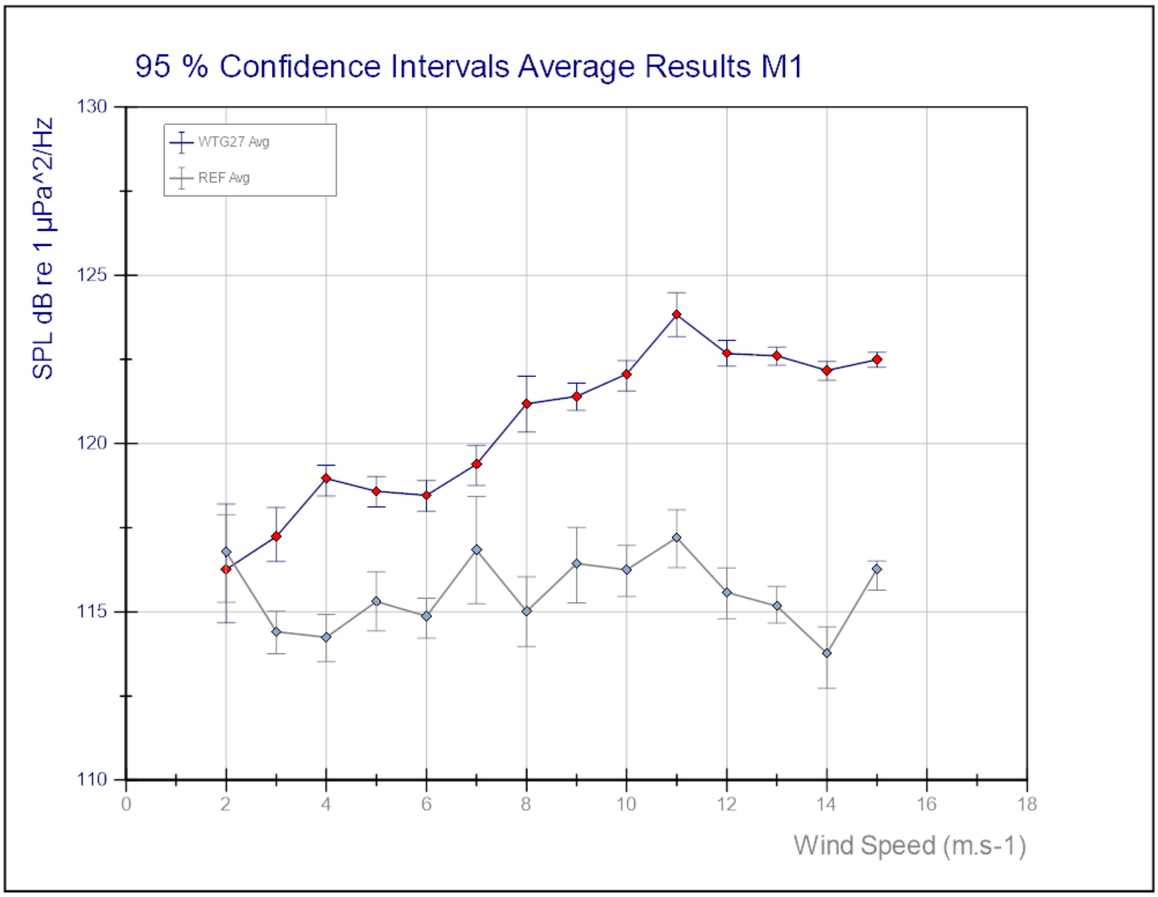


Figure 30 Broad-band turbine spectral noise levels at 100 m from WTG27 and in the reference position sorted as a function of wind speed for the first period (Mission 1). For each result the uncertainty is estimated based on a 95 % Confidence Intervals (CI) statistical test.

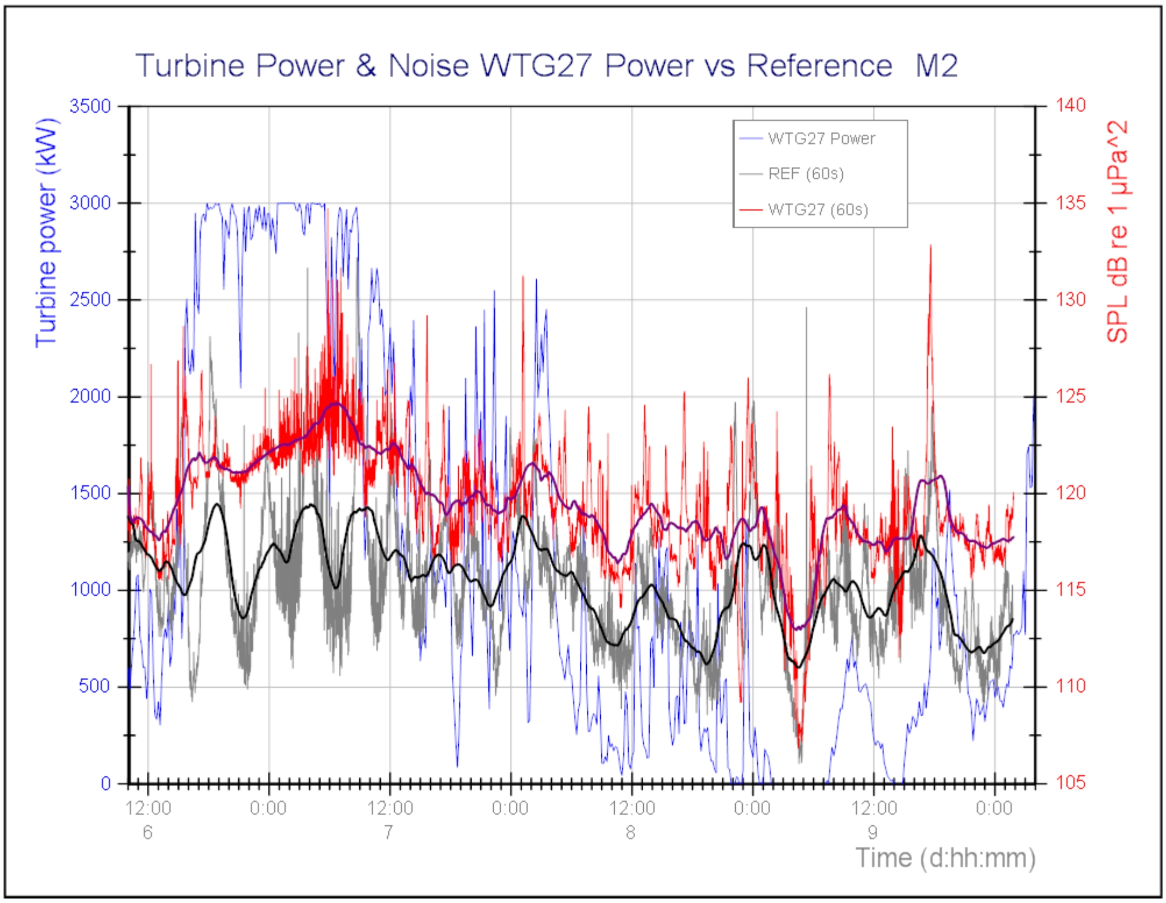


Figure 31 Broad-band noise levels (averaged over 60 s) of Mission 2 measured at 100 m from WTG27 and in a reference position 7.4 km to the north of the OWEZ wind farm (REF). In this period the wind condition increased in a shorter period, but also in this result the ramping up of the turbine noise level 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.

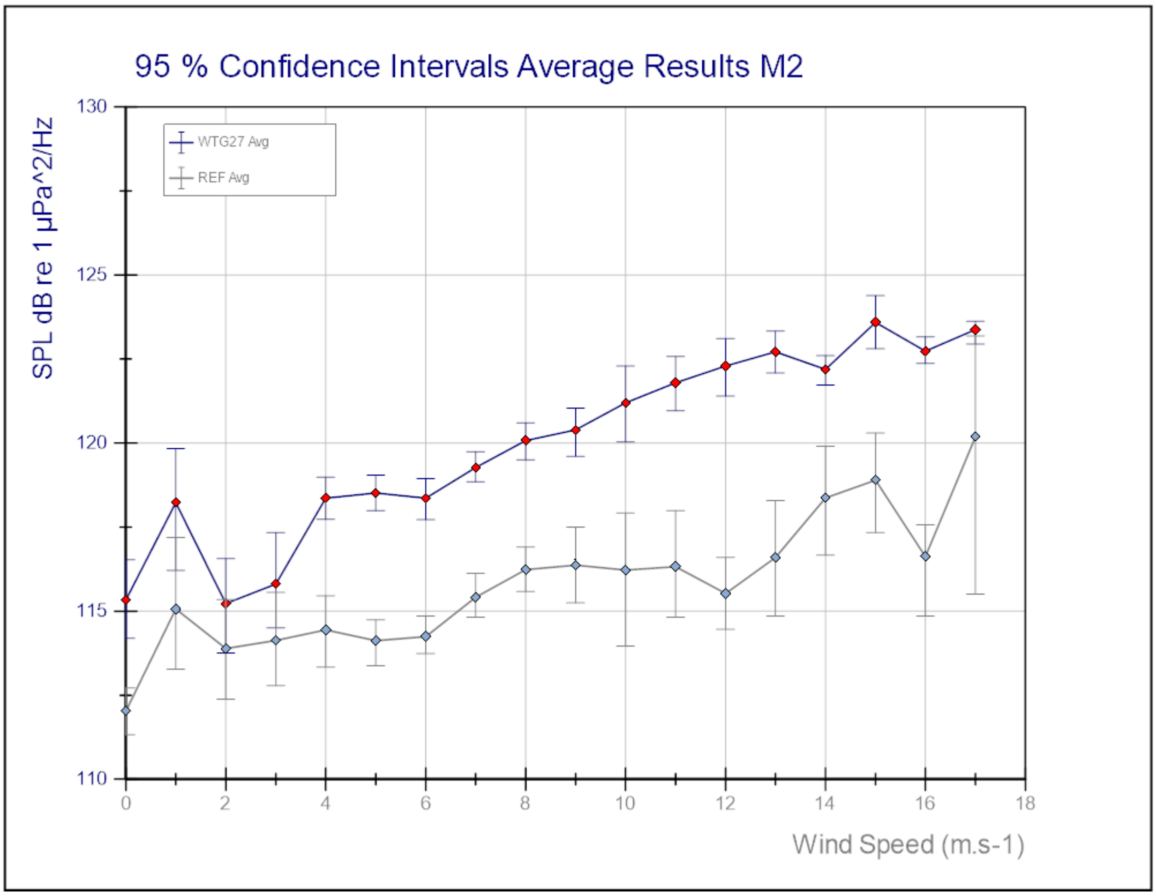


Figure 32 Broad-band turbine spectral noise levels sorted as a function of wind speed for the second period (Mission 2). For each result the uncertainty is estimated based on a 95 % Confidence Intervals (CI) statistical test. The results show that the sea state condition had a bigger effect on the levels, 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.

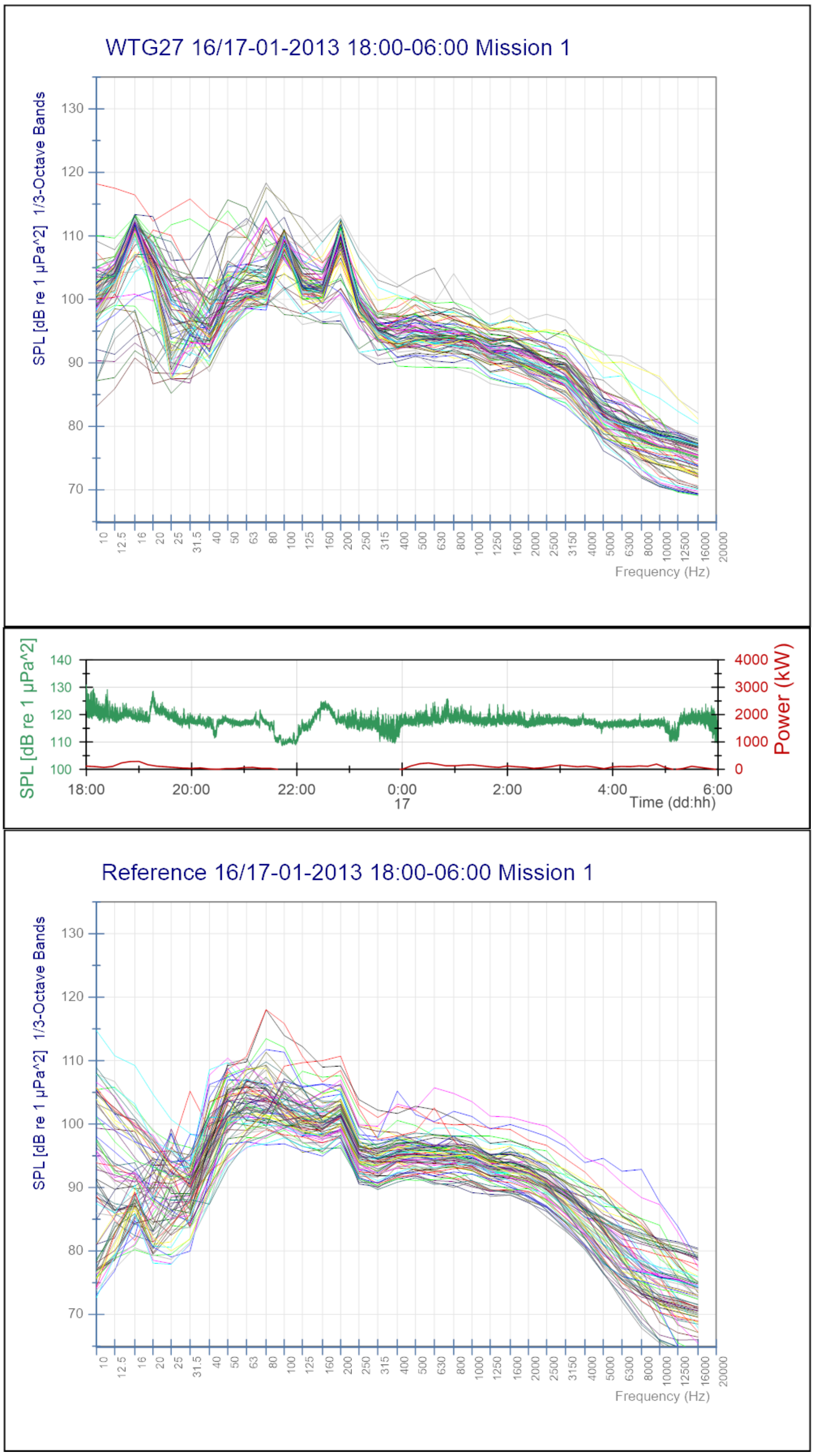


Figure 33 Third-Octave spectra of turbine noise sampled per 10 minutes over a night-time period of 12 hours. Each 10-minute sample is the linear average of a 1 s sample over 10 s. The power production in the sampled period was marginal (< 200 kW), but the turbine noise contours are well expressed in the 16 Hz-, 100 Hz- and 200 Hz-bands.

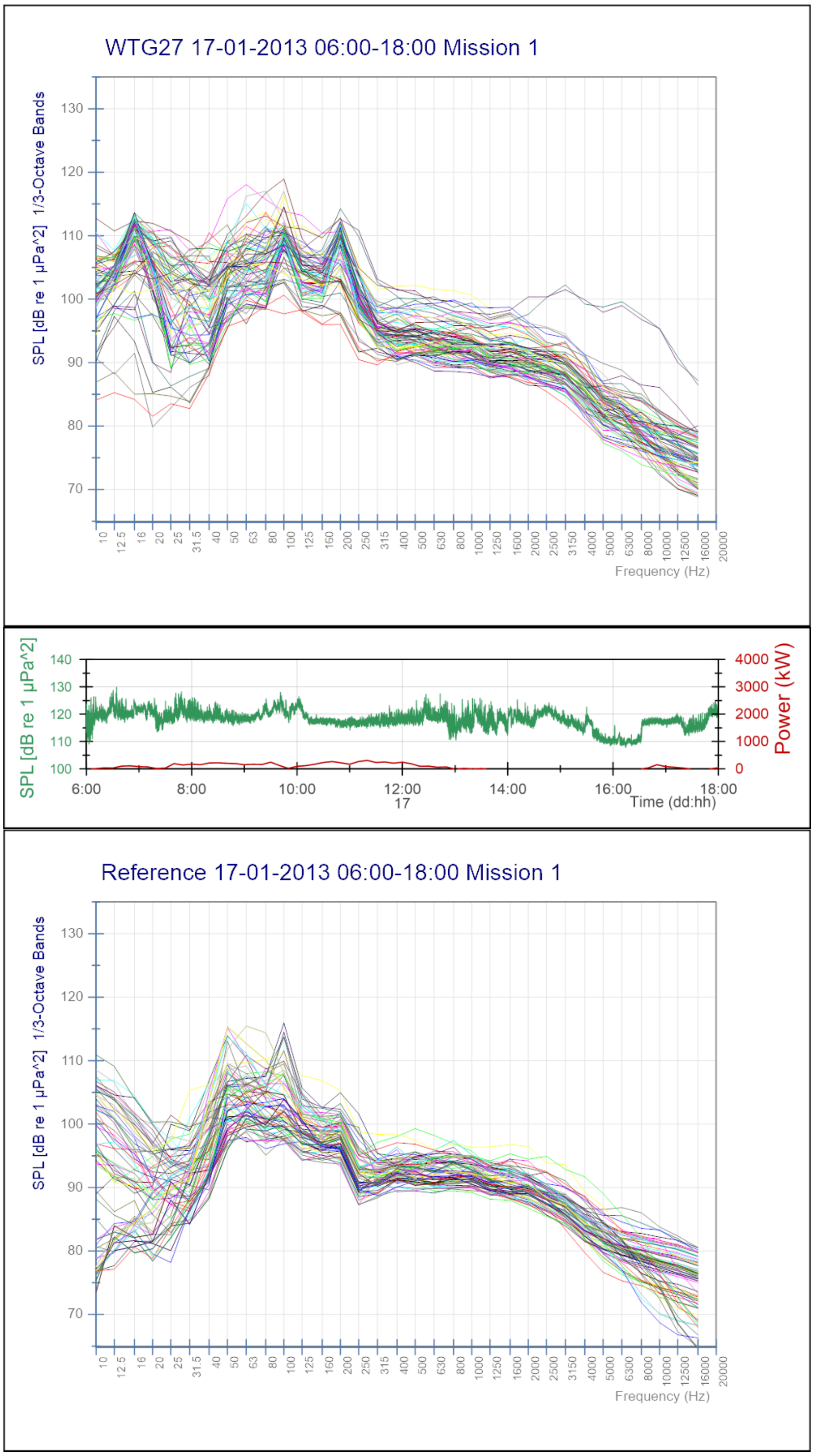


Figure 34 Third-Octave spectra of turbine noise sampled per 10 minutes over a day-time period of 12 hours. Each 10-minute sample is the linear average of a 1 s sample over 10 s. The power production in the sampled period was still marginal (< 200 kW), but the turbine noise contours are well expressed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

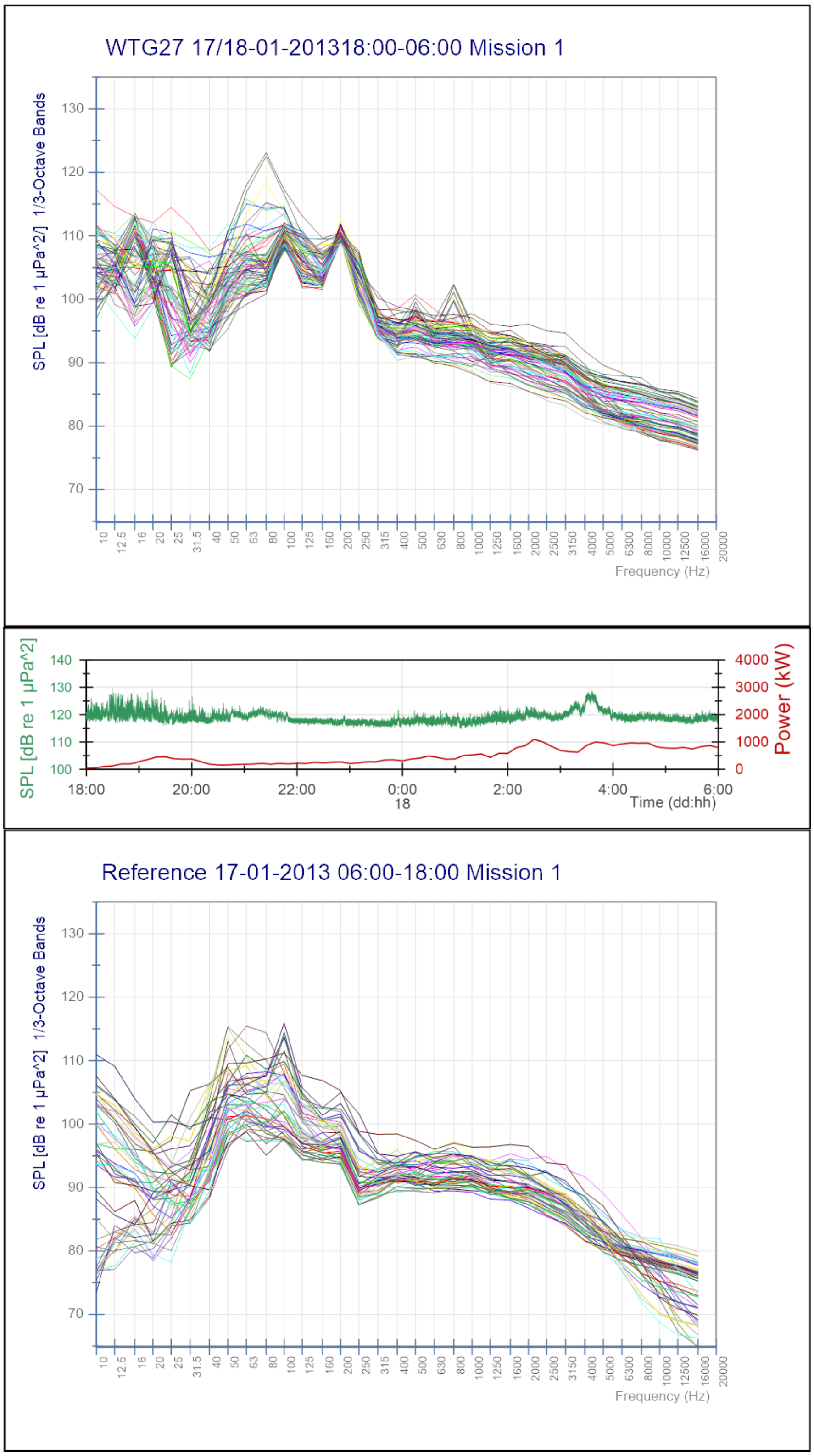


Figure 35 Third-Octave spectra of turbine noise sampled per 10 minutes over a night-time period of 12 hours. Each 10-minute sample is the linear average of a 1 s sample over 10 s. The power production in the sampled period increased to 1000 kW, but the turbine noise contours mainly expressed in the 100 Hz-band. The contribution in the 16 Hz-band disappeared.

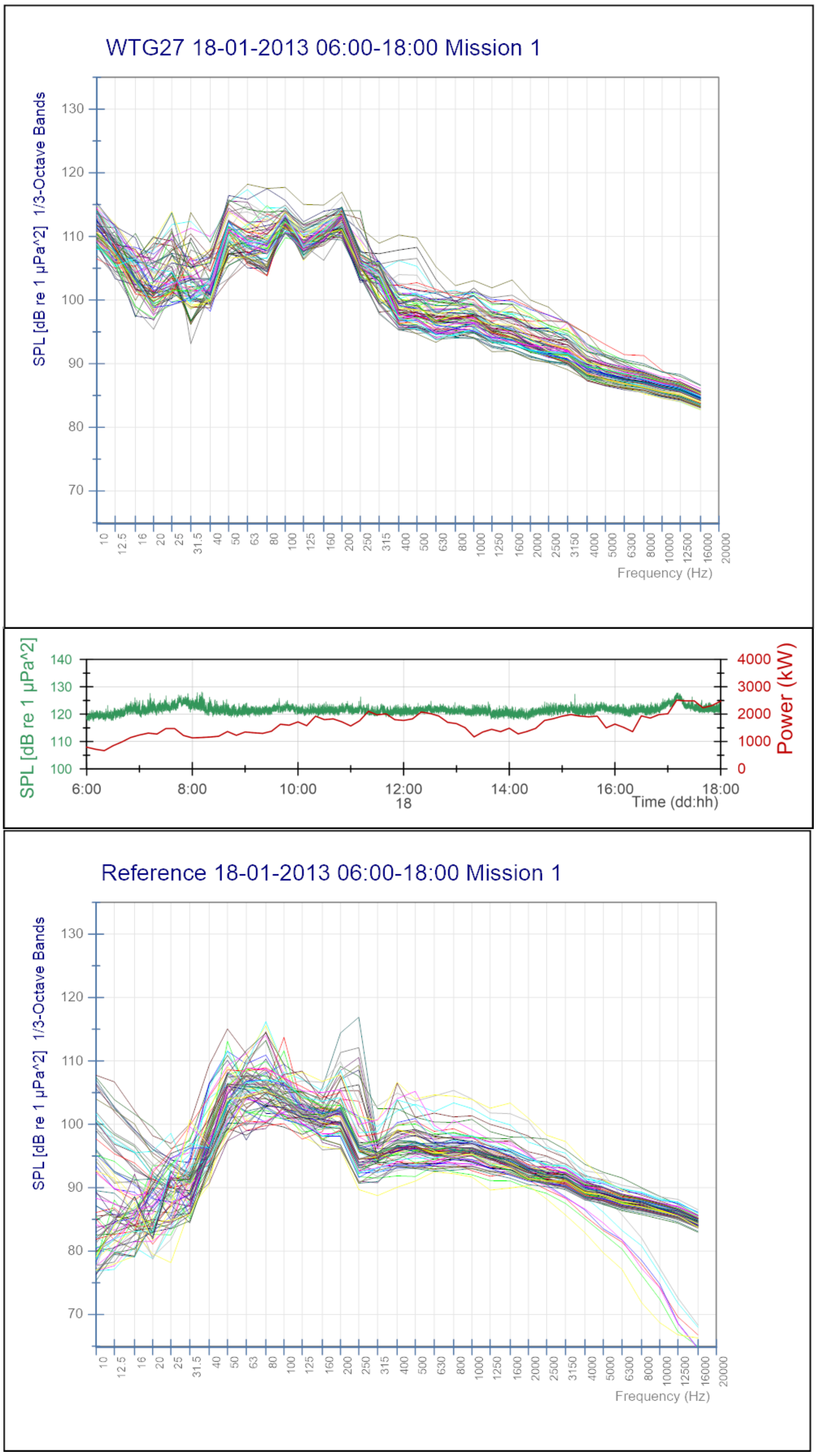


Figure 36 Third-Octave spectra of turbine noise sampled per 10 minutes over a day-time period of 12 hours. Each 10-minute sample is the linear average of a 1 s sample over 10 s. The power production in the sampled period increased from 1000 to 2000 kW, but the energy of turbine noise in the 16 Hz-band reduced. Ship noise is expressed in the reference graph.

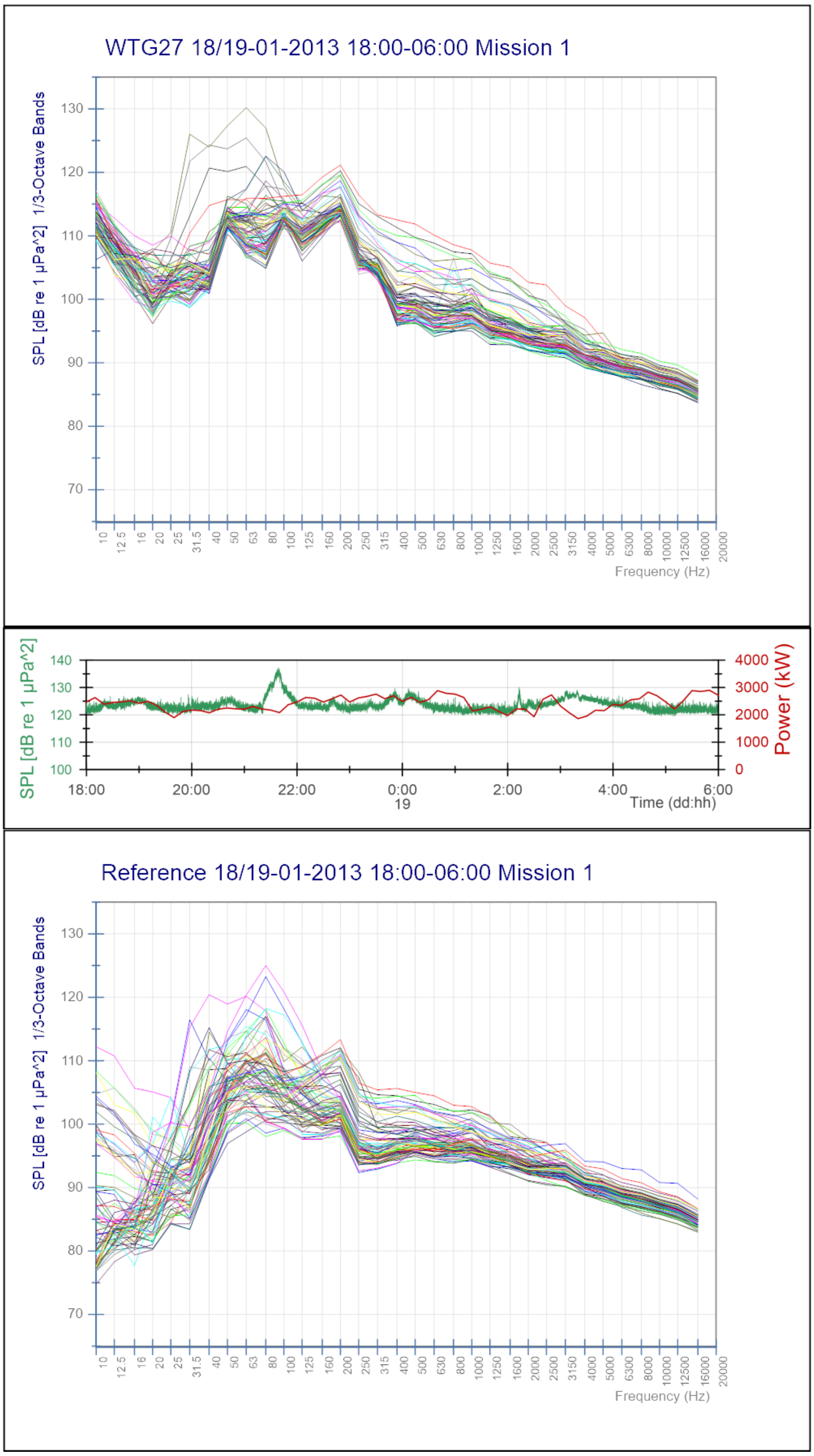


Figure 37 Third-Octave spectra of turbine noise sampled per 10 minutes over a night-time period of 12 hours. Each 10-minute sample is the linear average of a 1 s sample over 10 s. The turbine reached the max power condition and the turbine noise in the 16 Hz band disappeared. The main energy contours 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.

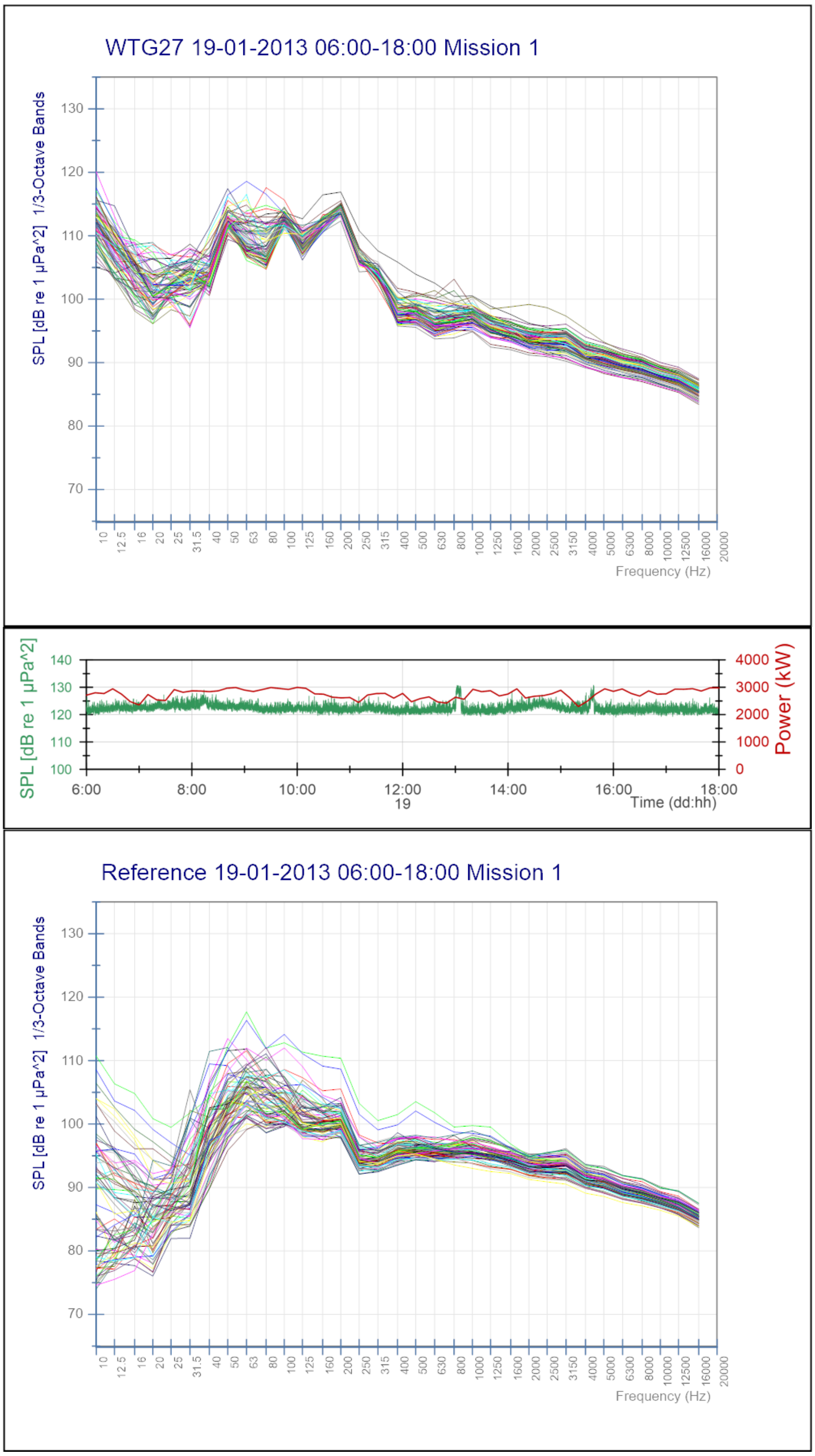


Figure 38 Third-Octave spectra of turbine noise sampled per 10 minutes over a day-time period of 12 hours. Each 10-minute sample is the linear average of a 1 s sample over 10 s. The turbine produced the max power with noise contours mainly expressed in the 50 Hz-, 100 Hz- and 200 Hz-bands. The cut-off of frequencies in bands < 16 Hz caused a gap in the energy in bands < 50 Hz.

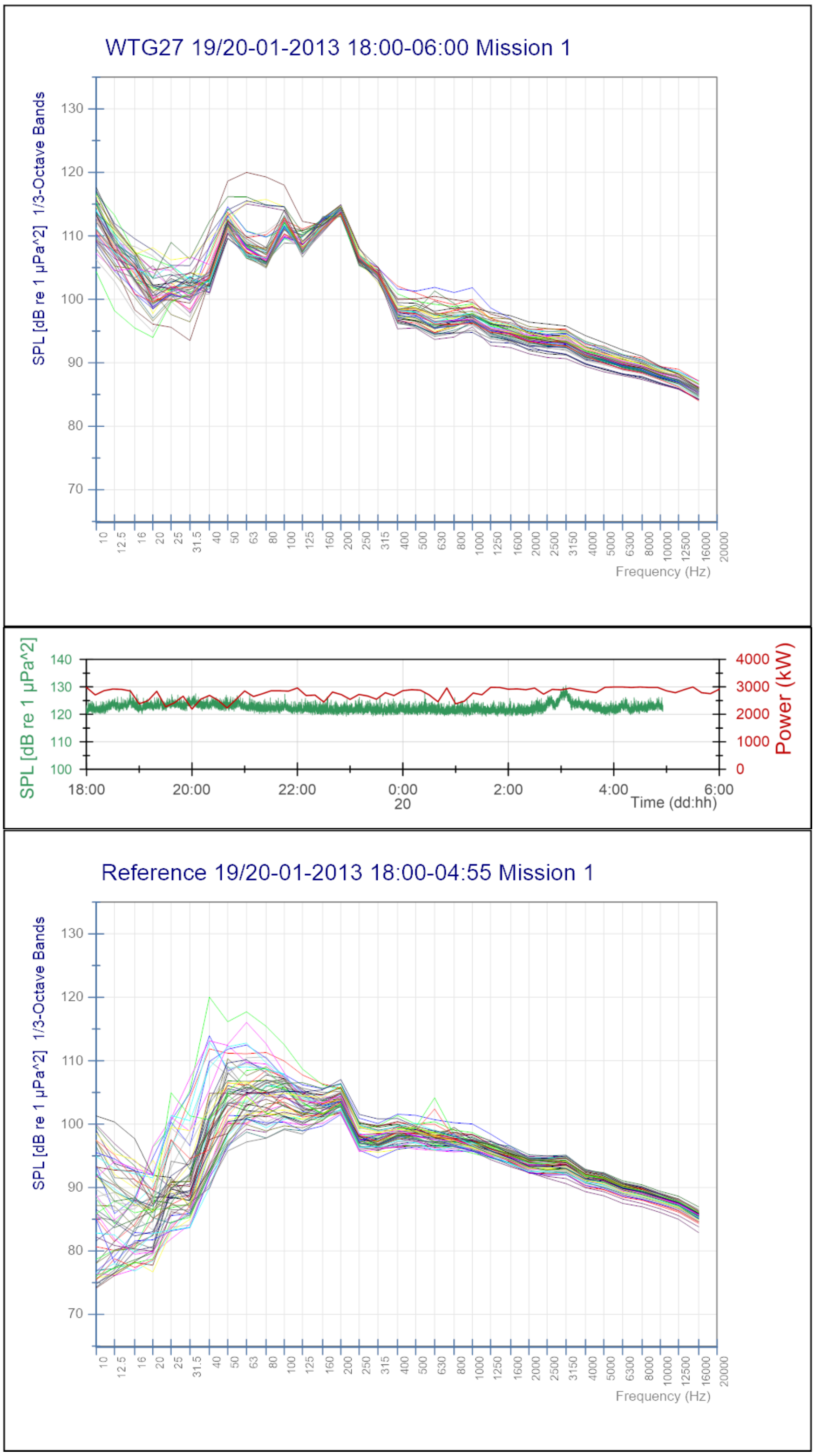


Figure 39 Third-Octave spectra of turbine noise sampled per 10 minutes over a night-time period of nearly 11 hours. Each 10-minute sample is the linear average of a 1 s sample over 10 s. The turbine produced the max power with contours of the spectrum mainly depended by energy in the 50 Hz-, 100 Hz- and 200 Hz-bands.

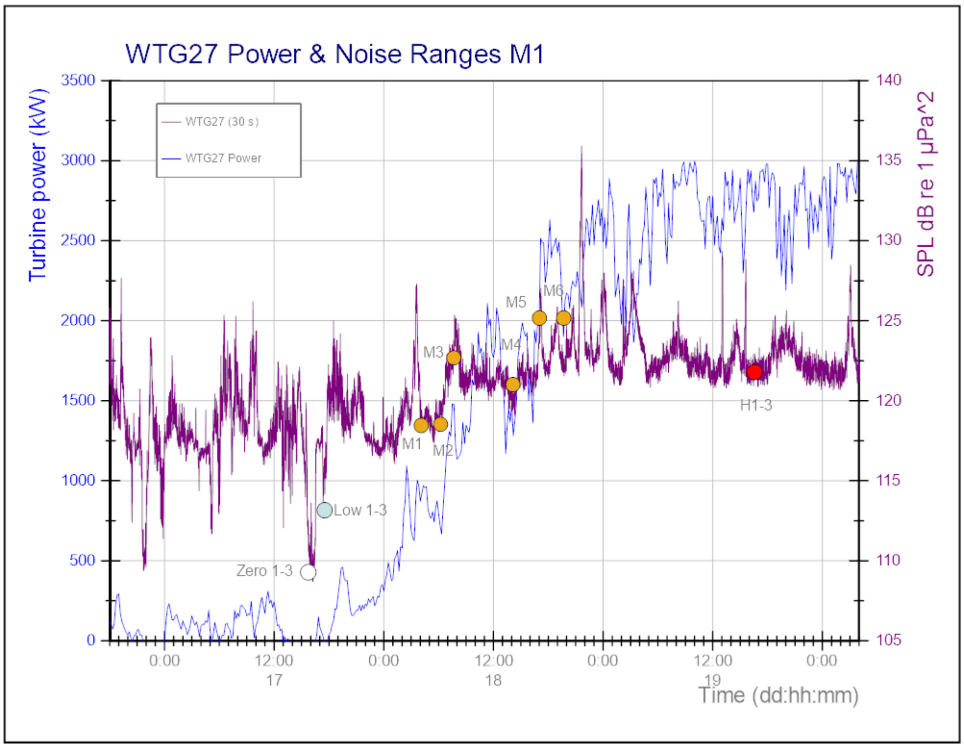


Figure 40 Broad band noise levels (average 30s) against turbine power and the marked ranges where Third-Octave analysis was applied.

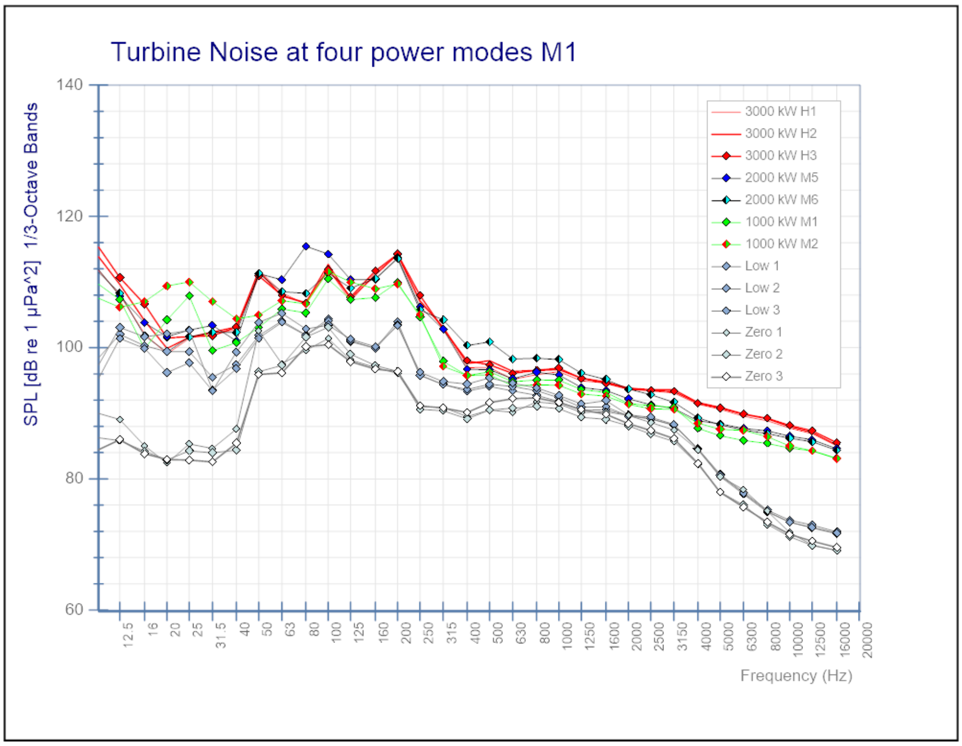


Figure 41 Turbine noise in Third-Octave bands (60 s linear averaged 1 s samples) at power ranges from zero to 3000 kW. The results express that the noise is becoming significant as soon as the turbine starts in the bands ≥ 50 Hz and that the noise does not increase much at power ranges above 1000 kW. Operational conditions are listed in Appendix B, Table 4.

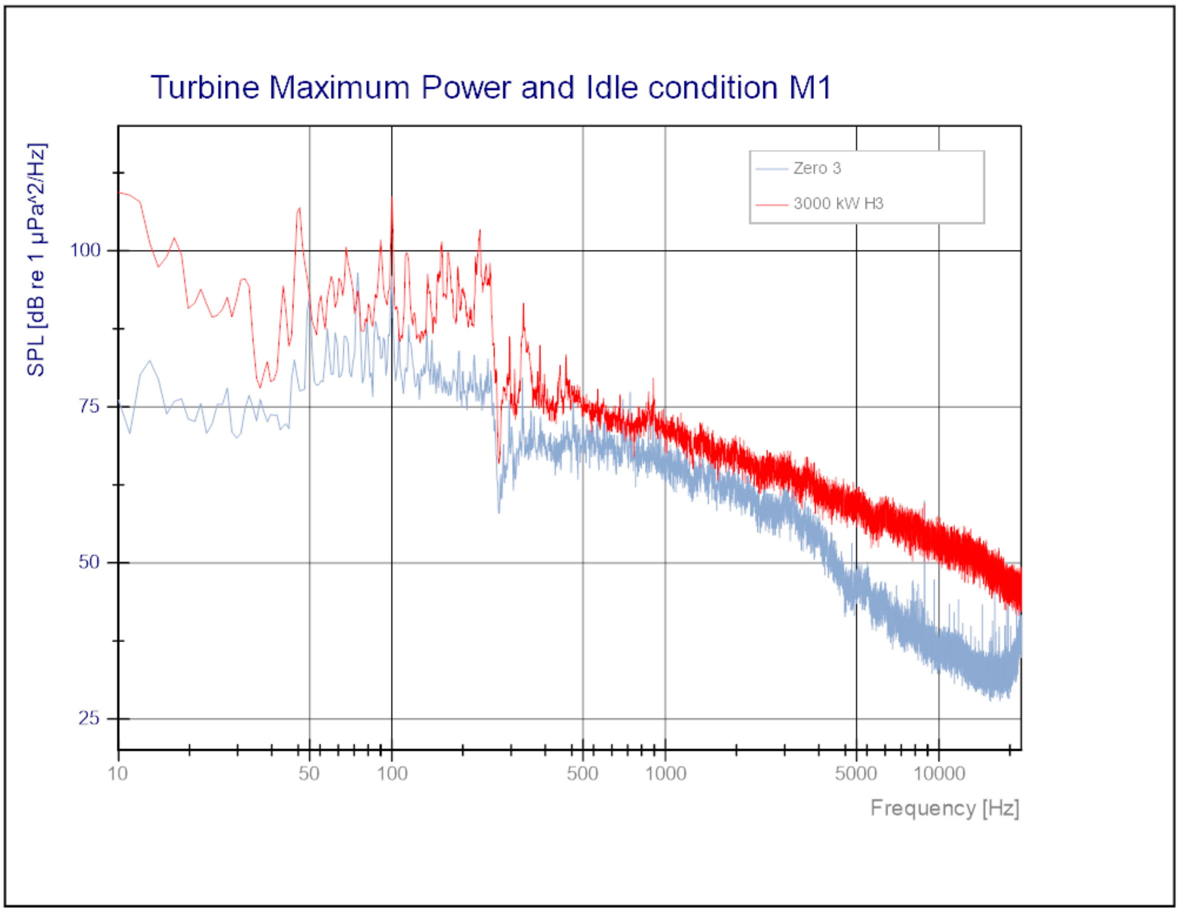


Figure 42 Overview of narrow-band analysis (Fast-Fourier Transformed, 1 s blocks, average length 10 s, 50 % overlap) of the maximum power condition taken on 19 Jan marked as "H3" in Figure 40 and 41 against the idle mode condition of the turbine on 17 January 2013 16:14 (marked as "zero 3" in Figure 40 and 41). The analysis shows the noise peaks attributed to the turbine and rotor transmission system.

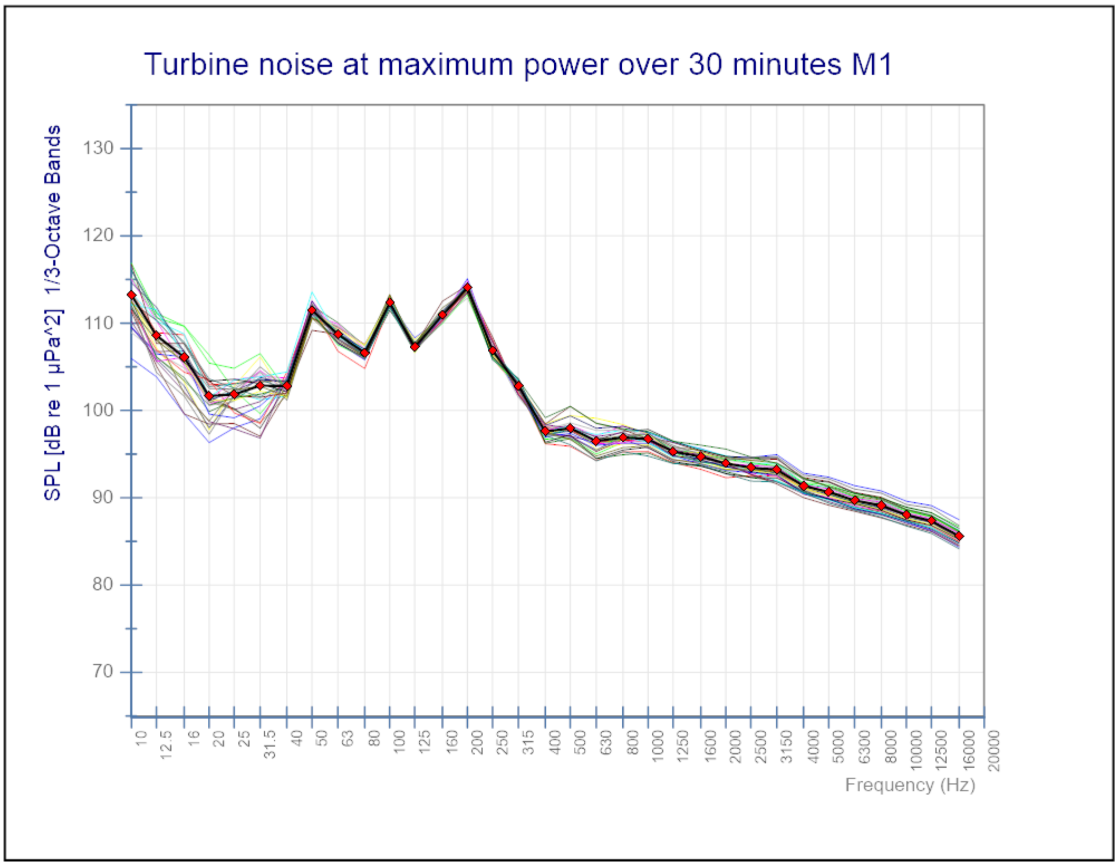


Figure 43 Third-Octave spectra at maximum turbine power condition on 19 January 2013 sampled with 1 minute-intervals between 16:25 and 16:55. In this period there was no contribution of ship-noise. The marked track is the calculated average. The contours of the turbine noise are mainly in the 50 Hz-, 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

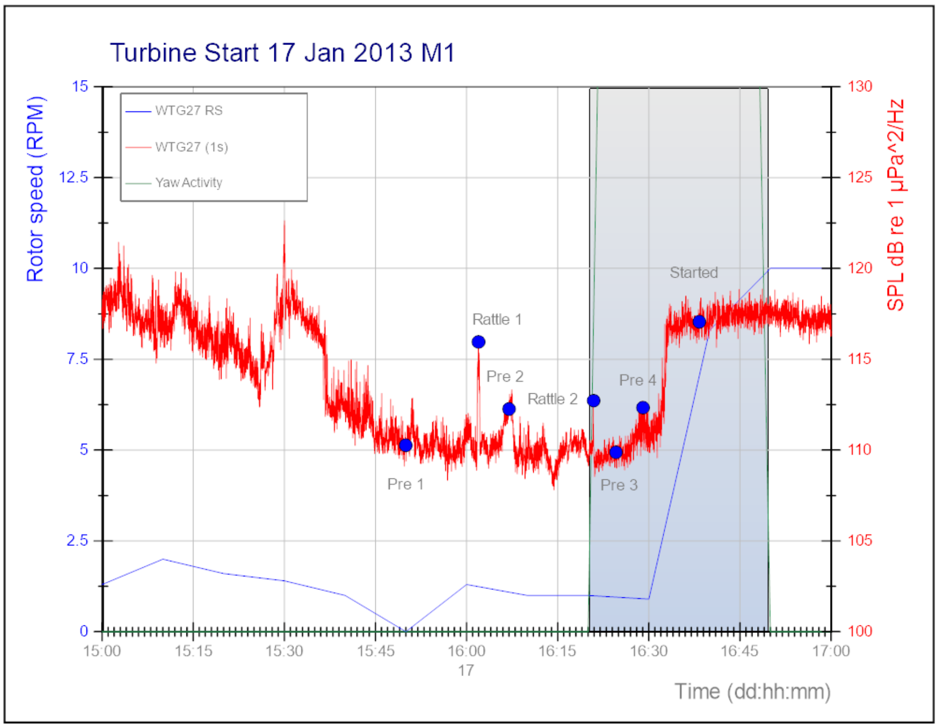


Figure 44 Starting of the turbine from idle mode on 17 January 2013 with two conditions of decoupling noises of the rotor blade piston mechanism. The marked area refers to the Yawing-activity. The turbine related data is listed in Appendix B, Table 5. The Third-Octave noise spectra at the marked conditions are shown in Figure 45.

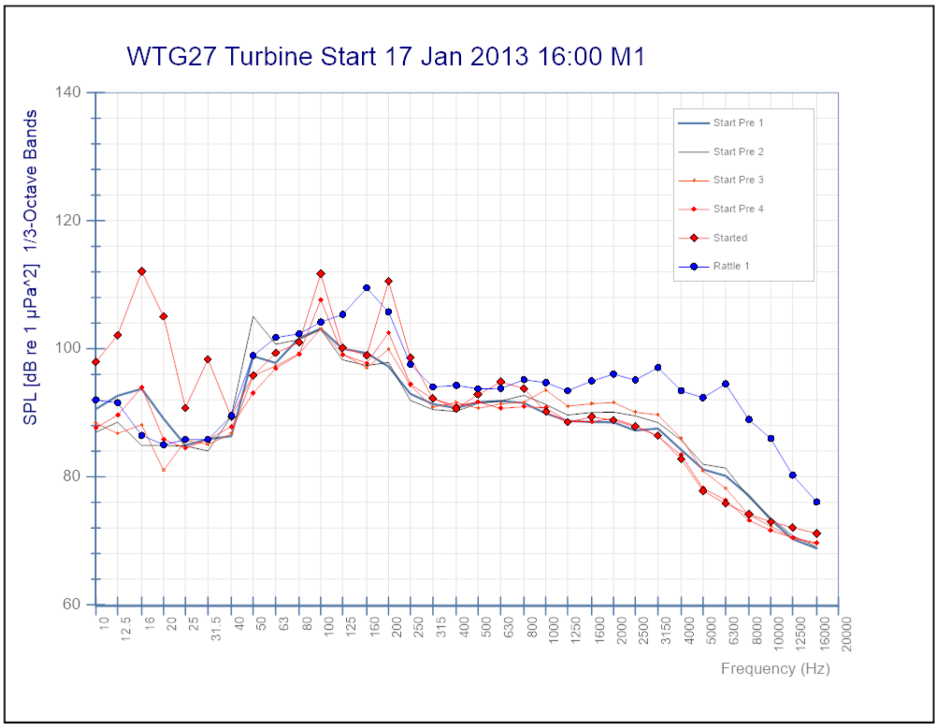
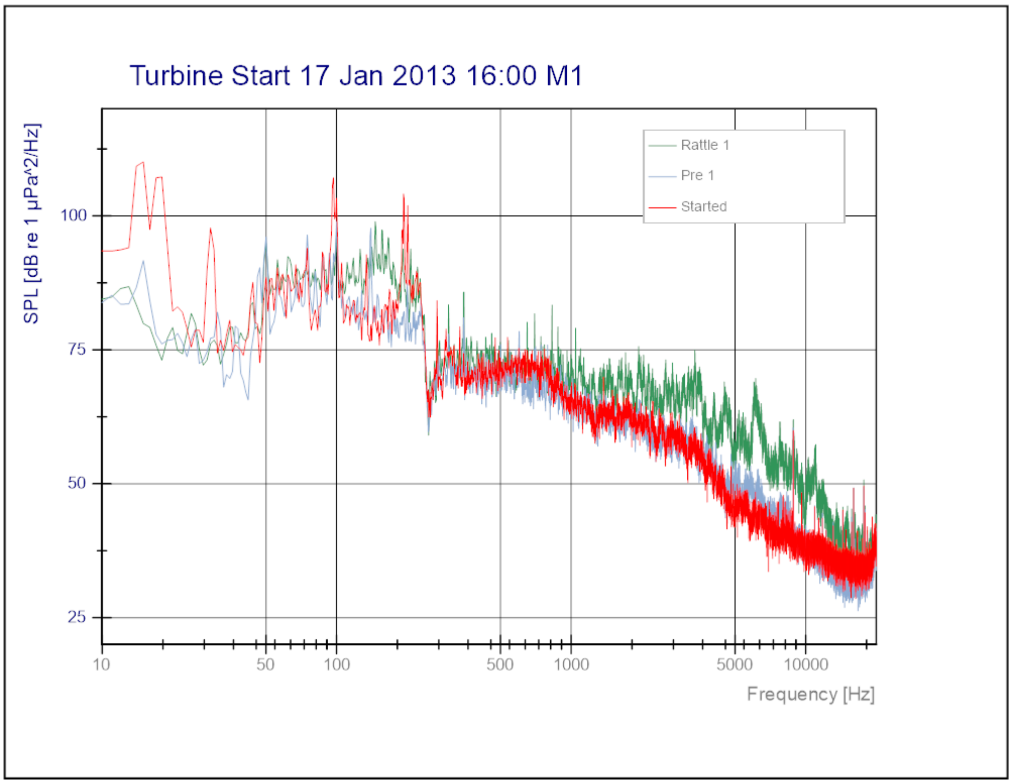


Figure 45 Third-Octave noise spectra of moments in the start-up of the Turbine on 17 January 2013. Each result is the linear average of 1 s samples over a 10 s period. The rotational speed of the turbine shaft is the most dominant element of the spectrum. The incidental rattling noise caused some increased higher frequency contribution in particular around 3 kHz.



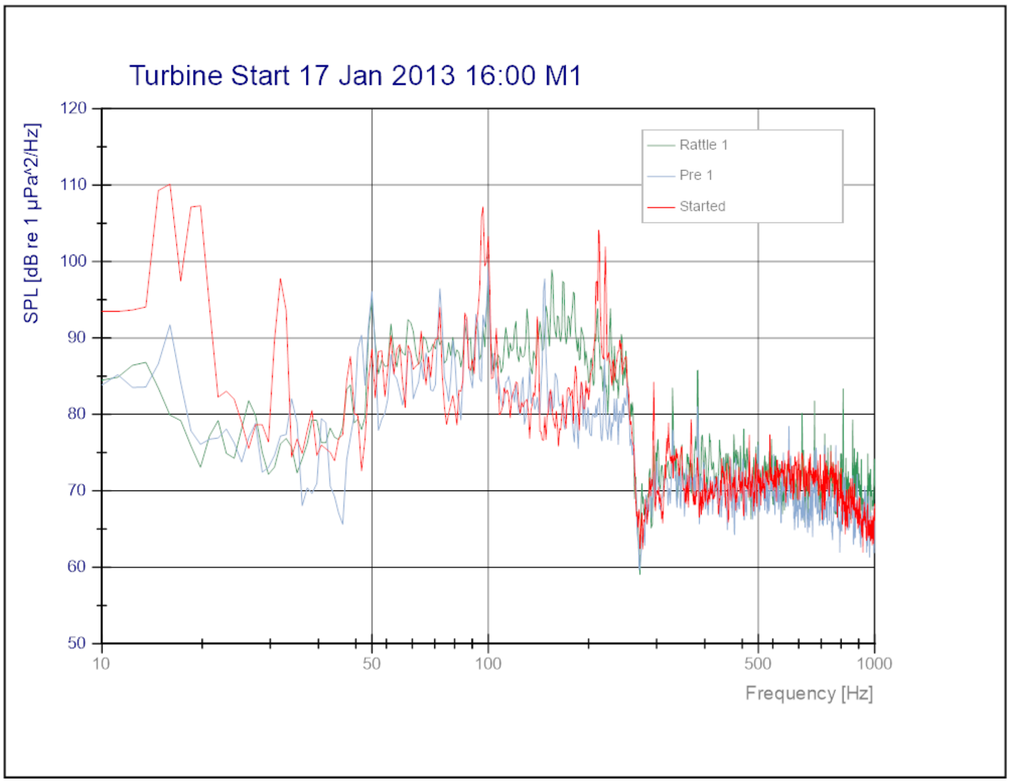


Figure 46 Overview of narrow-band analysis (Fast-Fourier Transformed, 1 s blocks, average length 10 s, 50 5 overlap) in the full frequency range and the LF-zoom-in. Moments are taken shortly before and after the start of the Turbine on 17 January 2013, including the rattling noise attributed to the rotor blade pitch mechanism and refer to the marked analysis displayed in Figure 44 and 45.

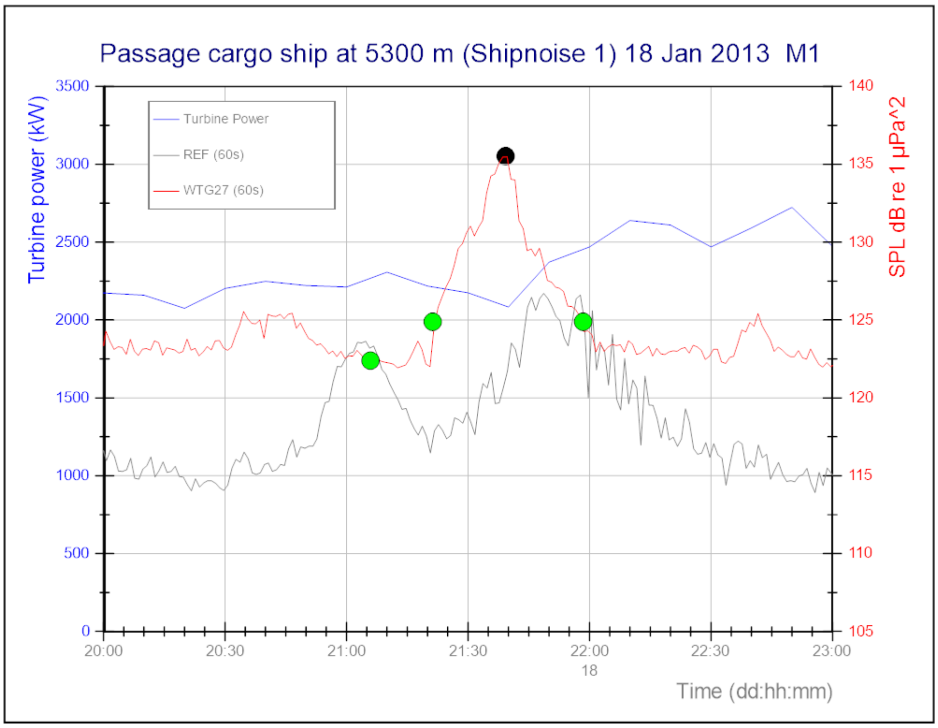


Figure 47 Detail of broad-band noise peak on the passage of a cargo vessel on 18 January. This ship passed the WTG27 hydrophone at a shortest distance of 5234 m. The vessel's noise increased the turbine level from 21:20 and 22:00. At the marked moments Third-Octave analysis was applied.

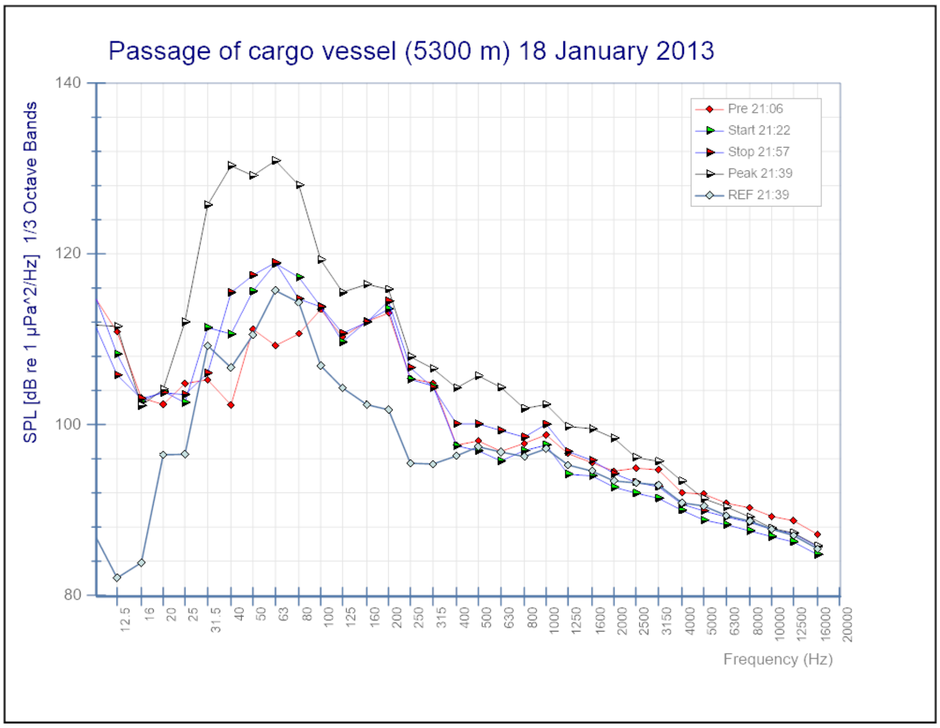


Figure 48 Detail of broad band noise peak on the passage of a cargo vessel on 18 January. This ship passed the WTG27 hydrophone at a shortest distance of 5234 m measured. The vessel's noise masked the turbine noise level from 21:20 to 22:00. At the marked moments Third-Octave analysis was applied.

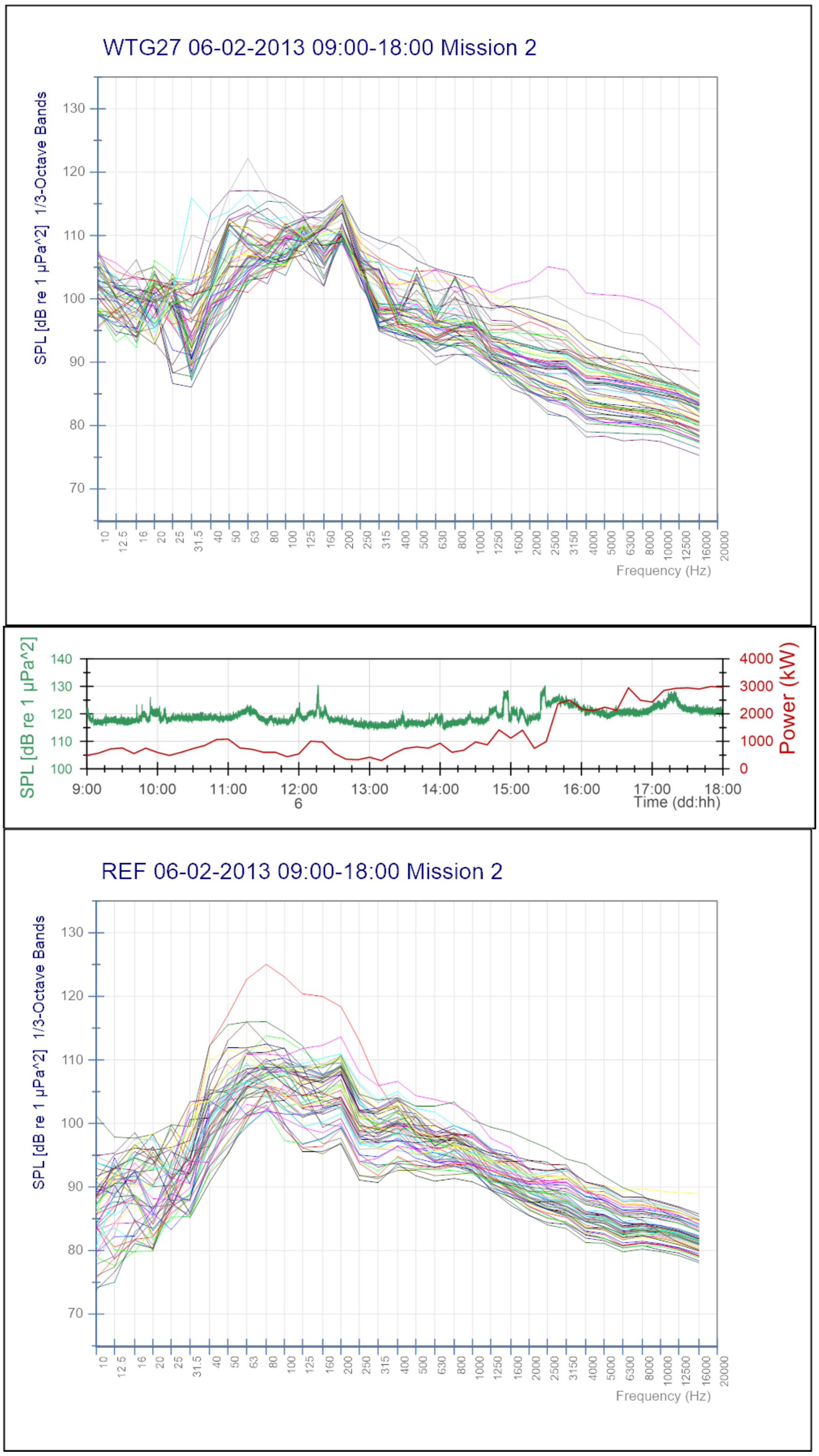


Figure 49 Third-Octave spectra of turbine noise sampled per 10 minutes over a day-time period of 9 hours on Mission 2. Each 10-minute sample is the linear average of a 1 s sample over 10 s. The turbine produced increased to maximum power condition with contours of the spectrum not as sharp as on Mission 1, but recognized in the 100 Hz- and 200 Hz-bands. The contours are partly masked by shipping noise.

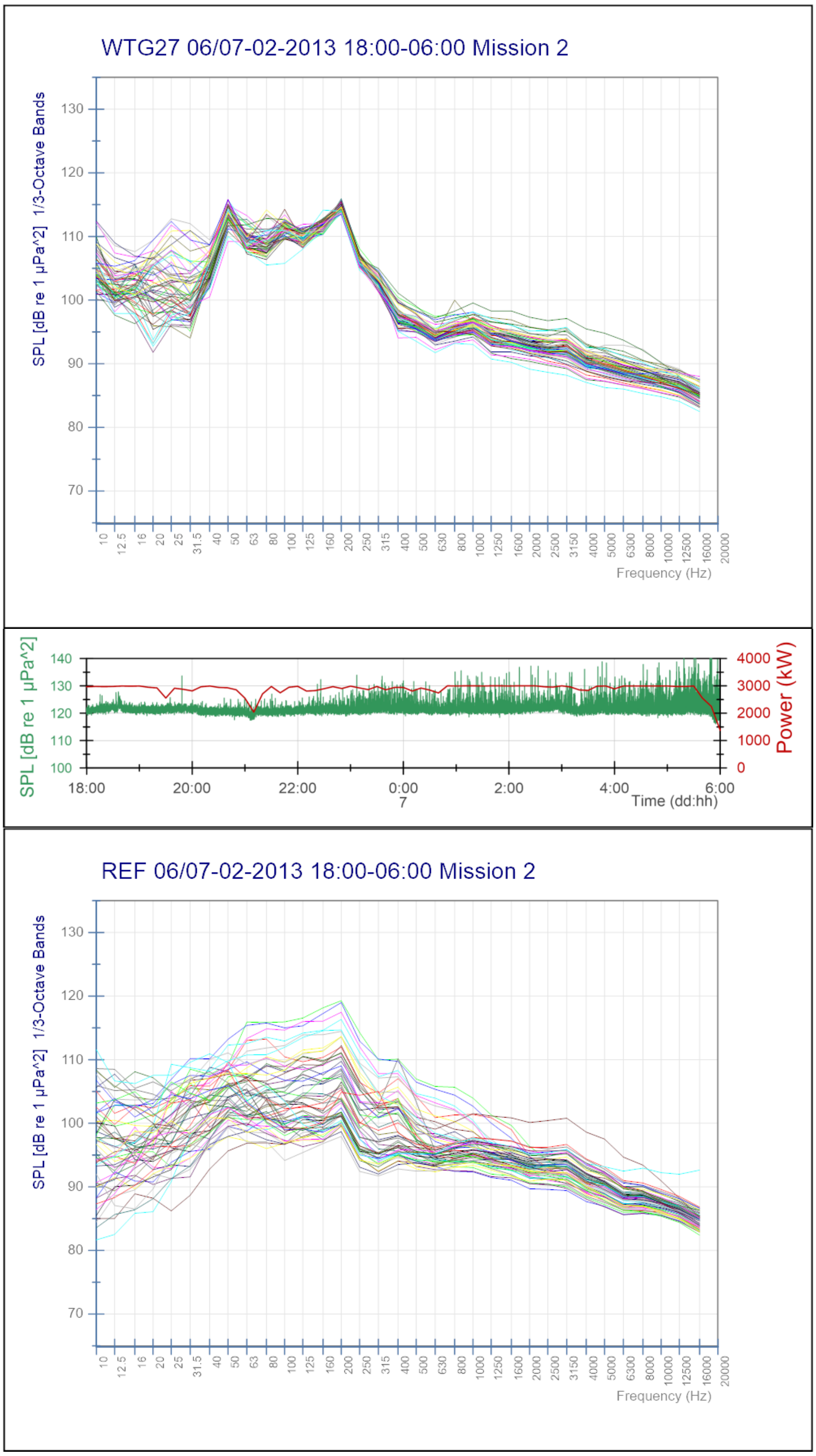


Figure 50 Third-Octave spectra of turbine noise sampled per 10 minutes over a night-time period of 12 hours on Mission 2. Each 10-minute sample is the linear average of a 1 s sample over 10 s. The turbine produced the max power with a decline at the end of the period with sharp contours of the spectrum 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.

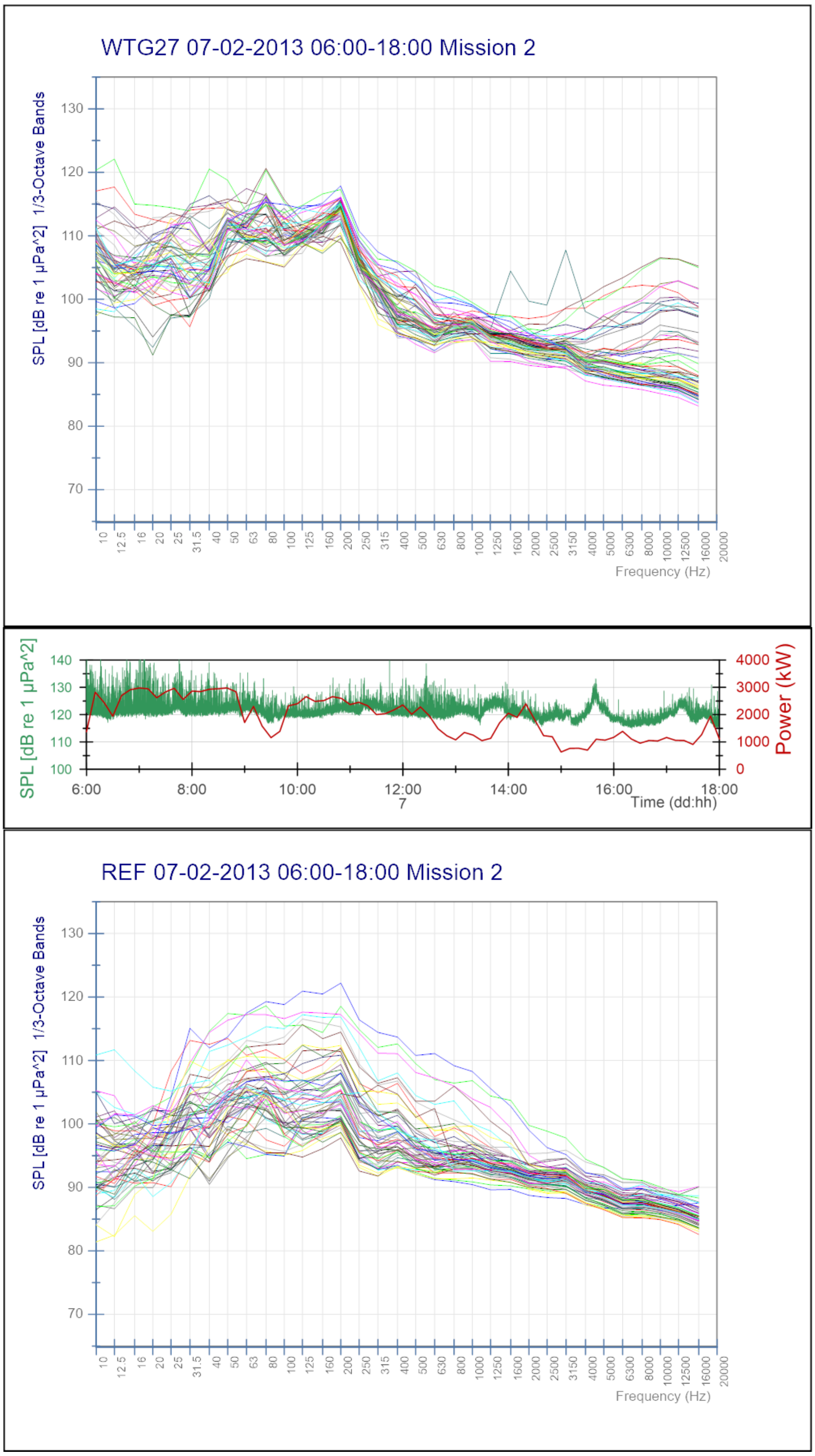


Figure 51 Third-Octave spectra of turbine noise sampled per 10 minutes over a day-time period of 12 hours on Mission 2. Each 10-minute sample is the linear average of a 1 s sample over 10 s. The turbine operated between maximum and medium power range. The contours of the turbine spectrum were partly masked by shipping noise.

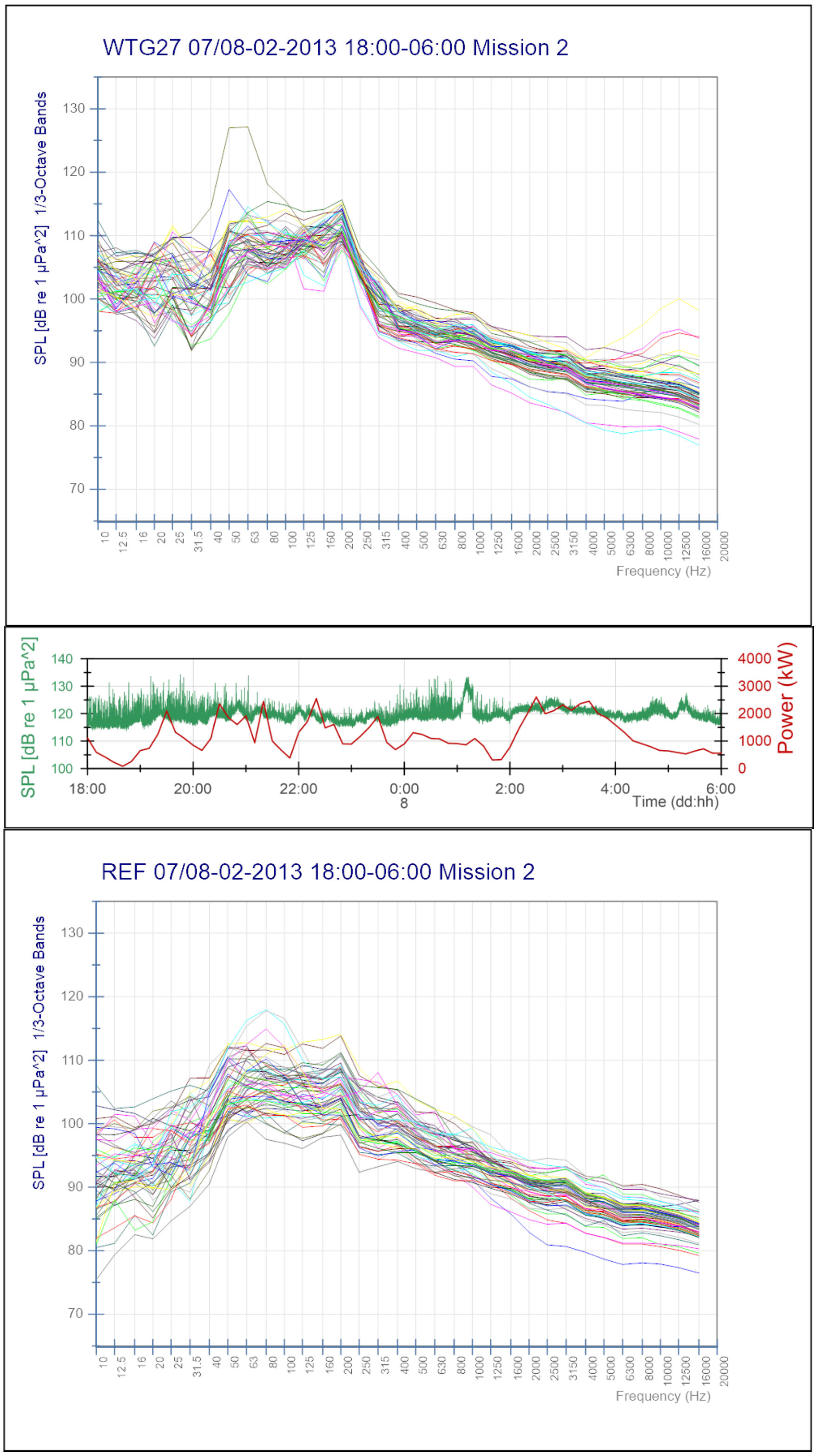


Figure 52 Third-Octave spectra of turbine noise sampled per 10 minutes over a night-time period of 12 hours on Mission 2. Each 10-minute sample is the linear average of a 1 s sample over 10 s. The turbine power was variable and operated mainly in the medium power range. The contours of the spectrum were only visible in the 200 Hz-band.

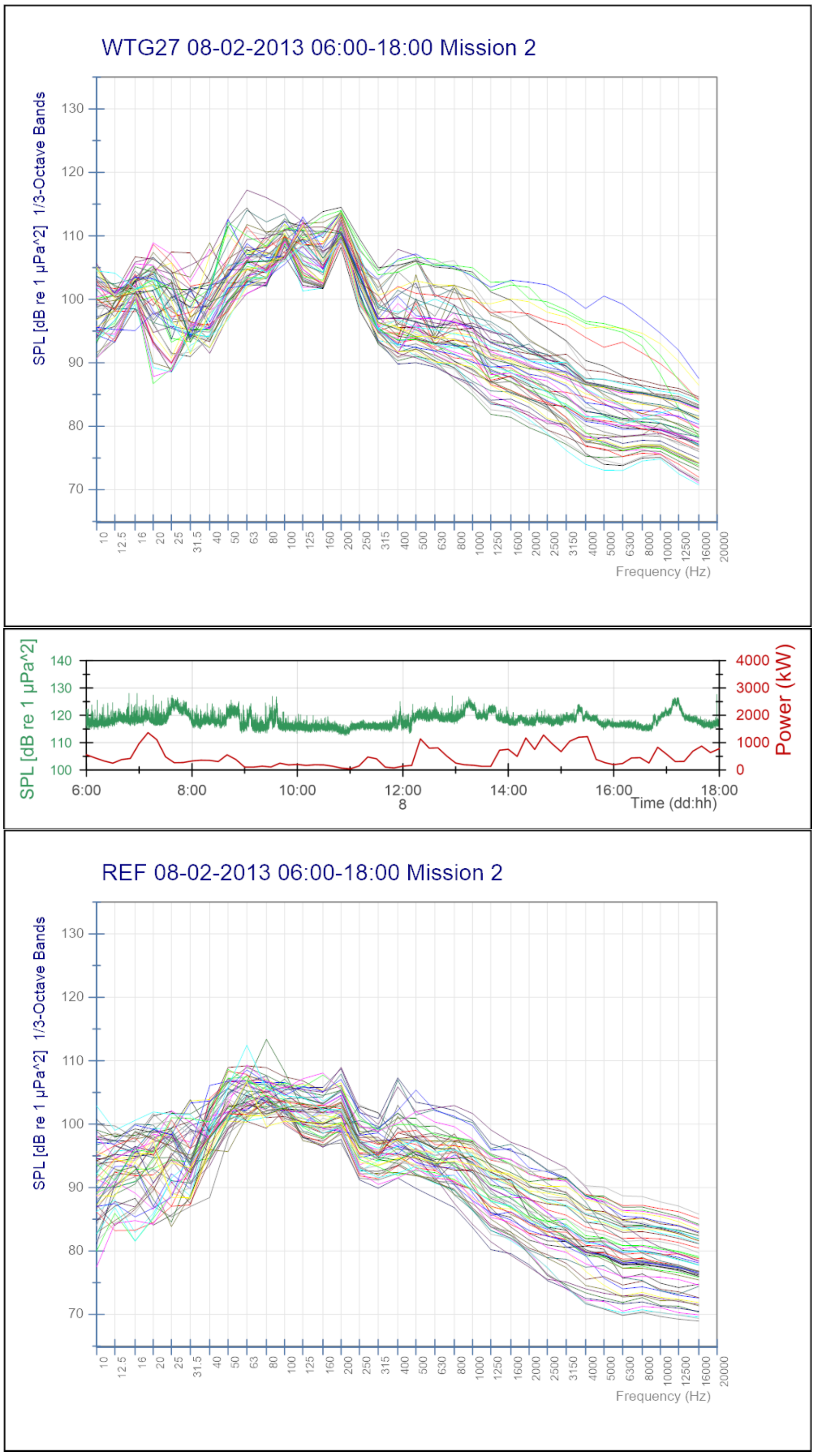


Figure 53 Third-Octave spectra of turbine noise sampled per 10 minutes over a day-time period of 12 hours on Mission 2. Each 10-minute sample is the linear average of a 1 s sample over 10 s. The turbine operated in the lower power range with maximum around 1000 kW. The turbine spectrum is recognized 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.

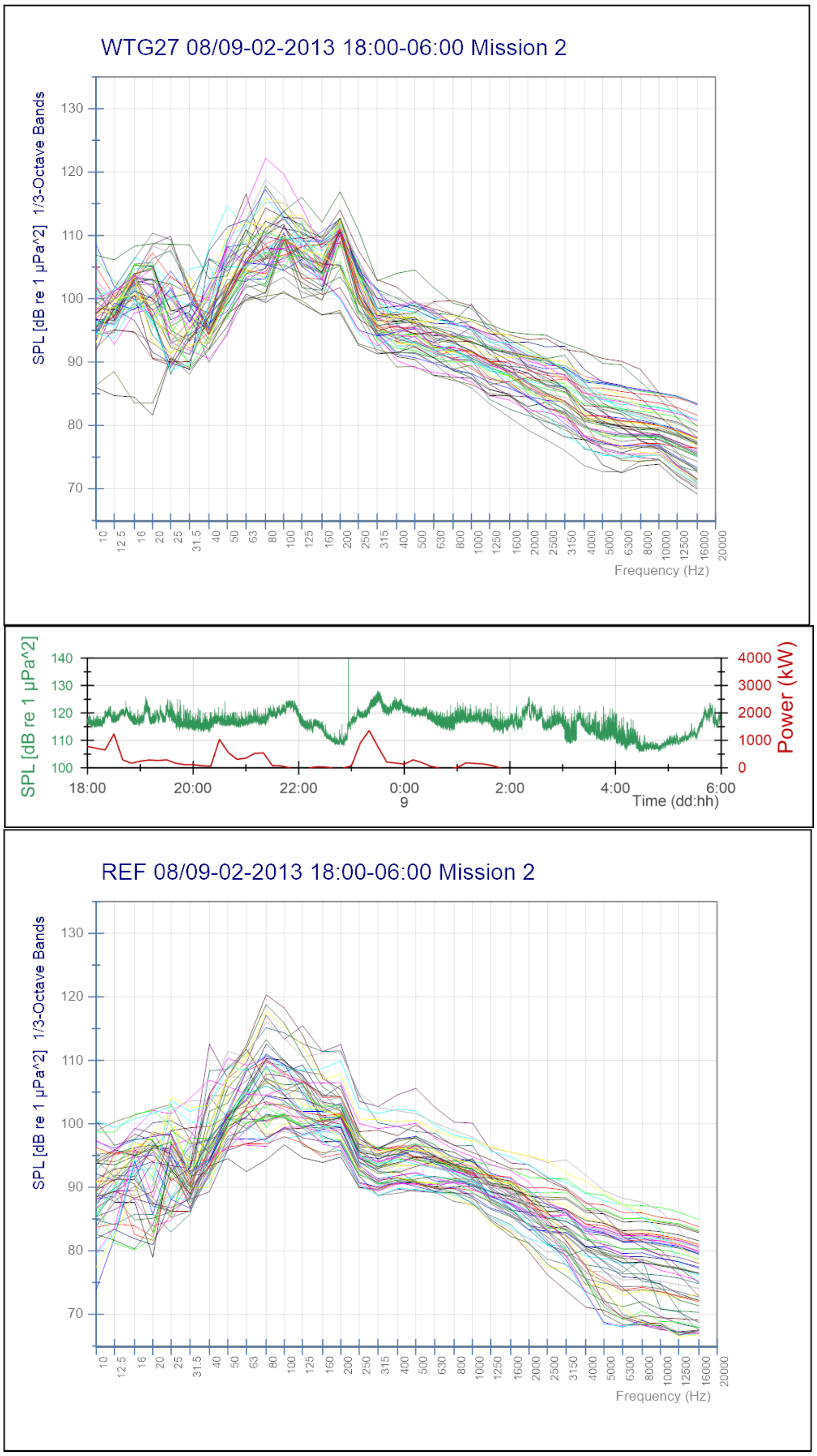


Figure 54 Third-Octave spectra of turbine noise sampled per 10 minutes over a night-time period of 12 hours on Mission 2. Each 10-minute sample is the linear average of a 1 s sample over 10 s. The turbine operated mainly in the low power range with three peaks of 1000 kW. The contours of the turbine spectrum are pronounced mainly in the 200 Hz- and to a minor extend in the 100 Hz-band.

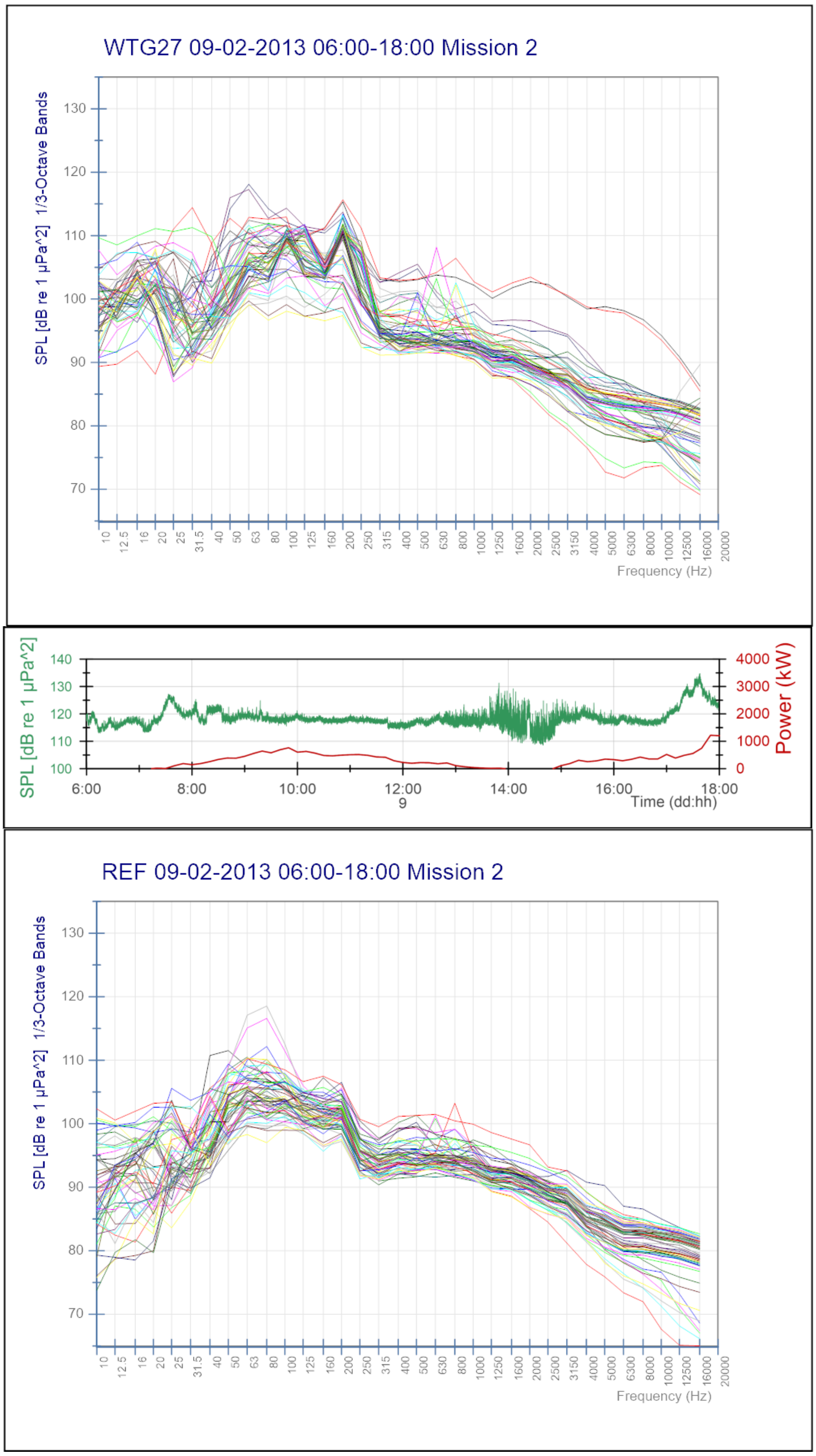


Figure 55 Third-Octave spectra of turbine noise sampled per 10 minutes over a day-time period of 12 hours on Mission 2. Each 10-minute sample is the linear average of a 1 s sample over 10 s. The turbine operated in the lower power range. The contours of the turbine spectrum recognized in the 100 Hz- and 200-Hz bands.

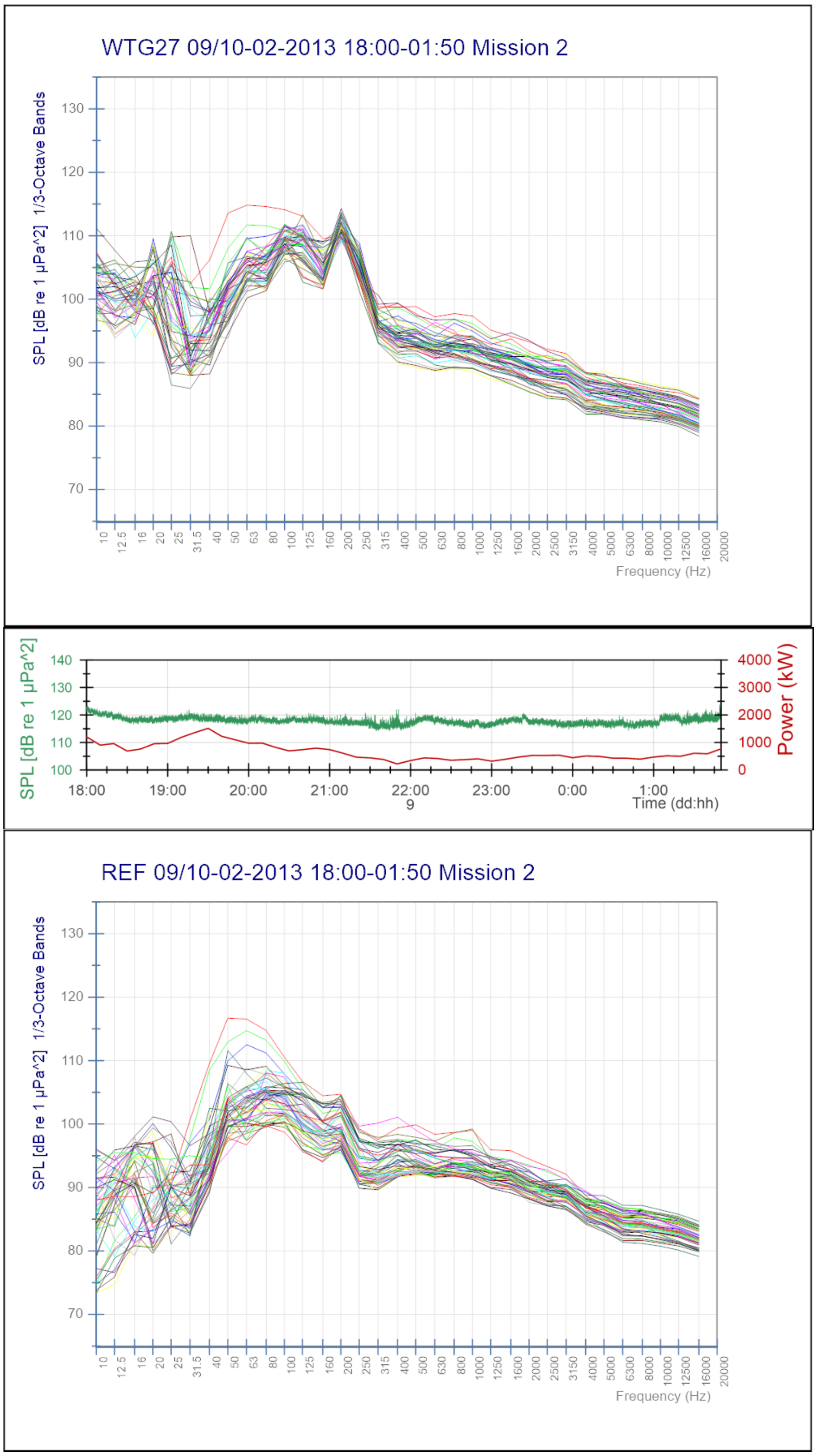


Figure 56 Third-Octave spectra of turbine noise sampled per 10 minutes over a night-time period of 7 hours and 50 minutes on Mission 2. Each 10-minute sample is the linear average of a 1 s sample over 10 s. The turbine power varied between 500 and 1000 kW. The contour of the turbine spectrum was particularly pronounced in the 200 Hz-band.

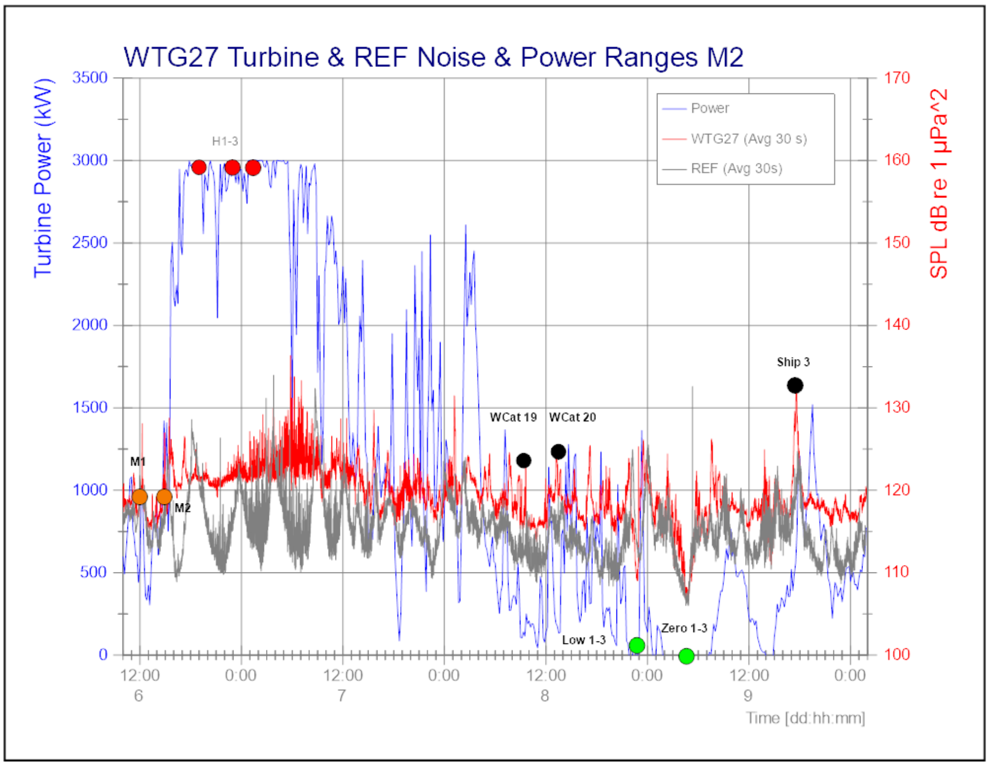


Figure 57 Broad band noise levels (average 30s) against turbine power and the marked power ranges where frequency analysis was applied.

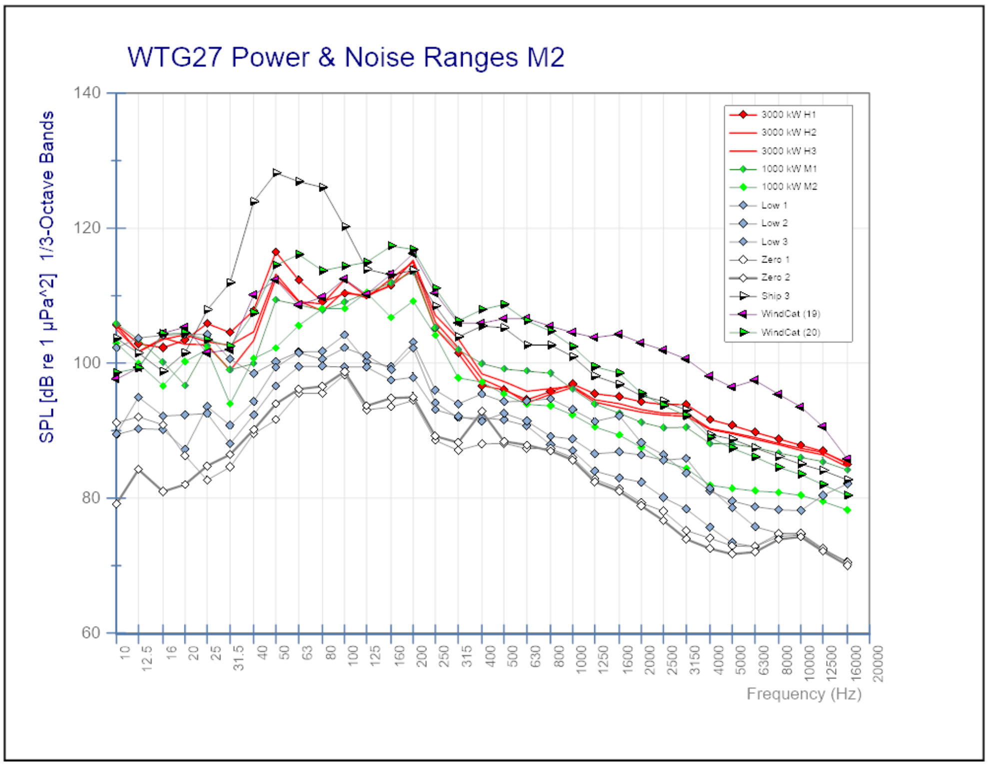


Figure 58 Noise levels filtered in Third-Octave bands (60 s linear averaged 1 s samples) of idle, low, medium and maximum turbine power ranges, marked in Figure 57, including the noise spectra of 3 ship noise events, WindCat noise case 19 & 20 (Appendix C, Table 9) and the passage of a larger vessel not related to wind farm operation (Ship 3).

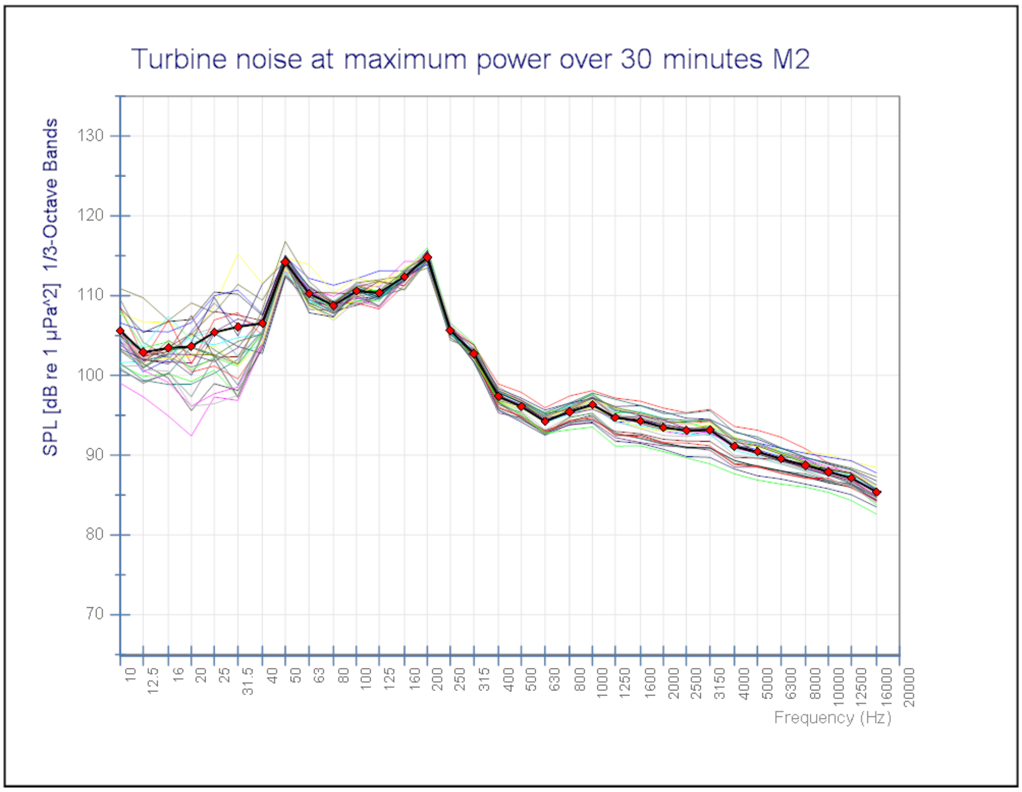


Figure 59 Third-Octave spectra at maximum turbine power condition on 7 February 2013 sampled with 1 minute-intervals between 00:21 and 00:51. In this period there was no contribution of ship-noise. The marked track is the calculated average. The contours of the turbine noise are mainly in the 50 Hz- 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 43).

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

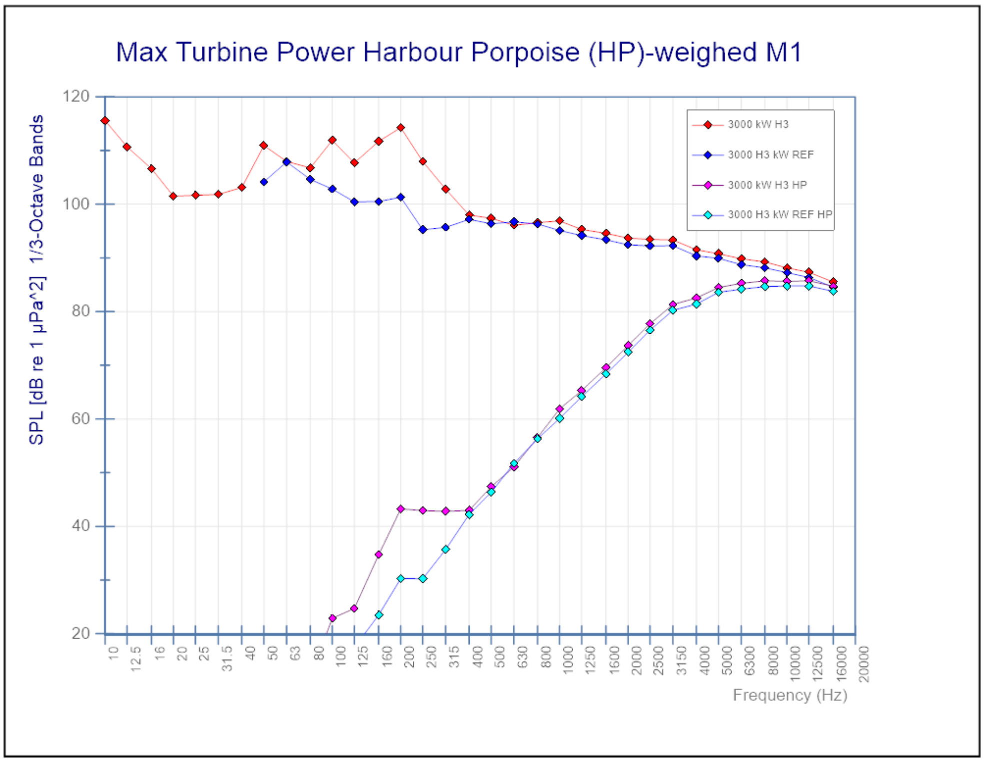


Figure 60 Turbine noise spectrum measured at maximum power condition weighed against the hearing curve of harbour porpoise. The graph shows that a very low part of the energy remains above the reference level at frequency bands < 315 Hz where this species is not a specialist.

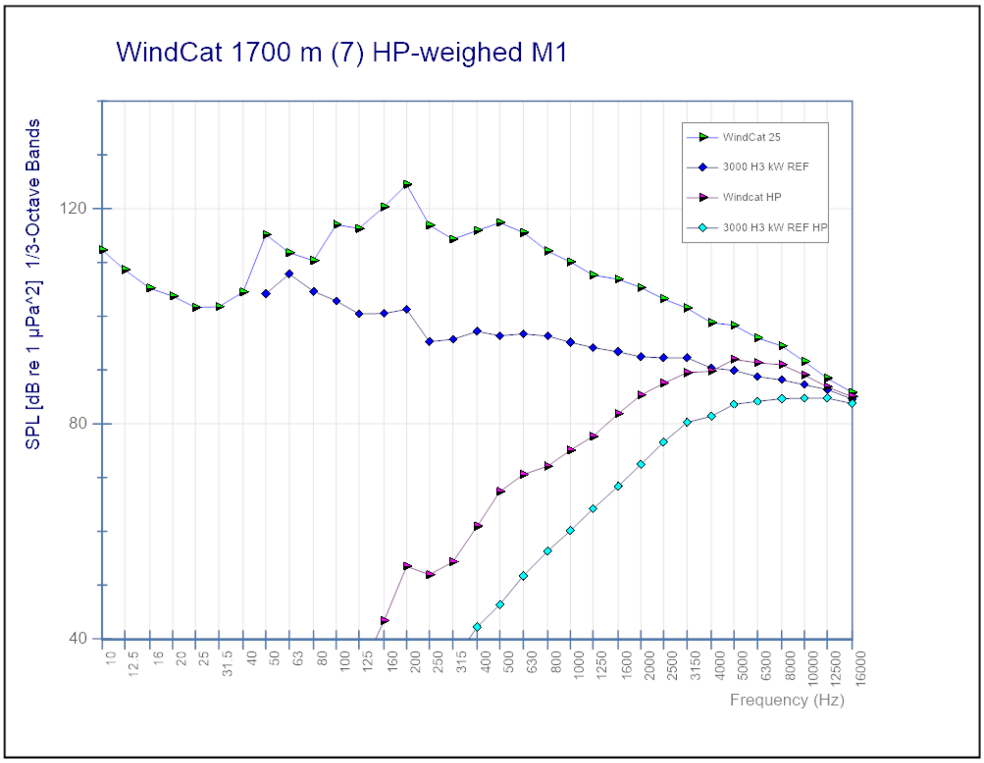


Figure 61 WindCat noise spectrum measured at 1700 m (WTG21-case 7) filtered against the hearing curve of harbour porpoise. The filtered result is well above the weighed reference spectrum

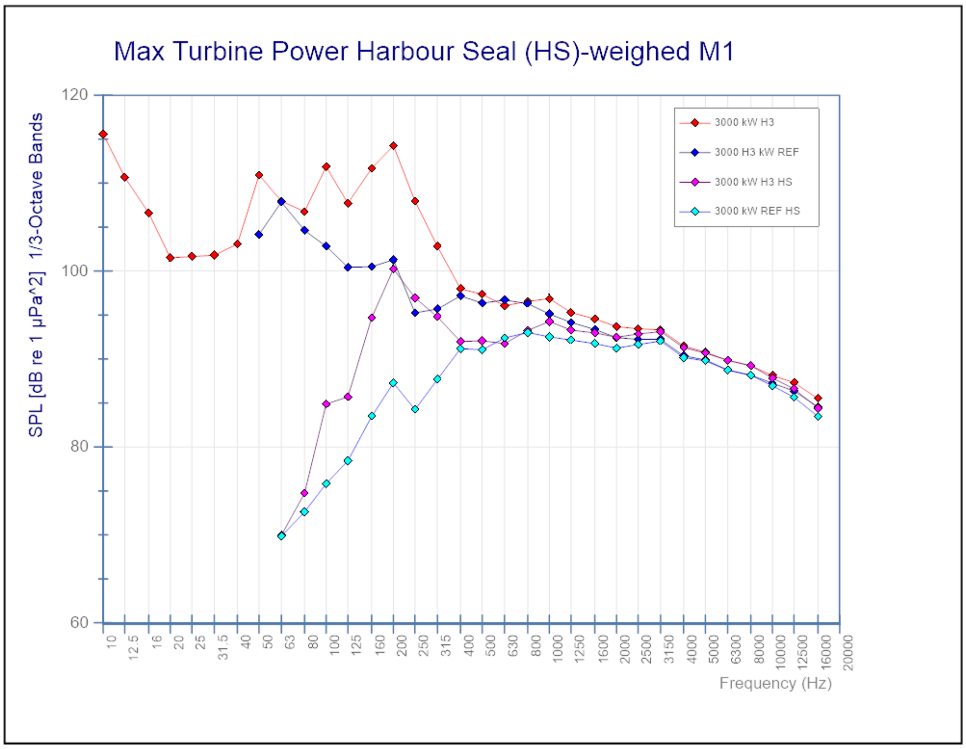


Figure 62 Turbine noise spectrum measured at maximum power condition weighed against the hearing curve of harbour seal. The graph shows that a significant part of the energy <400 Hz remains above the reference level. The higher sensitivity in the lower frequency range is well expressed in this result and it is likely this animal is able to hear the noise.

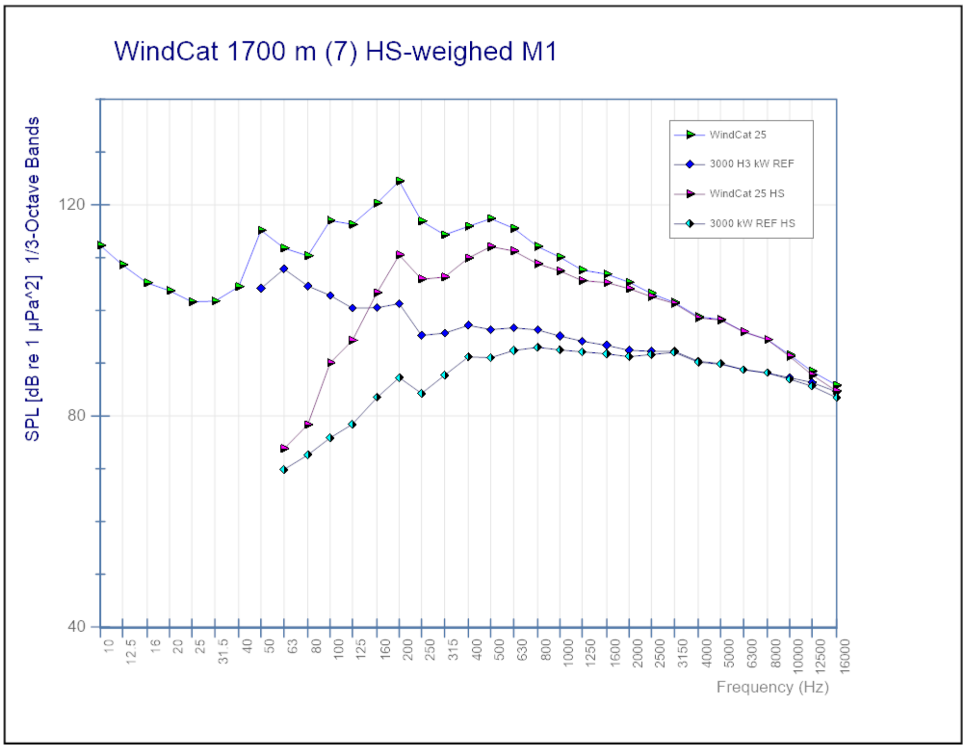


Figure 63 The filtered results of WindCat noise to the hearing curve of harbour seal show that this type of noise remains detectable on almost the full range of the spectrum.

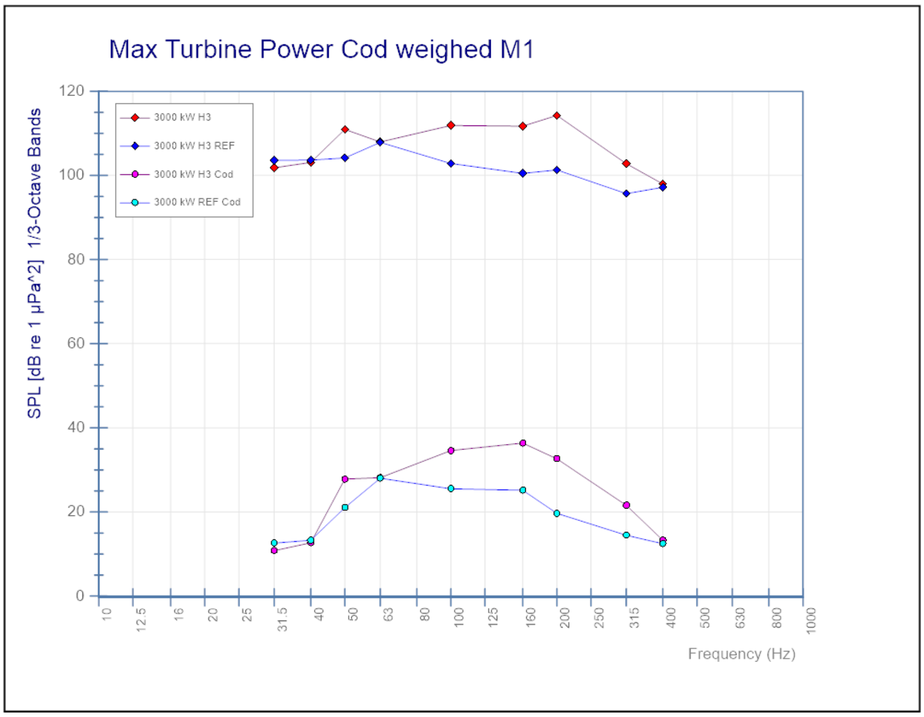


Figure 64 Turbine noise spectrum at maximum power condition weighed against the auditory thresholds of Atlantic cod (Gadus morhua) according the study of Hawkins et al., 1973. The weighed results for cod indicate that this species is sensitive over the full unmasked spectrum of turbine noise to a maximum of 10 dB above the background noise at 160 and 200 Hz.

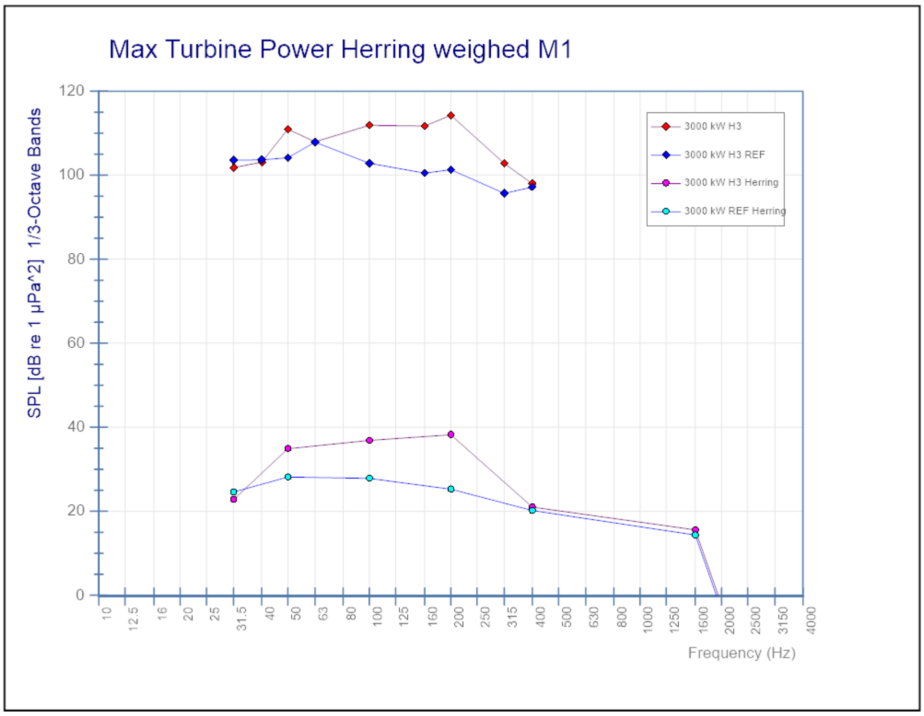


Figure 65 Turbine noise spectrum at maximum power condition weighed against the auditory threshold of Atlantic herring (Clupea harengus), according the study of Enger, 1967. The results after weighing show that a small part of the energy is filtered and that this species is sensitive in the full unmasked spectrum to a maximum of 10 dB at 200 Hz.

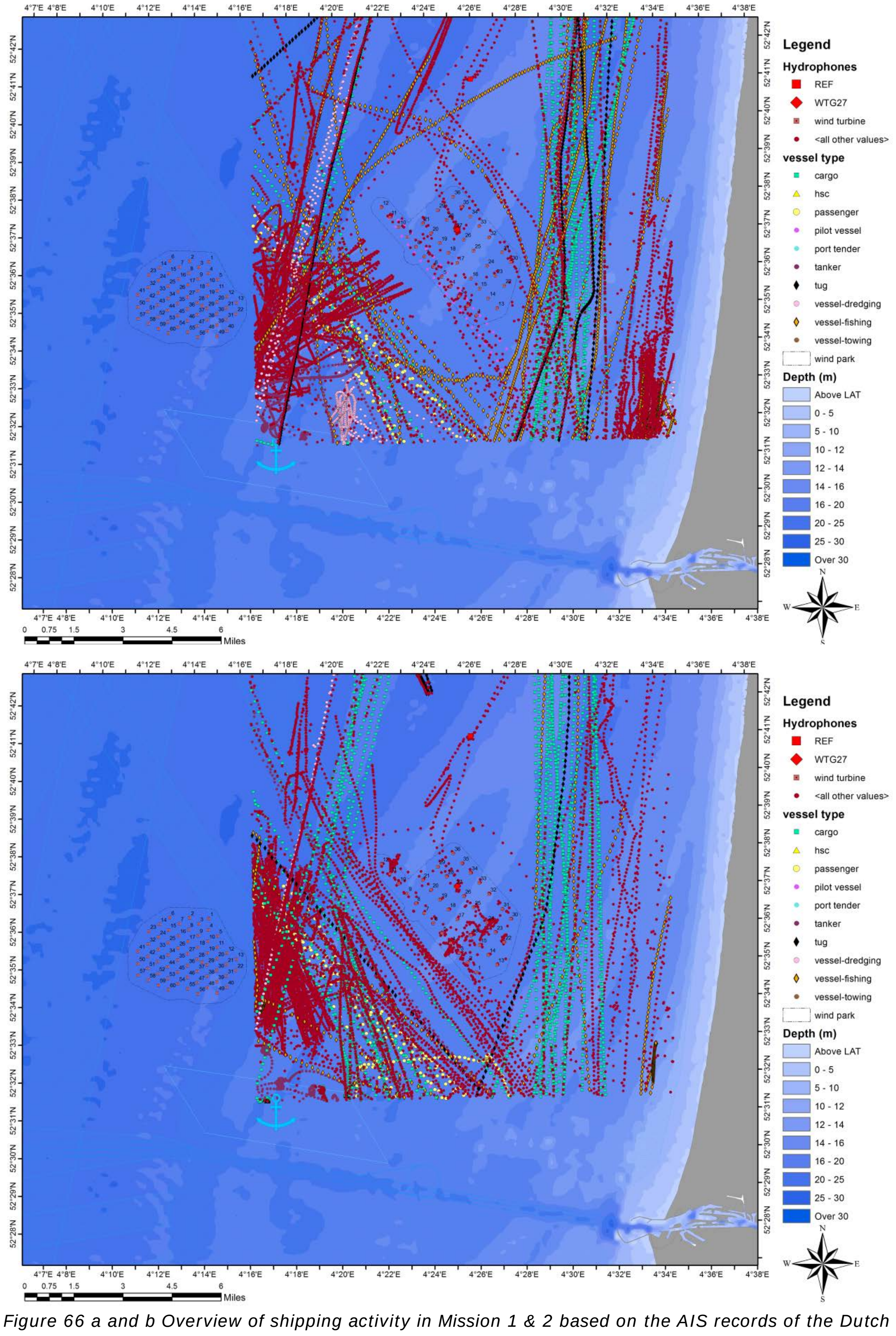


Figure 66 a and b Overview of shipping activity in Mission 1 & 2 based on the AIS records of the Dutch coastguard, provided by Marin, Wageningen, NL.

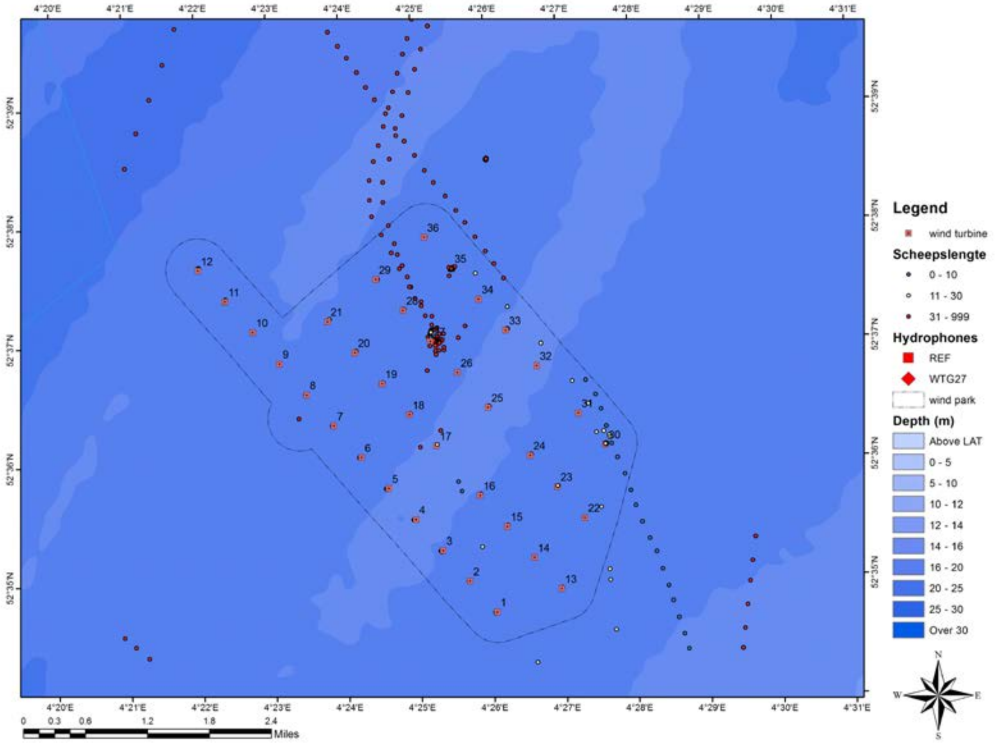


Figure 67 Shipping Activity on 16 January 2013 from 06:00 to 17:00 with MS "Terschelling" at WTG27 on the moment of the deployment of the equipment and a fishing vessel sailing at the east side of OWEZ.

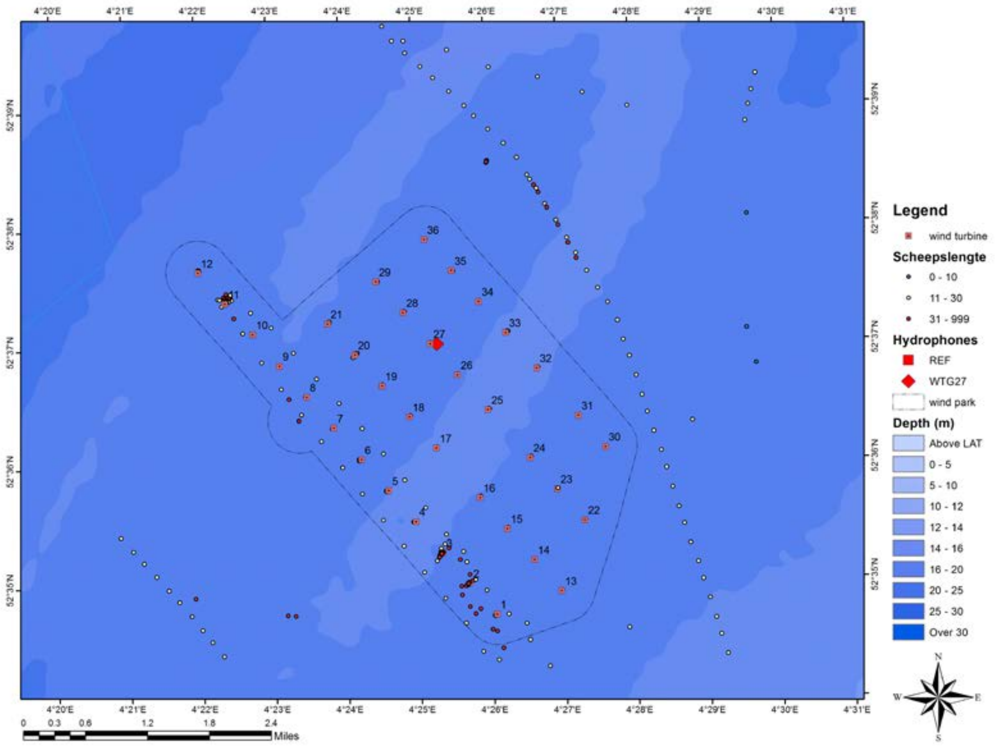


Figure 68 Shipping Activity on 17 January 2013 (06:00 to 17:00) with WindCat type of vessels at WTG11, 02 and 03 and a fishing vessel sailing at the east side of OWEZ.

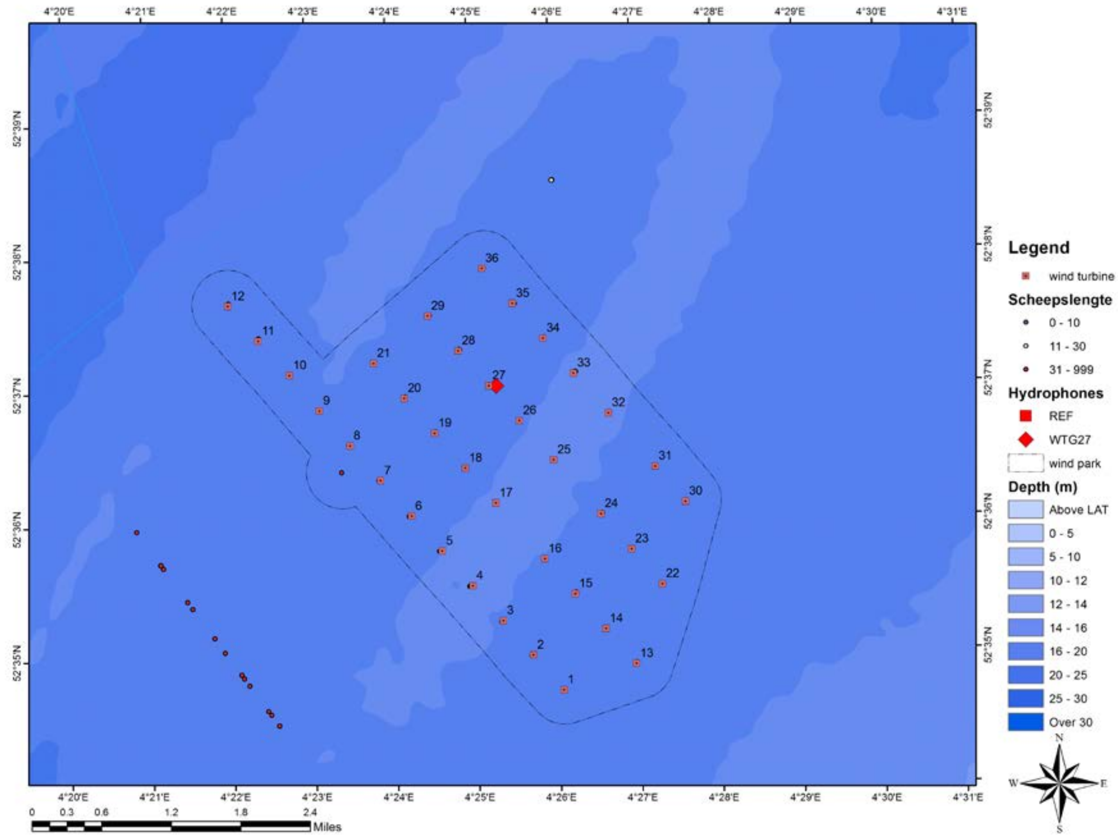


Figure 69 AIS detected track of a cargo vessel (163 m length, 6.1 m depth) passing OWEZ on 18 January between 21:00 and 22:00. The speed of the vessel was 20 knots. The acoustic detection is the highest measured peak of Mission 1 illustrated in Figure 47 and 48.

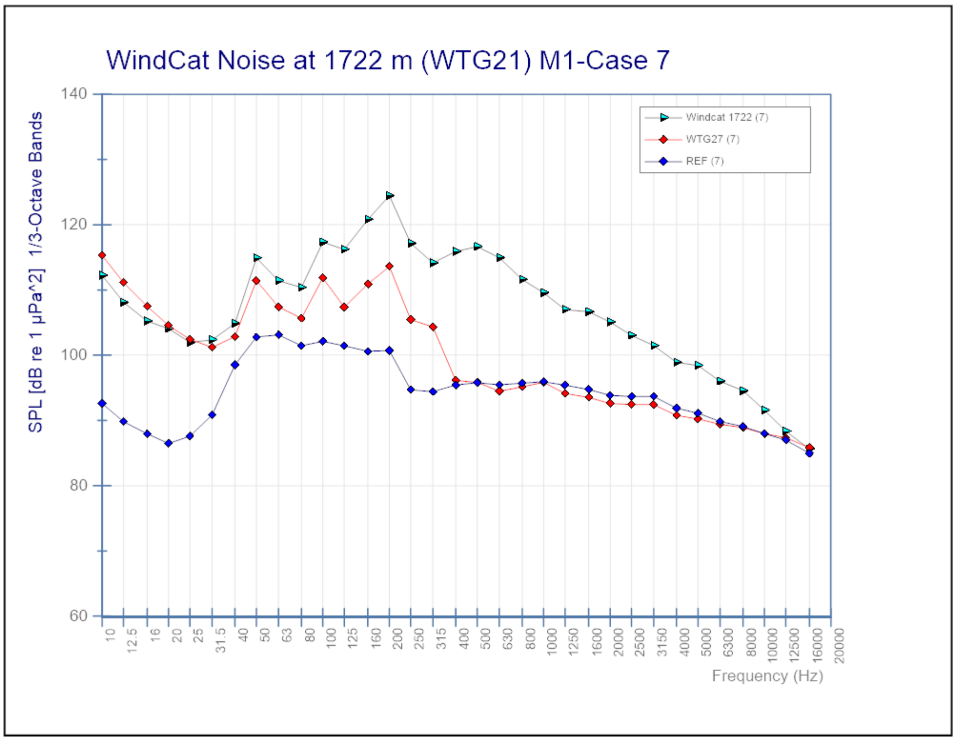


Figure 70 WindCat noise developed on landing at WTG21 (distance of 1722 m, Case 7) with the turbine noise spectrum 6 minutes after the event and the reference noise spectrum measured at 7400 m north of OWEZ. The turbine power was 2562 kW at a wind speed of 11.8 m.s^{-1} and a rotor speed of16 RPM.

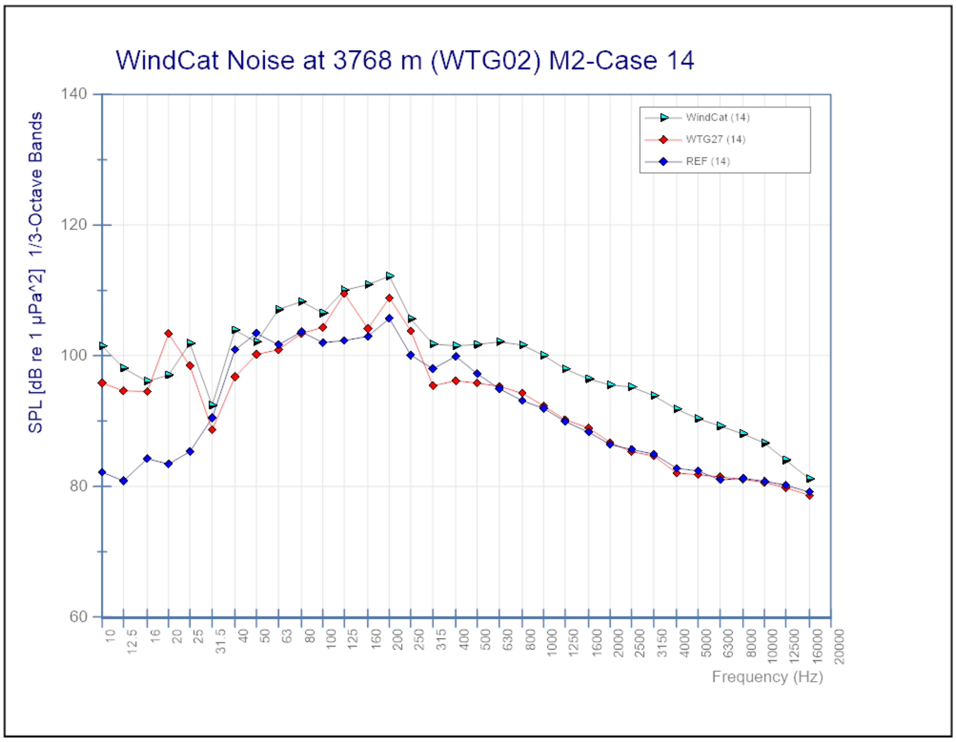


Figure 71 WindCat noise developed at the maximum measured distance of 3768 m, while landing at the terminal of WTG02 with the turbine noise spectrum 6 minutes before the arrival and the reference noise spectrum measured at 7400 m north of OWEZ. The turbine produced 753 kW at a wind speed of 7.4 m.s^{-1} and a rotor speed of 13.4 RPM.

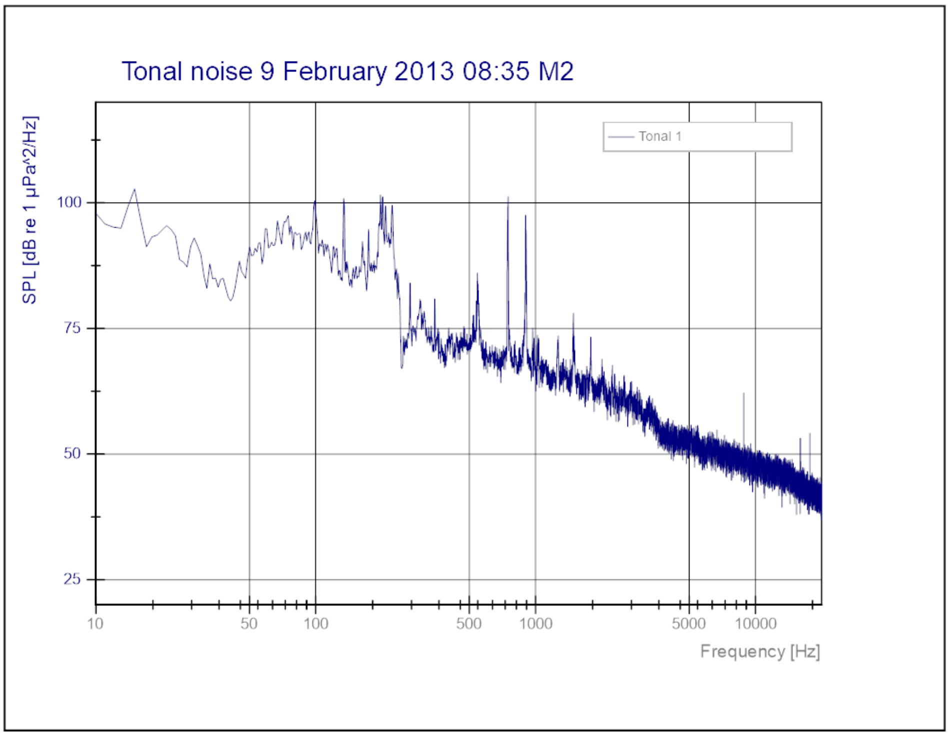


Figure 72 Narrow-band analysis of tonal type of noise on 9 February 2013 08:35:52 (FFT 10 s average length, 1 s block, 50 % overlap). The noise appeared as soon as the WTG propulsion was lowered after landing at WTG11 and is probably attributed to noise of main engines in idling/low power mode.

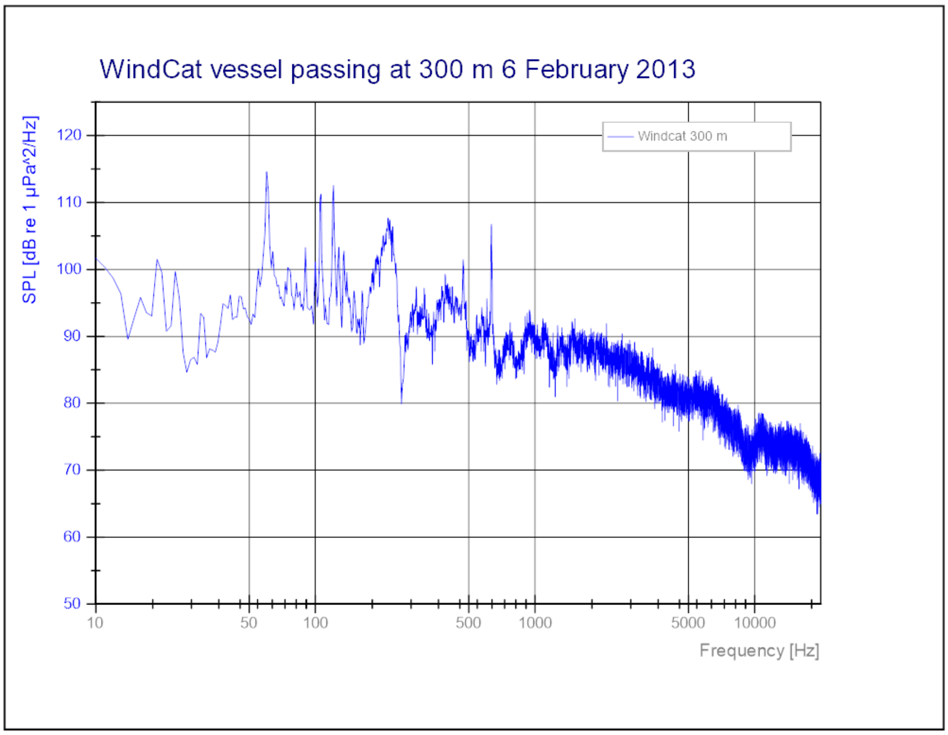


Figure 73 Narrow-band analysis of WindCat vessel noise on 9 February 2013 08:35:52 (FFT 10 s average length, 1 s block, 50 % overlap). The vessel passed the hydrophone at 150 m.

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

Lists of first period M1

Table 4 Turbine Noise as a function of Turbine Power.

Range (nr)	Date	Time	Power WTG27 (kW)	Wind Speed ($m.s^{-1}$)	Rotor Speed (RPM)	Rotor Blade Angle (°)	SPL 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 5 Turbine Noise Levels during the starting from idle mode on 17 January Mission1

Range (nr)	Date	Time	Power WTG27 (kW)	Wind Speed ($m.s^{-1}$)	Rotor Speed (RPM)	Rotor Blade Angle (°)	Yawing Activity (s/10 min)	SPL 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 6 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 9 WindCat Noise period M1 & M2

Range (nr)	Date	Time	Power WTG27 (kW)	Wind Speed ($m.s^{-1}$)	Rotor Speed (RPM)	Rotor Blade Angle (°)	SPL 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 7 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 8 Overview of shipping noise detections. The Case numbers are linked to the analysed cases of WindCat noise in Table 9.

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

Case (nr)	Date	Detection Intervals	OWEZ related Vessel (WindCats)			Other Ships
			Interval (hh:mm)	Distance (m)	WTG (nr)	Interval (hh:mm)
		16:43-17:36				00:53
		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

Case (nr)	Date	Detection Intervals	OWEZ related Vessel (WindCats)			Other Ships
			Interval (hh:mm)	Distance (m)	WTG (nr)	Interval (hh:mm)
		05:10-06:50				01:40
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 9 WindCat Noise noise and turbine condition while landing at the WTG terminal.

Case (nr)	Date	Detection Intervals	Distance (m)	WTG (nr)	SPL Pre/Post dB re 1 $\mu Pa^2/Hz$	SPL WindCat dB re 1 $\mu Pa^2/Hz$	Delta SPL 1/3 Octave bands dB re 1 μPa^2	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 10 Turbine Noise Levels 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

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

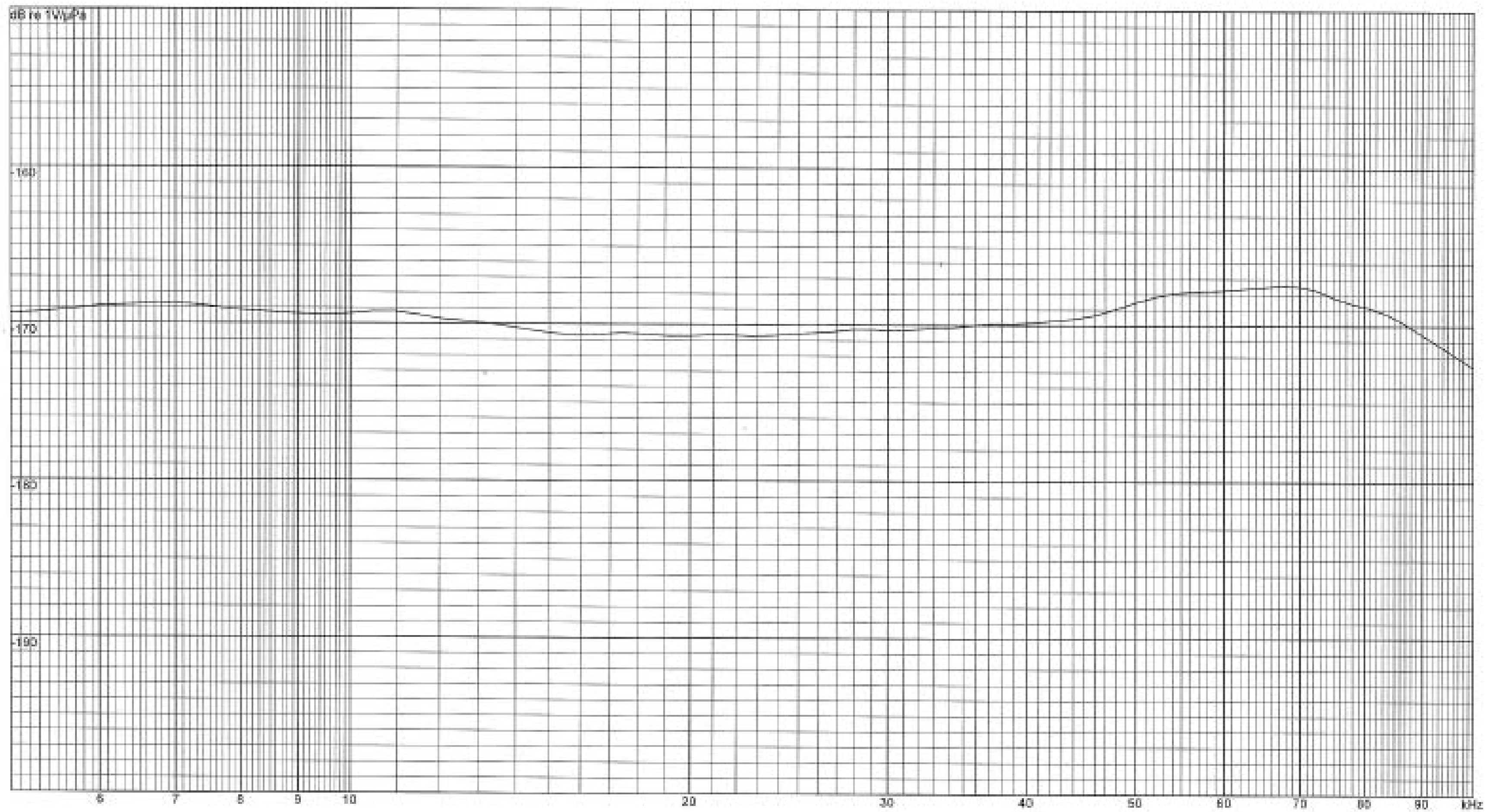
4.1. Visual inspection	Passed
4.2. Absolute Acoustical Sensitivity Level	Passed
4.3. Frequency Response Measured in Acoustic Coupler, FW A	Passed
4.4. Frequency Response Measured in Acoustic Coupler, FW C	Passed
4.5. Electrical Inherent Noise Level, FW A	Passed
4.6. Electrical Inherent Noise Level, FW 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.

HYDROPHONE SENSITIVITY

RESON

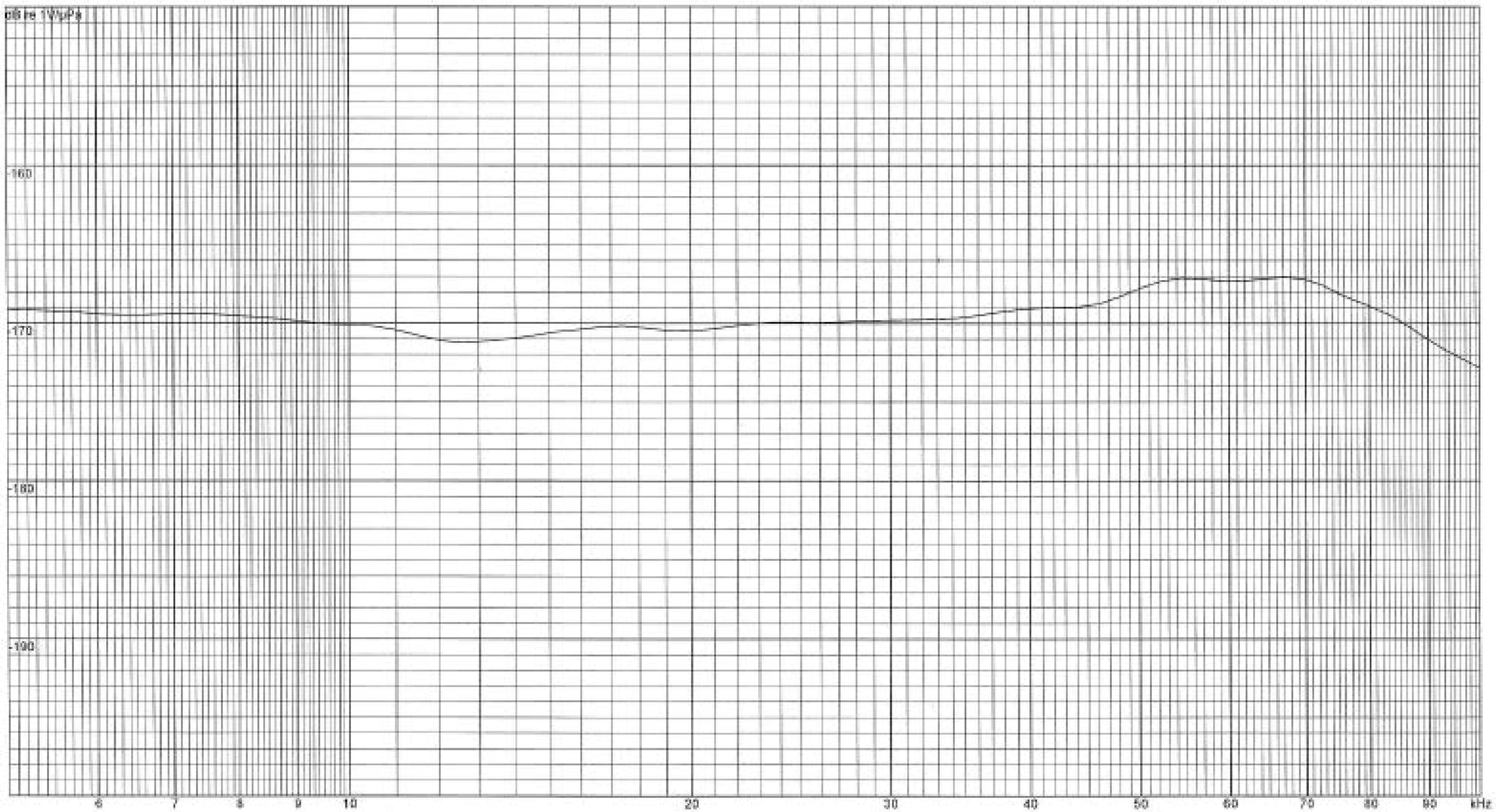
Under Test:	TC4032-1	Amplitude:	10.0 Vrms	Temperature:	21.60°C
S/N:	1009004	Pulse Width:	214.3 µs	Depth:	1.2 m
Reference:	TC4033	Rep Rate:	50.0 ms	Distance:	0.60 m
Date:	2009-09-16	Averages:	8	Tested by:	HHP 090916
Session, Run:	10526, 19				
Comment:	PHO @ 250Hz: -169.2dB.				



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.

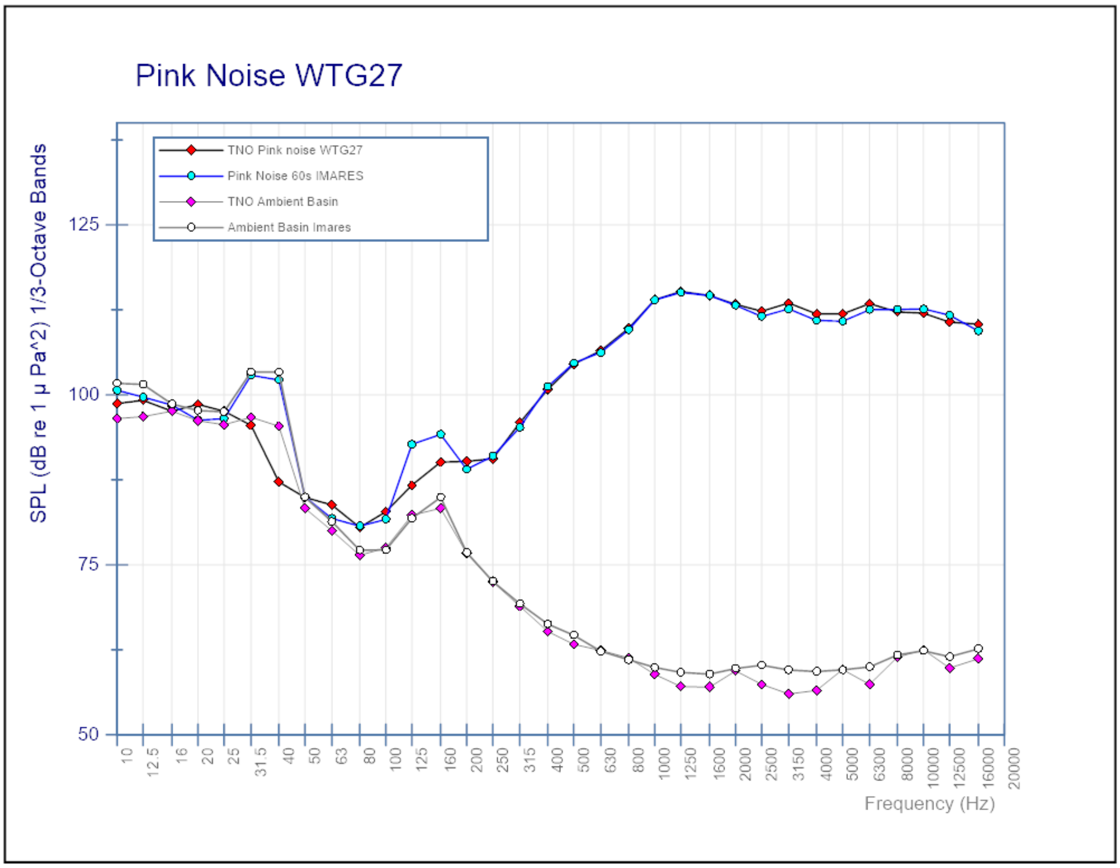


Figure 74 Hydrophone and conditioning hardware exposed to a pink noise type of signal and compared to a equivalent TNO reference hydrophone. The results are similar with some deviation in the LF range in the 100 to 160 Hz bands and are attributed to minor changes in the hydrophone positions in relation to the wavelength limitation in relation to the basin dimension.

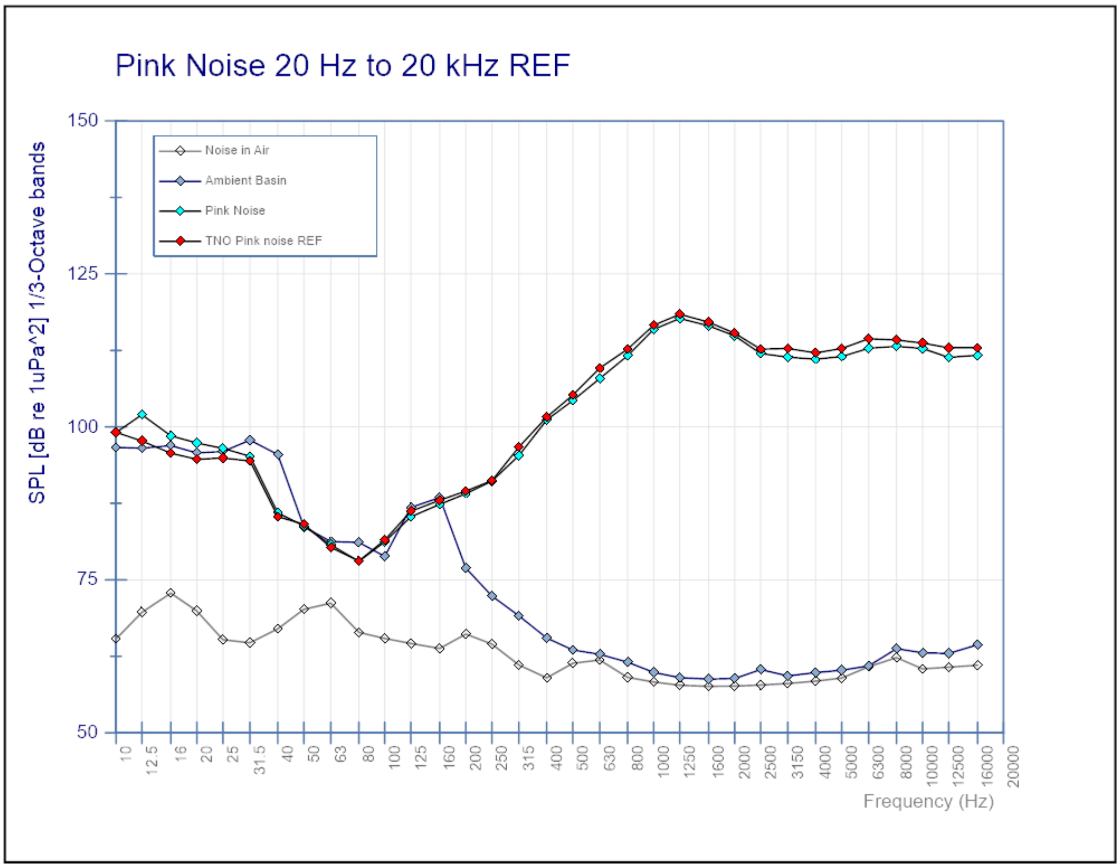


Figure 75 Hydrophone and conditioning hardware used in the refrence position exposed to a "pink noise" type of signal and compared to a equivalent TNO reference hydrophone. The results are similar with some deviation in the LF range in the 100 to 160 hz bands and are attributed to minor changes in the 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 11.

Table 11 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 76).

Figure 76 Received position of yawing noise 600 m from WTG09 and 10 applied on the records of file 9 to 12 (Table 12). 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 12, 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 windfarm. 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 windfarm 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 12).

The wind speed conditions during the measurements are illustrated in Figure 77 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.

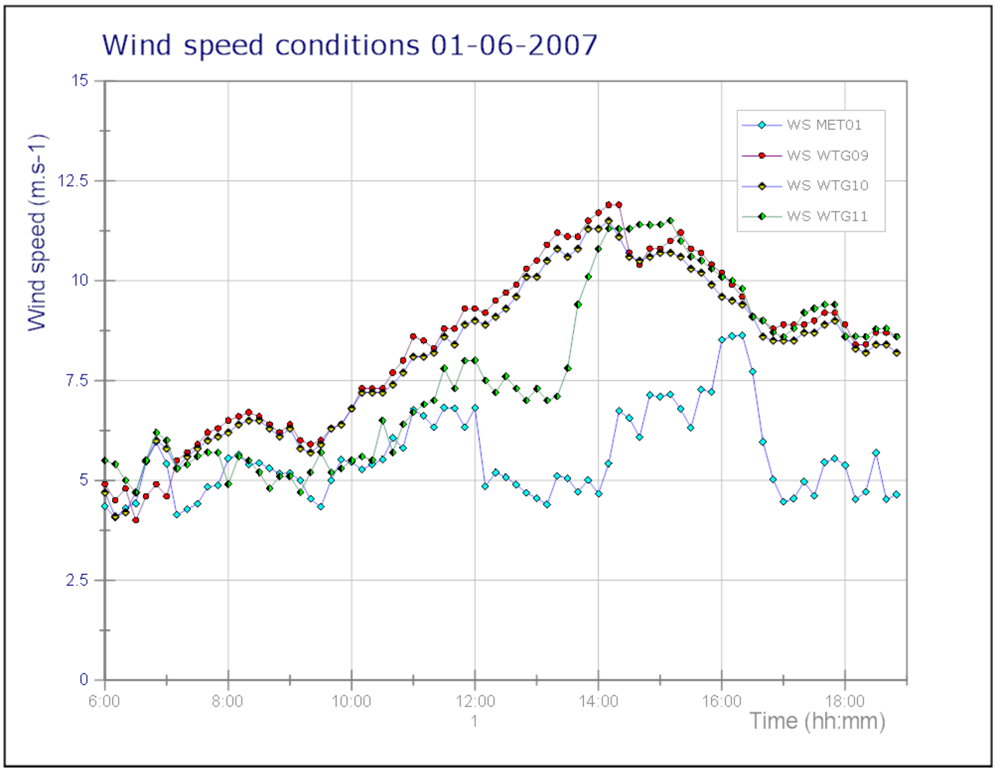


Figure 77 Wind speed conditions during the measurements taken from the OWEZ Meteo mast sensor "Met_01 South" and the wind speed sensors on the nacelles of WTG09, 10 and 11.

The wind condition and turbine power production data are listed in Table 12. 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 12 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 restart of WTG11 after maintenance is expressed in Figure 78, which shows the engine noise contribution during the yawing of 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.

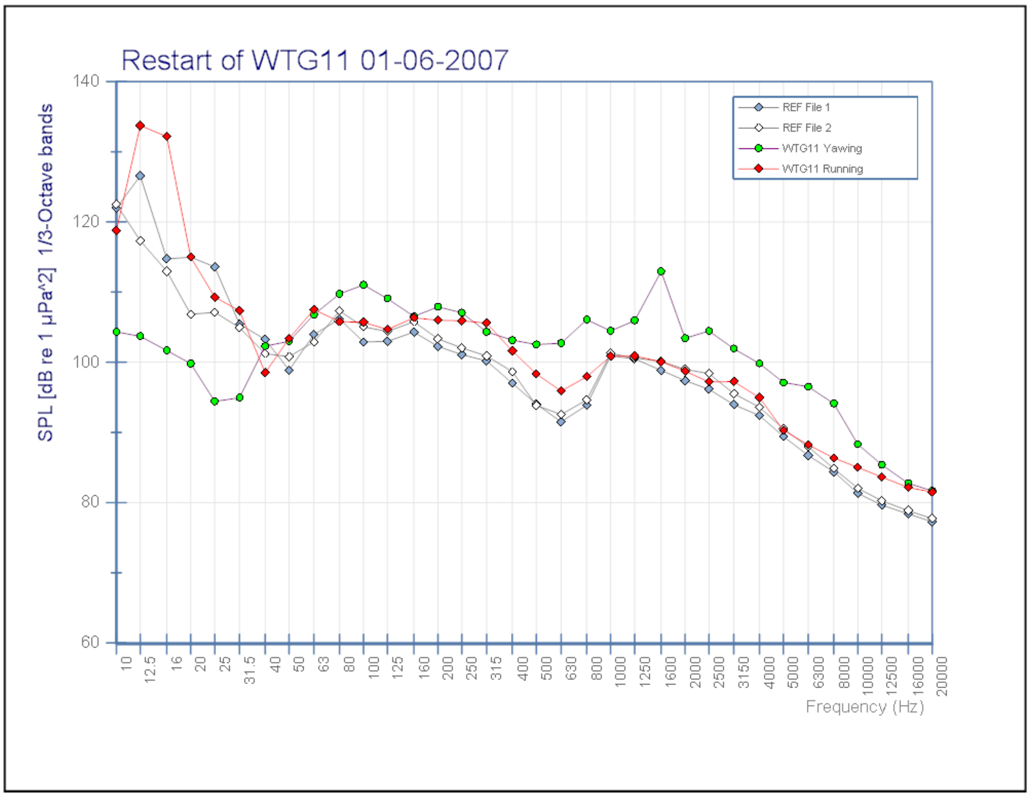


Figure 78 Restart of WTG11 with the contribution of engine noise peaking in the 1600 Third-Octave band.

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 79).

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.

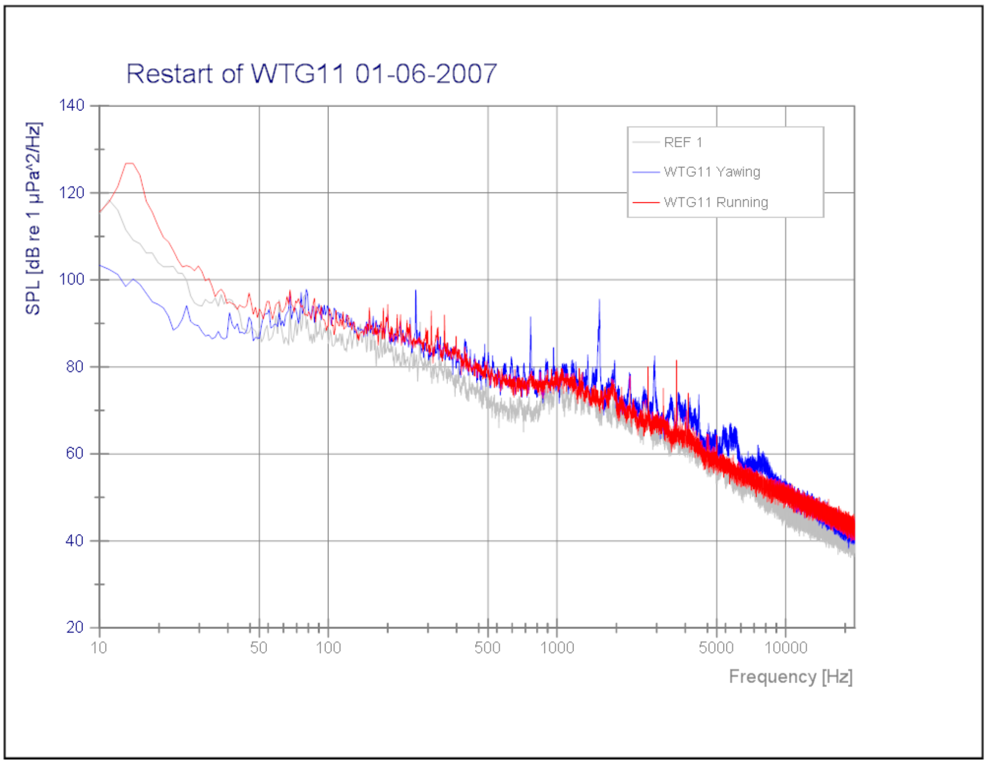


Figure 79 Narrow-band FFT-analysis of the yawing noise of WTG11 against the running mode shortly after completion of the operation showing some sharp peaks at 282, 766 and broader around 1500 Hz (FFT 20 s average length, 1 s block, 50 % overlap).

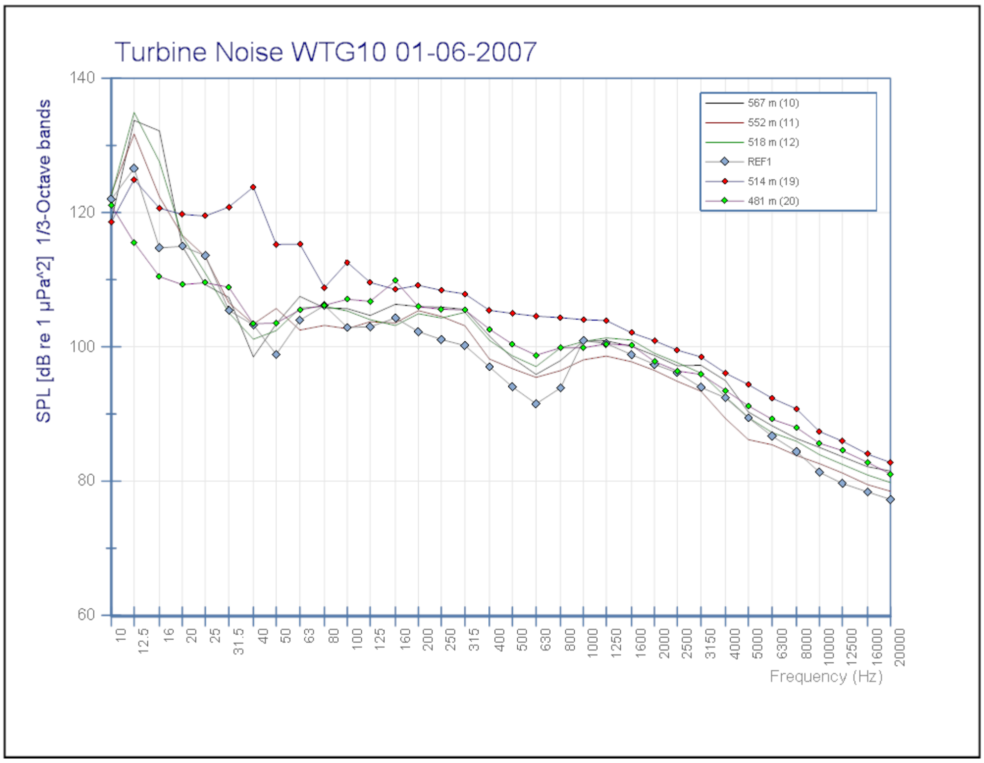


Figure 80 Noise filtered in Third-Octave bands measured in a symmetrical distance range of 480 to 567 m from WTG09 and 10. A minor contribution of turbine noise can be observed in the 100 Hz Third-Octave band received at 481 m.