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Measurement and interpretation of underwater noise during construction and operation of offshore windfarms in UK waters

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Executive Summary

Subacoustech Ltd has been contracted by The Crown Estate on behalf of the Collaborative Offshore Wind Research Into the Environment (COWRIE) to measure the underwater noise generated by offshore windfarms during construction and operation. The purpose of the programme of measurements is to provide information which will aid the estimation and minimisation of the impact of noise during the lifecycle (construction, operation and decommissioning) of windfarms.

Previous reports have established that pile driving during windfarm construction creates high levels of underwater noise. Injury of marine species could be caused by the pile driving noise at distances of the order of 100 metres, and behavioural effects at ranges of the order of 10 kilometres or more. To further document the noise levels created during pile driving, further measurements are presented herein, taken during pile driving on five windfarms, at North Hoyle, Scroby Sands, Kentish Flats, Barrow and Burbo Bank.

The measurements indicate that the Source Levels of these five pile driving operations varied between 243 and 257 dB re 1 Pa @ 1 metre, having an average value of 250 dB re 1 Pa @ 1 metre. The Transmission Losses were characterised by values of geometric loss factor N of 17 to 21, and absorption factor of 0.0003 to 0.0047 dB/m.

The measurements are analysed in the dB_{ht} metric, which weights noise according to the hearing sensitivity of marine species of animals, and thus indicates the likely loudness of the noise. The concept of noise dose, used to estimate the cumulative effect of noise on humans, may also be extended to marine mammals by this means. On this basis, a method which is relatively simple to calculate and apply is proposed for estimating areas around a pile driving operation within which the two key auditory effects of noise will occur. This method may be summarised as "Provided animals are free to flee the noise, those within the area bounded by the 90 dB_{ht} level contour will strongly avoid the noise. Animals within the area bounded by the 130 dB_{ht} level contour may suffer injury or permanent damage to hearing". Since the injury ranges indicated by the measurements do not exceed a few hundred metres, they indicate that observation by marine mammal observers and soft start procedures might be effective in reducing these effects of the noise.

Measurements are also presented of noise during the operation of the North Hoyle, Scroby Sands, Kentish Flats and Barrow offshore windfarms. In general, the level of noise created by operational windfarms was found to be very low and no evidence was found of noise levels that might have the capacity to cause marine animals to avoid the area. The environment of a windfarm was found to be on average about 2 dB noisier for fish, and no noisier for marine mammals, than the surrounding area. This is no more than variations which might be encountered by these animals during their normal course of activity.

1 Introduction

Concern has been expressed over the possible effects of underwater noise in degrading the underwater habitat. Underwater noise is created by many human activities, such as fisheries, oil and gas exploration and production, ship traffic and offshore construction. The underwater environment may be characterised as a medium in which light is poorly transmitted but through which sound propagates over long distances. Hence, marine animals may rely heavily on sound to communicate, to exploit and investigate the environment, to find prey and to avoid obstacles.

At the most extreme levels of exposure, underwater explosive blast may even cause death and lethal injury to marine animals. This is less likely at the lower levels of noise encountered during most other offshore construction activities, but even in the absence of physical effects there is a residual risk of the noise causing behaviour changes in marine mammals and fish.

Since the impacts caused by waterborne noise cannot yet be completely predicted or fully understood, Subacoustech Ltd has been contracted by The Crown Estate on behalf of the Collaborative Offshore Wind Research Into the Environment (COWRIE) to measure the underwater noise generated by offshore windfarms during construction and operation. The purposes of the programme of measurements are to evaluate the pre-existing background noise environment, to rate noise during operation of windfarms in terms of its potential for environmental effect, and to provide information which will aid the estimation and minimisation of the impact of noise during the lifecycle (construction, operation and decommissioning) of windfarms.

Two previous reports have been provided under this programme to COWRIE; the first, by Nedwell *et al*. (2003) dealt with an assessment of underwater noise arising from offshore wind turbines and its impact on marine life. The second, by Nedwell and Howell (2004), contained a review of offshore windfarm-related underwater noise sources. This present report incorporates a précis of the salient findings of these earlier reports where this augments the new findings presented here.

This report presents a further significant body of underwater noise measurements taken in the intervening period at windfarm sites in the UK. Measurements of noise during pile driving, and measurements of operational noise, have been taken. A detailed analysis of the measurements has been made which indicates the properties of the noise. An estimation of the possible behavioural and physical effects on a selection of the most common species of fish and marine mammals is also presented, using both conventional analysis and the dB_{ht} (*Species*) scale. The approach of using both unweighted noise assessment metrics and frequency weightings for representative species of marine animal is consistent with that proposed by other researchers (Madsen *et al*. 2006, for example).

2 Considerations for the assessment of underwater noise

2.1 Introduction

The purpose of this report is to document measurements of the noise created during the pile driving of windfarm foundations, and of the operational noise from windfarms.

A previous report (Nedwell *et al.* 2003) concluded that underwater noise may be generated during a number of stages in the lifetime of a windfarm:

1. during pre-construction - geophysical/seismic surveys to assess site efficacy and vessel traffic to and from the site;
2. construction – through the use of pile drivers, drilling and cable laying;
3. operation – over a 20-25 year period;
4. decommissioning – using mechanical cutting and explosives as well as shipping movements to and from the site.

The report concluded that, of all the windfarm related noise sources, the relative potential for environmental effect was as follows (greatest risk first):

1. Foundation decommissioning using explosives.
2. Piled foundation installation and windfarm related geophysical survey.
3. Drilling, rock laying, cable trenching, diver tools.
4. Vessel and machinery, wind turbine operation.

Because no decommissioning of a windfarm site is yet required, and other techniques such as water jet cutting are becoming available, no measurements of blast have been required or are currently anticipated, and hence this has not been addressed in this report.

Previous reports (Nedwell *et al.* 2003) have established that pile driving during windfarm construction creates high levels of underwater noise. Injury of marine species could be caused by the noise in the immediate vicinity of the pile driving, at distances of the order of 100 metres, and behavioural effects at ranges of the order of 10 kilometres or more. To further document the noise levels created during pile driving, further measurements are presented herein, taken during pile driving on four windfarms, at North Hoyle, Kentish Flats, Barrow and Burbo Bank.

Finally, measurements of the noise created during the operation of windfarms are presented. Because it was thought to be a relatively low level source of noise, and due to the limited number of operational windfarms, operational noise has not been addressed in previous reports. Measurements are presented of noise during the operation of the North Hoyle, Scroby Sands, Kentish Flats and Barrow windfarms.

The effects of noise on underwater animals may range from injury to behavioural effects such as avoidance; the measurements presented herein have consequently been interpreted using the best available methods, to indicate what effects the noise may have, and the range within which each effect may occur.

2.2 Interpretation of the effects of underwater sound

It is often not appreciated that a measurement of sound is of no use without a means of evaluating its significance. For an estimate to be made of whether an animal will be affected by noise, both a metric and a criterion are required. A metric is a system of measurement and analysis that facilitates the quantification of some particular characteristic of the noise. The criterion is a level of noise, expressed using this metric, where it is estimated that a given effect will occur.

It is common that the underwater sound pressure is measured, and statements such as "the peak pressure was 200 dB re. 1 µPa" made without being able to relate this to an effect on the environment. Indeed, pressure itself may not be the relevant quantity to measure.

Considering the effects of blast from an underwater explosion may help to clarify this point. The peak level of the blast may be used as a criterion for some types of physical injury, such as "rib imprint" chest wall injury. This works because the peak pressure is an indication of the broadband spectral level of the blast wave, and the injury results from a broadband mechanism. However, lung injury to divers is a low-frequency mechanism, since it involves large displacements of body tissue as the lung collapses under the pressure of the incident wave. The likelihood of lung injury is therefore likely to depend on the level of low-frequency energy rather than the peak pressure of the blast. It may be shown that the likelihood of injury in this case depends not on the peak pressure but on the impulse, or integral of pressure over time, of the blast wave (Parvin *et al.* 2007), since the impulse may be considered to be a measure of its low frequency energy. Quoting a level of sound in pressure may have no value whatsoever in determining its severity in terms of lung injury. Therefore the quality of the estimate of the possible effect(s) of the noise exposure depends on the availability of a suitable criterion. Furthermore, this criterion must be expressed in an appropriate metric, which, in this case, would be impulse rather than pressure.

Where the intention is to estimate the more subtle behavioural or audiological effects of noise, caused by "unbearable loudness", hearing ability has to be taken into account and simple metrics based on unweighted measures are inadequate. For instance, it has been determined that in humans a metric incorporating a frequency weighting that parallels the sensitivity of the human ear is required to accurately assess the behavioural effects of noise. The most widely used metric in this case is the dB(A), which incorporates a frequency weighting (the A-weighting), approximating the human hearing ability (see Kryter 1985, for example). At lower levels noise may also interfere with the communication of marine animals. This effect has not been specifically addressed within this report, but the range at which noise falls to background level is presented, which may be used as an upper limit of the possible extent of masking.

The means by which sound is recorded, analysed and interpreted, and the criteria that are used as limits, therefore depend on the effect that is being considered. Effects may be considered as splitting into non-auditory effects, such as the body injuries caused by very high sound pressures typical of blast, and auditory effects, such as hearing impairment and avoidance reaction caused by sound being perceived as unbearably loud.

2.3 Non-auditory effects

The most important non-auditory effects of sound comprise lethality and physical injury. Impulsive (short duration) sound waves at very high levels can cause death or severe injury in human divers, marine mammals and fish (Parvin *et al.* 2007).

The level of an underwater impulsive pressure wave that will cause lethal and physical injury is generally prescribed in terms of both the peak pressure level and impulse. The peak pressure of a blast wave is the maximum level of overpressure, that is, the pressure above the local ambient pressure caused by the shock wave. Impulse is a more sophisticated measure of blast, which may be thought of as the average pressure of the wave multiplied by its duration (Barrett 1996). The importance of impulse is that, in many cases, a wave acting for a given time will have the same effect as one of twice the pressure acting for half the time. The impulse of both these waves would be the same.

The impulse, I, is formally defined as the integral of pressure over time and is generally considered to be given by

$$I = \int_0^\infty P(t)\,\delta t$$

where I is the impulse in Pascal-seconds (Pa.s), P(t) is the acoustic pressure in Pa of the blast wave at time t.

However, this definition is problematic as it may readily be shown that it tends to zero as t increases. Inspection of the method by which impulse has historically been measured indicates that a better measure is probably given by

$$I_{max} = Max\left[\int_0^t P(t)\,\delta t\right]$$

where *Max* indicates the maximum value of the integral term in brackets as t increases. Generally, the maximum value is given by the integral of the first peak of the blast and for many applications this simplification may be adequate.

Criteria for injury and death are generally based on both the peak pressure and impulse of the blast wave, and have been developed using either human volunteer subjects, or submerged terrestrial animals. Due to current ethical concerns, much of the best material dates back many years, and most of the data has been extensively reinterpreted and republished. Authors presenting original data include Cameron *et al.* (1943), Christian and Gaspin (1973) Wright (1951), Bennett (1955), Bebb and Wright (1954), Fletcher *et al.* (1976), Yelverton *et al.* (1976) and Rawlins (1974 and 1987).

Christian and Gaspin suggest 14 Pa.s as a safe level below which there has not been a recorded injury. In contrast, Rawlins (1987) reports that received impulse levels of 700 Pa.s are lethal where they are combined with high peak pressures.

In the context of windfarm construction, only pile driving has been identified as having a high enough noise level to be capable of causing injury. There has been at least one documented case of pile driving noise causing fish kill (Abbott and Bing-Sawyer 2002).

2.3.1 Criteria for lethal and physical injury

The criteria used for injurious and lethal levels of noise can be applied to the impulsive noise from pile strikes. However, these criteria should be applied with caution. Blast waves are of short duration, and are characterised by a simple and roughly exponential wave. As a consequence the spectrum of the blast tends to be broad and flat, with sound energy spread equally over all frequencies. However, the impulse from pile driving is more complex, and resonances in the pile, seabed, and associated machinery can cause peaks in the spectrum.

The injury mechanisms of underwater animals may also be frequency dependent. For instance, in human divers exposed to underwater sound, there is a lung resonance at a frequency of about 25 Hz (Parvin 1998). The possibility therefore arises of resonant peaks in the frequency spectrum coupling to the frequencies of particular injury mechanisms.

However, at the current state of knowledge, it is not possible to quantify these effects. Until better information is made available, it is suggested that the criteria for blast are cautiously applied to pile driving.

A recent review of the above work for the UK Government Department of Business, Enterprise and Regulatory Reform (Parvin *et al.* 2007) determined that:

- death, or injuries of sufficient severity that may lead to death in a short period of time, occur where the incident peak pressure sound level typically exceeds 240 dB re. 1µPa, and the impulse 700 Pa.s;

- physical injury to organs such as the lungs, liver, intestines, and other soft tissues surrounding gas-containing structures of the body may occur where the incident peak pressure sound level exceeds 220 dB re. 1µPa, and the impulse 14 Pa.s

2.4 Auditory effects of underwater sound

2.4.1 Hearing impairment

At high enough sound levels, (generally taken to be in excess of 180 dB re. 1µPa) and particularly where there are repeated high level exposures from activities such as impact pile driving, seismic operations, or for continuous wave sound such as sonar, the underwater sound has the potential to cause hearing impairment in marine species. This can take the form of a temporary loss in hearing sensitivity, known as a Temporary Threshold Shift (TTS), or a permanent loss of hearing sensitivity, known as a Permanent Threshold Shift (PTS). For transient noise such as pile driving this may occur where marine mammals are exposed to the underwater noise from a number of repeated pile strikes.

Some information is available concerning hearing damage in fish, including TTS measurements on goldfish (Cox *et al.* 1986, 1987), cod (Enger 1981), and Oscar fish (Hastings *et al.* 1986).

Both Schlundt *et al.* (2000) and Nachtigall *et al.* (2004) noted temporary threshold shifts in bottlenose dolphins exposed to high level sound. Kastak *et al.* (1999) noted the onset of TTS in harbour seals, sea lions and elephant seals exposed to octave band noise.

2.4.2 Cumulative effects of noise exposure; the Noise Dose

A cumulative effect of exposure to underwater noise by marine animals may be damage to their hearing. In humans, exposure to noise at levels at and above 90 dB(A) is likely to cause damage to a proportion of the exposed population with continued exposure. Very high levels may cause damage after relatively short periods, even when the noise is intermittent. Thus, hearing loss occurs in people who have had a small number of high level exposures, such as are caused by gunfire, as well as in people who are exposed to noise of lower levels but throughout a working day, such as those working in industrial sites using noisy machinery. There is consequently a trade off between the length of exposure and the level of the sound. Noise exposure can cause nerve deafness due to the damage or degeneration of hair cells in the organ of Corti in the inner ear. The damage is permanent; once degeneration has occurred it does not heal and cannot be remedied.

The criterion that has been developed to determine the likelihood of auditory injury is based on the concept of Noise Dose. The limiting Noise Dose, at and above which hearing damage will increasingly occur, is that equivalent to exposure to noise for 8 hours at a level of 90 dB(A). Trading of the time of exposure against the level is allowed. If the time is halved, an increase in level of 3 dB is allowed; for instance, a level of 93 dB for 4 hours or 96 dB for 2 hours is allowed. An upper limit of 130 dB is imposed since above this immediate and irreversible hearing damage may occur. The higher the Noise Dose above this limit the more rapid will be the damage. The limit is equivalent to a Noise Dose of about 29 Pa^2.sec.

The data from Schlundt *et al.* (2000) indicates that this effect translates to marine mammal exposure to underwater sound. In the study, short duration sound exposures (one second continuous wave) at levels of approximately 130 dB above hearing threshold caused a small TTS hearing injury in the bottlenose dolphin. The recent review by Madsen *et al.* (2006) highlighted that experiments with marine mammals demonstrate a near inverse relationship between sound exposure level and duration of exposure (i.e. the same equal energy Noise Dose relationship). The recent report by Thomsen *et al.* (2006) on offshore windfarm noise reviewed much of the information on TTS in marine mammals and concluded that, for short duration signals, pressure levels had to be 90 to 120 dB above the hearing threshold to induce a TTS.

As a consequence of the close analogy between the dB(A) and the dB_{ht}, an equivalent criterion for marine animals may be adopted, that an allowable species Noise Dose is that equivalent to 90 dB_{ht} (*Species*) for 8 hours, subject to an upper limit of 130 dB_{ht} not being exceeded. A similar weighting is allowed for shorter time exposures. In practice, the level of sound that an animal is exposed to may vary considerably, but if the level is known or can be estimated the equivalent Noise Dose may be calculated. The level may be termed the continuous equivalent level or dB_{ht} L_{eq}.

The level of sound and the allowable duration of exposure are tabulated in Table 2.1. The specific case of 5 hours, the typical time to drive a single pile during offshore windfarm construction, has been included.

Exposure Level (dB_{ht})	Exposure duration
90	8 hours
92	5 hours
99	1 hour
110	Approx 5 minutes
120	Approx 30 seconds
130	Approx 3 seconds

Table 2.1. Comparison of noise exposure level and duration for the same cumulative 90 $L_{EP,D}$ Noise Dose.

2.4.3 Static vs. moving animal models

Simple schemes have been used to provide safety ranges that are based on the concept of a static animal model. Such models assume that the animal makes no attempt to move away from the source of the noise. Where animals are constrained within a test environment, as is the case for the controlled marine mammal noise exposure tests that have been conducted (Schlundt *et al.* 2000, for example), animals exposed to these Noise Dose levels have been shown to develop a TTS that is equivalent to that which would be expected in humans.

It is of course possible that an unconstrained animal would elect to stay in the vicinity of a noise source such as piling. However, under open water conditions such an assumption is probably naïve. It is far more reasonable to assume that, at the high perceived sound levels associated with an exposure at 90 dB_{ht} (*Species*) or above, animals will move rapidly out of the vicinity of the sound, although it is possible that its course will be indirect. The behaviour may be considered to be an evolutionary response which prevents hearing damage to the animal. The observational data from Tougard *et al.* (2003) and Henriksen *et al.* (2003), which noted a decrease in vocalisation in the vicinity of piling, may indicate that this is the case, although it should be noted that the noise may also have had the effect of inhibiting vocalisations.

Figure 2.1 illustrates the cumulative Noise Dose that an animal would receive while fleeing from a noise source. The Source Level of the noise has been chosen to be 139 dB_{ht}, and a Transmission Loss of 20 log(R), where R is the range, has been assumed, such that at 1 km the animal would receive an allowable Noise Dose in one hour. The model assumes that the animal is at an initial range of 100 m from the source. Results are presented for animals fleeing where the radial component of their velocity (i.e. the rate at which they increase the distance between themselves and the source) is 1, 1.5 and 2 metres/sec. It may be seen that initially there is a rapid contribution to the Noise Dose, but as the animal flees the vicinity of the noise source the rate of accumulation of Noise Dose rapidly decreases. The total dose at the end of the hour is a very small fraction of the dose that would result if the animal were stationary. In other words, an animal that flees from noise provides a very effective mitigation of the auditory effect of the noise when compared with a stationary animal.

This conclusion is important because at the levels of sound and transmission losses measured and presented in this report, an animal that flees from the noise is unlikely to receive a Noise Dose causing auditory injury, unless it is within the immediate vicinity of the impact pile driving operation and receives auditory damage due to an excessive Noise Dose during the first few strikes. The measures that are required to prevent traumatic injury

The distinction between fleeing and static animal models is important, as the conclusions drawn using them are very different. A static animal model indicates that, at the levels of sound presented in this report for typical pile driving operations, cumulative auditory injury might occur to ranges of kilometres from the piling, at which distance the mitigation options are limited and expensive. In comparison, the fleeing animal model indicates that provided marine animals are not in the immediate vicinity of the pile driving prior to its inception, the animal will not accumulate enough Noise Dose to cause auditory injury. Typical critical ranges in the latter case are of the order of one or two hundred metres, and hence a wider range of detection and mitigation measures are available to prevent an animal receiving such a hazardous Noise Dose.

The term "critical distance" is used in this report to denote the distance from a source of noise within which an animal would have to be to receive a hazardous Noise Dose while fleeing from the noise.

2.4.4 Behavioural response

At greater range the underwater sound wave may not directly injure animals, but has the potential to cause behavioural disturbance. The dB_{ht} (*Species*) metric (Nedwell *et al.* 2005b and 2007) is probably the only metric which offers a means to quantify the risk of behavioural effect across a wide range of species having varying hearing ability. It gives a species-specific noise level referenced to an animal's hearing ability, and therefore a measure of the potential of the noise to cause an effect. The measure that is obtained represents the "loudness" of the sound for that animal. This is very important because even apparently loud underwater noise may have no effect on an animal if it is at frequencies outside the animal's hearing range. Nedwell *et al.* (2007) provides details of the experimental validation of the method, using fish as experimental subjects. A detailed description of the method of implementing the dB_{ht} (*Species*) by means of a FIR filter may be found in Howell and Nedwell (2004).

The dB_{ht} (*Species*) metric should not be regarded as a perfect scale, but as a more sophisticated approach to estimating the effects of noise than that provided by unweighted noise measurements and criteria, which imply that all species affected have a uniform sensitivity to sound over an unlimited hearing frequency range. In common with the dB(A) used for humans, it is a probabilistic model which estimates the probability of an individual reacting to a noise. Thus, it should also be noted that while the experimental work conducted to date indicates that while 90 dB_{ht} (*Species*) is a level above which virtually all individuals of a species will react to the noise, as the sound falls below this level a decreasing proportion will still react. Within this report, Thus, a distance from a noise source at which avoidance is estimated on this basis to occur should therefore be viewed as enclosing the area around the source within which the majority of individuals of a species will react; outside this distance a reaction will still occur, but in a decreasing proportion of individuals. It is possible that as the noise level falls habituation will limit the effect of the noise, but there is currently no information available to confirm this.

At its current state of development, the main uncertainties in estimating the probability of avoidance using the dB_{ht} (*Species*) metric lie in the limited range and quality of audiograms available to base the analysis on. A limited range of audiograms have been selected as the basis of the analysis contained in this report.

In principle, since the dB_{ht} (*Species*) metric offers a means of estimating the probability of individuals reacting, it might be possible to combine information on population density with an estimate of the proportion reacting *versus* range to achieve an estimate of the total numbers of a species affected, but this analysis is beyond the scope of this report.

There is a very limited range of other criteria currently in use for predicting and controlling auditory injury and behavioural disturbance caused by noise. Those that are used are generally based on unweighted measures of sound, such as peak or RMS pressure. Several authors are currently investigating the use of a weighted metric system similar to the dB_{ht} used in this study. Some of the results have been published in peer reviewed format at a time where this report was already completed to a great extent (Southall *et al*. 2007). It was therefore impossible to include these recent results here.

2.4.5 Audiograms

A brief description of the measurement of the hearing of underwater animals is relevant as it is required for one of the main methods of analysis of behavioural response used herein, the dB_{ht}. The quality of the estimate of behavioural effect will depend in part on the quality of the audiogram. Many of those published are suspect; where several audiograms are published by different authors it is rare that they agree, and the background noise level, which may have the effect of masking the hearing, is rarely quoted. The audiograms used in the analysis presented herein are believed to be the best that are available for relevant species.

An audiogram of an animal shows, as a function of frequency, the lowest level of sound that the animal can perceive. There are two principal methods for establishing audiograms, viz. behavioural methods and the Acoustic Brainstem Response, or ABR, method. In both methods sound at a single frequency and a known level is played by underwater projectors to the subject. In the behavioural method the subject is trained to respond in a particular way when it hears the sound being played to it. In the ABR method the electrical impulse in the auditory nerves that results from the sound being heard is measured, using cutaneous electrodes externally attached to the animal. For both techniques the sound is gradually lowered in level, until there is no longer a response by the subject; the sound level at which this occurs is taken as the subject's hearing threshold at that frequency.

Figure 2.2 shows the audiograms for a number of species of fish. In the analyses carried out for the results presented in this report the audiograms of the bass, cod, dab and herring have been used, and it will be seen that their most sensitive frequency ranges are around 60 Hz to 1 kHz. The herring is considered a hearing specialist, having high sensitivity, and the bass and cod are considered hearing generalists, the former having lower sensitivity and the latter higher sensitivity. A species of significance in many shallow water regions is the sole (*Solea solea)*. However, there is currently no audiogram for it, so another flatfish, the dab (*Limanda limanda*), a hearing generalist with poor hearing, has been used as a surrogate. It should be noted, however, that the assumption that similar species have comparable hearing sensitivity is not always correct.

Figure 2.3 shows the audiograms for a number of marine mammals. These animals are able to sense low frequency sound, but are most sensitive to underwater sound in the frequency ranges from 20 kHz to 200 kHz. Over this frequency range the audiogram data indicate that marine mammals are able to hear sound at levels down to approximately 40 dB re. 1   Pa.

Audiograms for a number of seal species are presented in Figure 2.4, and these indicate that seals are able to hear underwater sound over the frequency range from 100 Hz to approximately 100 kHz, with peak underwater hearing sensitivity for species of seal occurring over the mid-frequency range from approximately 1 kHz to 40 kHz.

The dB_{ht} analyses undertaken in this study are based on the auditory sensitivity data presented in the audiograms presented in Figures 2-2, 2-3 and 2-4.

Generally, the audiograms indicate that fish are sensitive to low frequency sound below 1 kHz, and that marine mammals are very sensitive to sound of frequencies above 1 kHz. Currently there are no accurate audiogram data available for the larger (mysticete) marine mammal species such as the blue whale, humpback whale and minke whale. Many of these species are known to use low frequency vocalisations for communication and hence are also likely to be sensitive to the low frequency components of underwater sound.

2.5 Figures

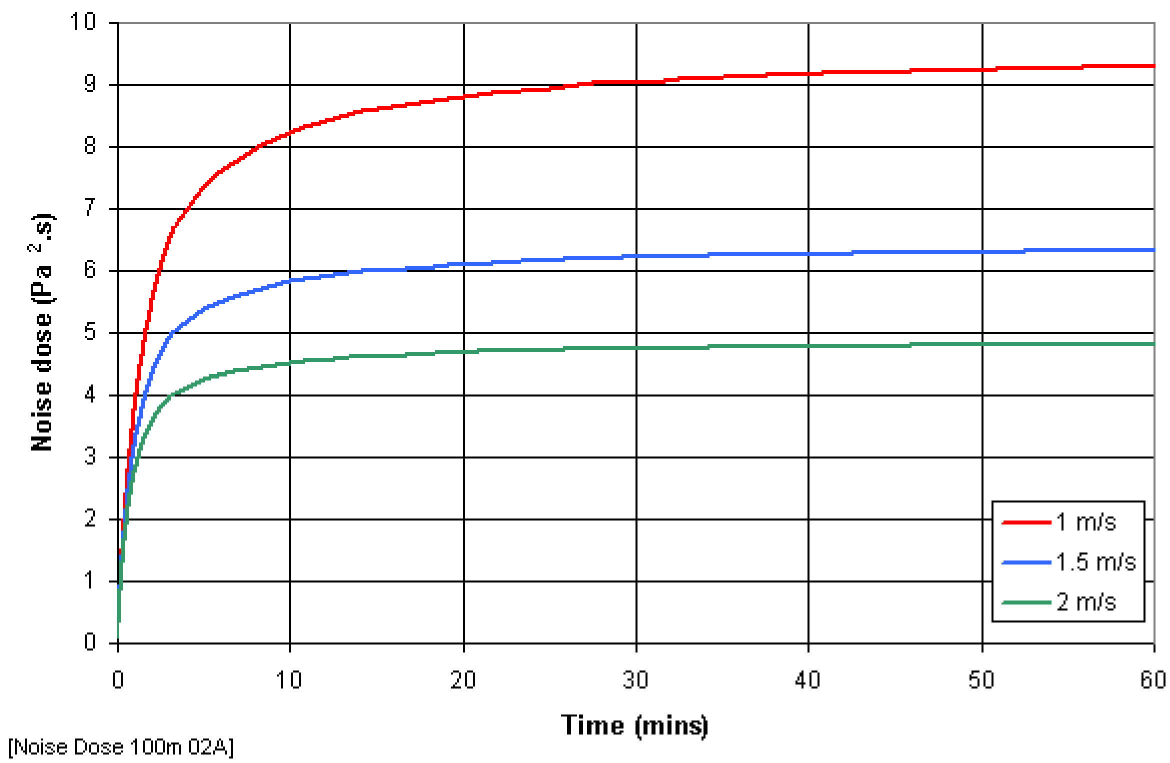

Figure 2.1. Noise dose received by an animal fleeing at various rates from an initial distance of 100 m from the noise source.

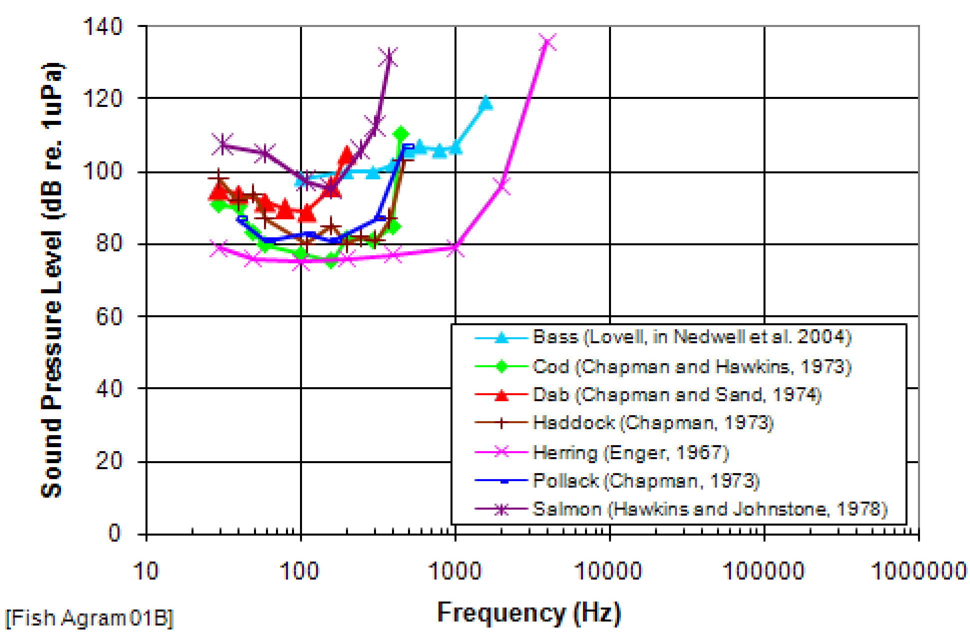

Figure 2.2 Hearing threshold data for species of fish.

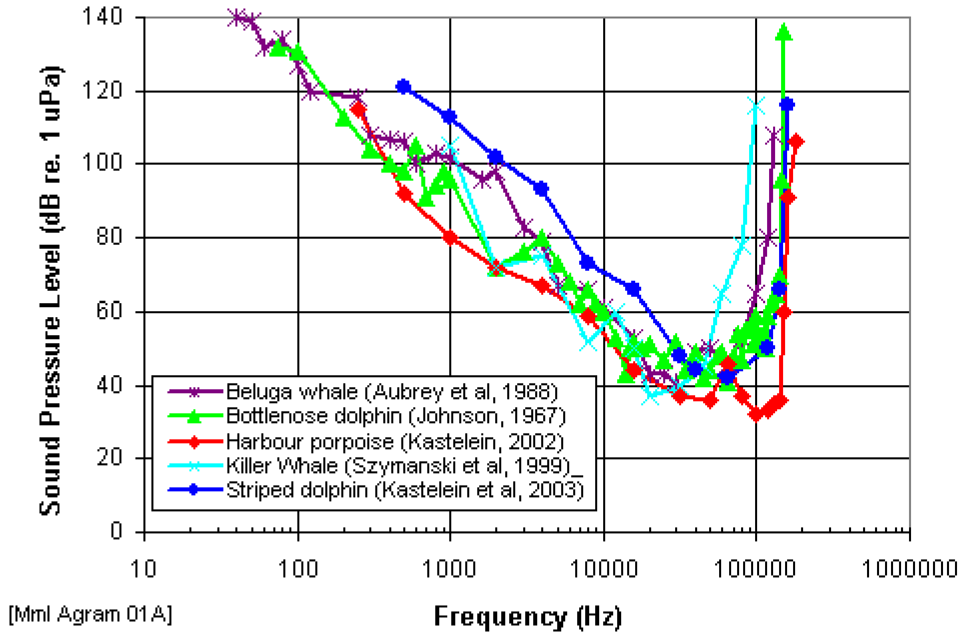

Figure 2.3 Hearing threshold data for species of marine mammal.

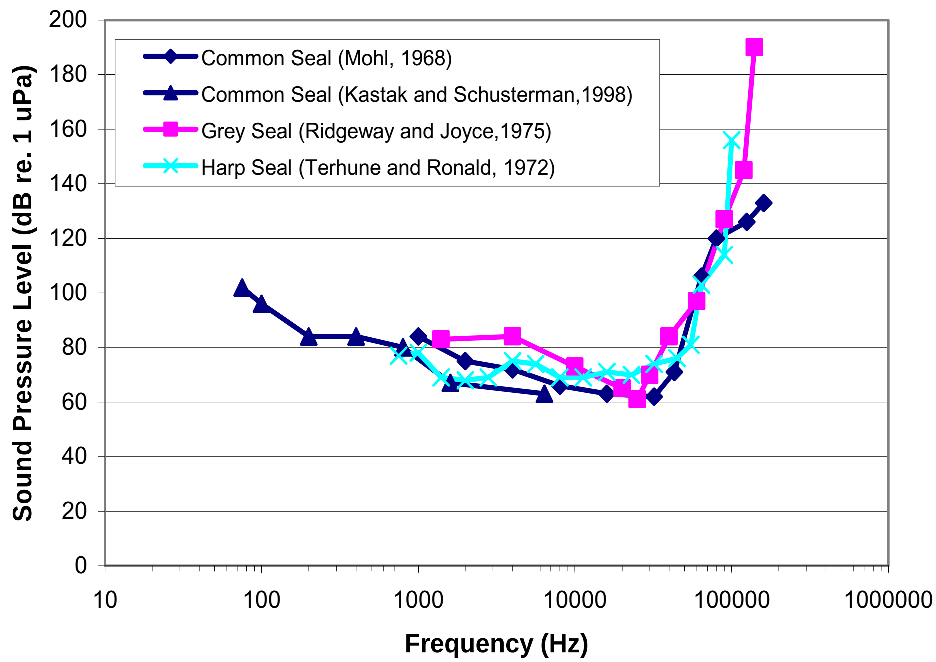

Figure 2.4. Hearing threshold data for species of seal.

3 Instrumentation and methodology for measurement of noise of offshore windfarms

Most of the measurements of background noise or piling presented in the literature are in environmental terms narrowband, in that they terminate at a frequency of 10 kHz or so. This probably arises in the main from their origin in research for military applications such as the design of sonar systems. However, where the interest lies in estimating the effects of noise on marine animals with hearing at frequencies that may exceed 100 kHz, such measurements are completely inadequate.

Measurements taken over a limited bandwidth may also not characterise the noise properly, with broadband measurements yielding different results. For example, a measurement taken over a frequency range of say 10 Hz to 10 kHz has a bandwidth of approximately 10 kHz. However, measurements made over the broadband range from 10 Hz to 120 kHz have an additional bandwidth of about 110 kHz, that is, an additional bandwidth that exceeds it by a factor of over 10. If we consider integrating a frequency spectrum to obtain the overall sound pressure level, it is of course obvious that even where the high frequency spectral level is lower, frequencies in this upper band may contribute more energy than those in the lower band. Hence, overall levels, for instance of background noise, may appear lower where the frequency range of the recording is limited.

For this programme of work a standard was adopted where measurements covered the frequency range of 1 Hz to over 120 kHz (data always oversampled at 350 kHz). This spans the entire frequency range over which fish and marine mammals can hear. Recording over this range is not trivial, both in terms of sample rate required and hence the quantity of data acquired, and the dynamic range that is required to adequately span a spectral dynamic range and temporal dynamic range that together may exceed 150 dB.

Sound measurements were taken using Brüel & Kjær hydrophones. For the measurements close to the pile being driven a Type 8105 hydrophone was used, while for the measurements at greater distances, and for measurements at operational windfarms, a Type 8106 hydrophone was used. The latter type has a higher sensitivity than the former, and could overload if the sound level is high, as it is in the close vicinity to a pile being driven. The calibrations of the hydrophones are traceable to the Danish Primary Laboratory of Acoustics (DPLA) and the American National Institute of Standards and Technology (NIST) International calibration standards. Copies of the calibration charts supplied with the hydrophones are given in Appendix B.

The calibrations of the hydrophones were also tested with a Brüel & Kjær Type 4223 pistonphone calibrator with WA0658 coupler prior to use. The calibrator operates at a nominal frequency of 250 Hz and was calibrated and traceable to International Standards.

Brüel & Kjær claim a flat frequency range of the 8106 hydrophone of 7 Hz to 80 kHz. However, a particular benefit of the well specified frequency calibration is that an inverse filter could be used to flatten the response of the hydrophone as required. Brüel & Kjær suggest that the low frequency response can be extended to 0.25 Hz by this method. Despite the low and high frequency roll off, the 8106 hydrophone is still more sensitive than most other hydrophones even at the extremes of its frequency range. The dynamic range was also found to be in excess of 90 dB, making it one of the few hydrophones that is suitable for the measurement of noise with a highly sloped spectrum, as is the case for shallow water background noise.

Where required, the time history was spectrally pre-emphasised prior to digitisation, subsequently de-emphasising the data in the digital domain to recover the signal in both amplitude and phase, before further processing. This provided an effective dynamic range in excess of 100 dB, ensuring that the relatively low level of high frequency components could be well sampled despite the dominance of low frequency components. This is critically important where measurements are to be related to potential effects on marine mammals that hear at very high frequency. Post measurement inspection of the spectrum indicated whether the use of the hydrophone had introduced any limitations into the measurement.

The Type 8106 hydrophone was connected to a Subacoustech Type 02 Power Supply/Precision Amplifier, the output of which was connected to a National Instruments Type 6062E A-to-D converter card. Figure 3.1 is a block diagram of the instrumentation chain. The Type 8105 hydrophone was connected to a Brüel & Kjær Type 2635 charge amplifier for conditioning of the signal before it was applied to the National Instruments DAQCard.

The hydrophone being used was hung from an anti-heave buoy, usually at depths between 5 and 10 m, but also at lesser depths if the water depth was not sufficiently great to use these standard depths. The hydrophone was weighted at its lower end with a small diver weight attached to its protective grid to keep it close to vertical. In use the hydrophone and buoy were deployed over the side of the vessel being used such that it tended to drift away from the vessel. The vessel's engines, depth sounder, and other equipment which might have contaminated the sound signal, were all shut off just prior to the hydrophone being deployed, and the vessel drifted freely. Additional small pellet buoys were attached at intervals to the hydrophone lead as it was fed out to support the lead and keep it at the surface. After a suitable length of cable had been fed out (up to 100 m) the hydrophone was pulled back to the side of the vessel and either retrieved back on board or allowed to drift away again as another set of measurements was taken.

The vessel’s position was obtained from a Garmin e-Trex GPS receiver. In the early part of the work the receiver’s reading was noted manually on the experiment logsheet, but later its output was fed directly to a USB connection on the computer and acquired along with the hydrophone signal.

At intervals during data acquisition wind speed measurements were taken using a small hand-held anemometer and noted.

Also, usually at the start and end of a series of acquisitions, measurements were taken of sea temperature and water depth using a Valeport conductivity, temperature and depth (CTD) meter. The signals from this instrument were applied to the National Instruments DAQCard and acquired by the notebook computer as for the hydrophone signals. In use the sensing head of the instrument was steadily lowered into and retrieved from the water at a rate that allowed it to adjust to the water's temperature.

The sound recordings were acquired at a sample rate of 350,000 samples/sec. Where required, hardware pre-emphasis sometimes was used prior to digitisation to improve the dynamic range of the measurement. After software de-emphasis the recordings had a wide frequency range, from 1 Hz to 175 kHz, thus covering the full audiometric frequency range of fish, human divers and marine mammals. The CTD probe's signals were sampled every second.

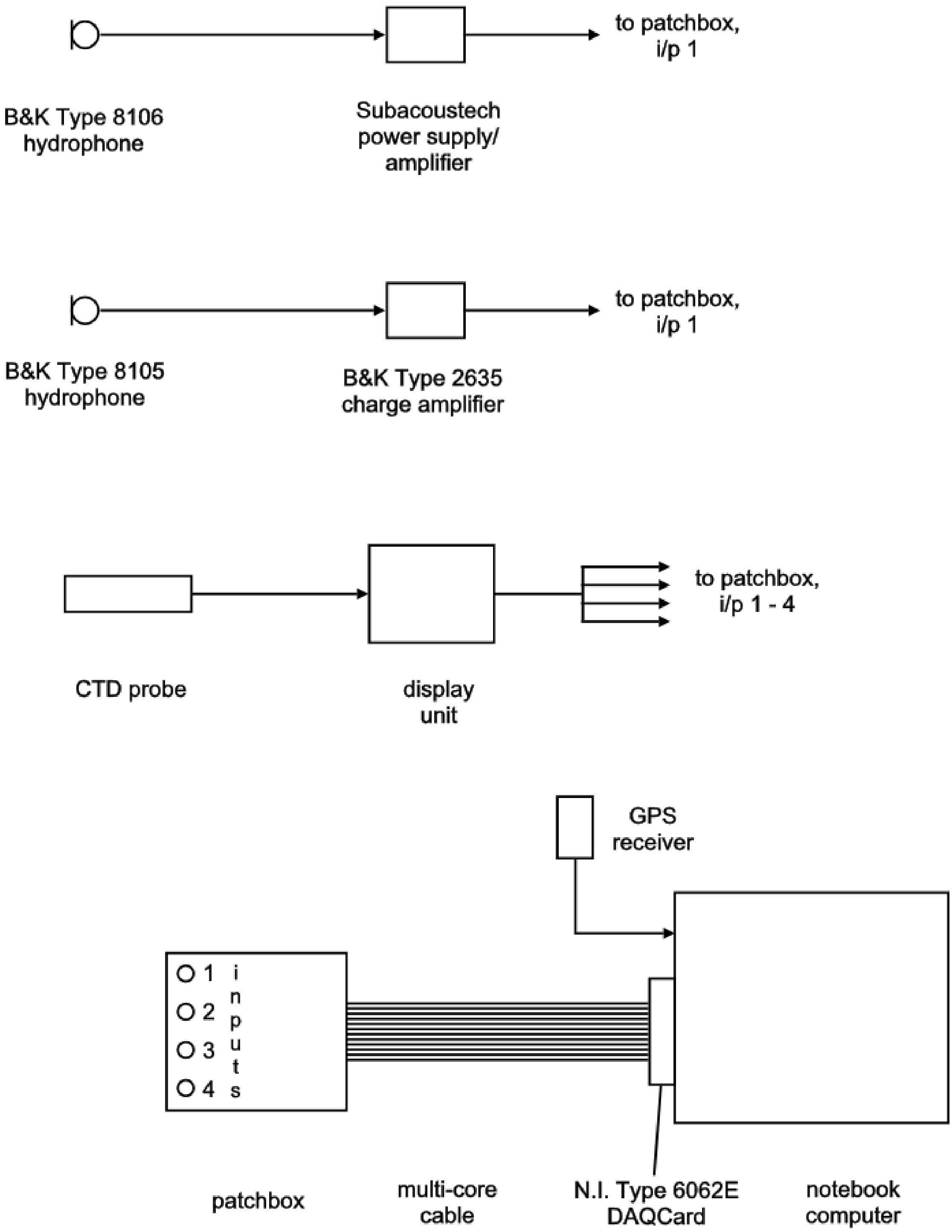

Figure 3.1. Block diagram of instrumentation used for measurements.

4 Measurements of pile driving noise

4.1 Introduction

This section provides a reanalysis of the pile driving noise previously measured at North Hoyle and Scroby Sands, and documented in a previous report (Nedwell *et al.* 2003). It also provides further measurements of pile driving noise during construction of the Kentish Flats, Barrow and Burbo Bank windfarms.

4.2 Typical features of the noise from pile driving operations

The majority of the analysis of the pile driving noise addresses the level of the noise as a function of the range from the pile driving, as this is critical in determining the range at which the pile driving may have an effect on the environment. The data are thus presented largely in the form of graphs which present level *versus* distance from the pile driving. However, it is instructive to first look at the detail of typical recorded waveforms.

Figure 4.1 illustrates a typical pressure time history (i.e. sound pressure *versus* time) for a five second period of pile driving. The time history was recorded at Burbo Bank, at a distance of 100 m from the pile driving.

The individual pile strikes may be clearly seen in the time history; there are three clear individual strikes in this period, in which the pressure rises very rapidly to a maximum; there follows a period of decaying oscillatory pressure, the duration of each strike being about 0.5 second. The majority of the arrival is due to waterborne sound, but it may be seen that at the tail of each wave is a small low frequency arrival which it is thought is probably due to substrate-borne vibration. The pressure reaches a maximum positive pressure of about 10^4 Pa, or 0.1 bar, and a negative value of just over the same value. The peak-to-peak pressure level of this wave is therefore approximately 206 dB re 1 Pa.

Figure 4.2 presents the same information, but this time at a distance of 10 km. It may be seen that the pile strikes are much more spread in time due to dispersion in the water and also due to a significant component of the sound propagating through the seabed, or in seabed-coupled water waves. The level of the wave has dropped significantly, to approximately 20 Pa peak-to-peak, or 146 dB re 1 Pa. This is approaching typical background noise levels of 130 – 140 dB re 1 Pa, and the noise may clearly be seen superimposed on the measurement, leading to its "ragged" appearance. These levels are typical of those that have been measured previously in the shallow coastal water of windfarm sites around the UK (Nedwell *et al.* 2003).

Figure 4.3 illustrates the spectra of the time histories illustrated in Figures 4.1 and 4.2. In addition, the background level of noise (recorded in periods where there was no pile driving) is illustrated. The figure presents the power spectral density of the pile driving noise as a function of frequency, for the two measurements at 100 m and 10 km. In all cases the level of noise from the measurements at 100 m of the pile driving is greatly above the background. It may be seen that the spectral level is generally of the order of 40-60 dB above that in the absence of pile driving over a wide frequency range from 100 Hz up to the highest frequencies presented of 100 kHz. It is important to note here that at short range there is substantial high frequency sound energy at frequencies from 100 Hz to above 100 kHz, but that at ranges of 10 km, the spectra highlight that much of the high frequency energy has been attenuated during transmission. There is, in general, no tonal content to the pile driving, although there are some low level broad peaks or swathes at about 35 and 70 Hz.

The measurements at 10 km are also above background, over a frequency range from about 10 Hz up to 10 kHz or so. Again, the spectrum is fairly flat without significant tonal components.

Figures 4.4 and 4.5 illustrate pile driving spectra, but in this case at a greater number of distances from the pile driving. The spectra are plotted on an isometric plot as a function of frequency and range. The background noise spectrum has also been illustrated; this has been placed adjacent to the measurement at greatest range. Whereas Figure 4.4 presents the range on a linear scale, Figure 4.5 presents it on a logarithmic plot, otherwise the two figures are identical.

It may be seen that the pile driving noise is indicated by a peak in the spectra at the shorter ranges, and at a frequency peaking at about 200 Hz. There is no indication from the figures of tonal components in the pile driving noise. It may be seen from Figure 4.5 that the propagation is relatively constant over a wide frequency band, and is roughly geometric (i.e. at a constant rate of decay when presented logarithmically).

4.3 Improved models for pile driving noise

Part of the object of the analysis of the data measured during pile driving operations for windfarm foundations was to attempt to form a simple model of the noise that would enable the information to be used subsequently for predicting noise in future pile driving operations.

Commonly, analysis of data attempts to separate the noise into the Source Level (SL), which indicates the level of sound leaving the pile driving source, and the Transmission Loss (TL), which represents the attenuation of the sound as it spreads. If these two parameters are known the level of sound at all points in the water can be estimated and its effects anticipated. The equation for sound propagation has the form

$L = SL - TL$, where L is the sound level at range R.

In the early stages of analysing the data on the noise from pile driving presented in Nedwell *et al.* (2003), a conventional straight line fit model (Geometric Loss, or GL, model) was used, which modelled sound losses due to spreading well, but did not incorporate absorption losses. Where measurements of sound are at low frequency, taken in deep water - for example at a hundred metres depth or more - and where the measurements are relatively near the source - for example from a few hundred metres to approximately ten kilometres - it is common that absorption losses are negligible. In these cases geometric losses caused by the spreading of the sound dominate the propagation, absorption can be ignored, and a simple GL model is adequate to describe propagation.

However, sound propagation in the shallows in which windfarms are usually placed differs greatly from the deeper water case. Frequently the surrounding water is only a few metres deep, and it has been found in the course of this work that the absorption losses can be very high. It is thought that this is because of the close coupling between hysteresis losses in the seabed and sound energy in the shallow overlying water channel.

Where the model is only used to predict sound over the ranges at which it was originally measured the straight line fit is adequate. However, if the model is used to extrapolate the measurements, say to estimate the Source Level or lethal effects at short ranges, or to estimate the large range at which the sound will fall to background level, the model will overestimate the sound level. To account for these effects a further term has been added to the Transmission Loss, *viz*. an absorption term proportional to distance travelled by the sound.

In the simple (GL) model, the Transmission Loss is modelled as

$$TL = N.\log R$$

In the model including absorption the Transmission Loss is modelled as

$$TL = N.\log R + \alpha.R,$$

so the resulting equation for sound propagation (termed the Geometric Loss/Absorption Loss, or GL/AL, model) is

$$L = SL - N.\log R - \alpha.R,$$

where L is the sound level at range R,
N is the geometric loss factor, and
α is the absorption loss coefficient.

Figure 4.6 illustrates an example of a GL/AL model fitted to the peak-to-peak noise measured during impact pile driving operations to construct the North Hoyle offshore windfarm. The figure illustrates the data fitted with two models, one the GL (straight line) fit and the other a GL/AL fit including absorption. It may be seen that although there is little difference in the data fits over the range at which the measurements were taken, with the GL/AL model the predicted Source Level, and the levels predicted at ranges beyond 10 km, are considerably reduced. Over the range in which the data is taken there is little to commend one model or the other, as both give a reasonable fit to the data. However, if the models are extrapolated, it may be seen that the curves diverge, and that the straight line fit predicts significantly higher levels both near to the source and at greater distances. It has been found, as a consequence of further measurements that have been taken of pile driving noise, that a fit including absorption (a GL/AL model) usually provides a much better model for extrapolation than the straight line fit.

Figure 4.7 again illustrates the GL/AL model but in this case fitted to the peak-to-peak harbour porpoise perceived sound level (i.e. in dB_{ht} (*Phocoena phocoena*) units), again during impact pile driving operations to construct the Barrow offshore windfarm. It may be seen that the fit enables a complex set of data to be represented in terms of a simple set of coefficients. This has two chief advantages. First, while analysing data to provide dB_{ht} values is computationally onerous, it is very easy to use this simplification to estimate, for instance, the distance at which the level would be estimated to drop to a given value. Second, where large amounts of data are represented graphically, it is much easier to plot the fit rather than the entire set of data points.

It may be noted that because absorption losses are much more dependent on the detailed bathymetry and geology of a site than the geometric losses, the use of the GL/AL model predicatively requires access to a suitable acoustic propagation model capable of predicting the absorption loss.

While preparing the figures presenting the dB_{ht} values for pile driving presented in this section it was found that a graph presenting seven species, along with seven full sets of data points, was not legible. Consequently, the dB_{ht} results presented in this section have been prepared using only the fit to the data.

4.4 Measurement of pile driving noise at North Hoyle and Scroby Sands

4.4.1 Introduction

The North Hoyle offshore windfarm, one of the earliest to go operational in the U.K., is located about 8 km off the north Wales coast between Rhyl and Prestatyn. The site is composed of predominantly gravelly sand with some small infrequent pockets of fine sand, gravel and clay. Underlying the superficial layers of 14 m or so is sandstone. The pile driving programme took place over five months and consisted of the driving of thirty steel piles into the seabed. The piles had an external diameter of 4 m, a wall thickness of 35 mm, a nominal length of 50 m and a weight of 270 tonnes. They were driven using a Menck MHU500T pile driving hammer. The average impact energy used to drive the piles was 450 kNm at an average of 35 blows per minute.

The farm is comprised of thirty 2 MW wind turbines, each standing in around 12 m of water with its hub at 67 m above mean sea level. Each hub has an 80 m diameter rotor attached to it. The turbines are spaced 800 m apart in the east-west direction, and 350 m apart in the north-south direction.

Figure 4.8 is a sketch map showing the location of the windfarm site and the transects along which pile driving noise measurements were taken.

The Scroby Sands windfarm, which has been operational since July 2004, is situated on Middle Scroby, a very shallow bank approximately 4 km off the Norfolk coast near Great Yarmouth. The farm is comprised of thirty 2 MW turbines, each mounted on a 4.2 m diameter steel monopile which has been driven to a depth of about 31 m into the seabed. The hub of each turbine is about 68 m above mean sea level, and each is fitted with an 80 m diameter rotor.

The water depth at the site varies considerably. At the centre of the farm the water depth is approximately 0.5 m below chart datum (lowest astronomical tide value), while along the northern edge the water depth is approximately 3.5 m below chart datum, and along the western edge the seabed drops quite sharply to a depth of 5 m below chart datum.

Figure 4.9 is a sketch map showing the location of the windfarm site and the transects along which pile driving noise measurements were taken.

4.4.2 Re-analysis of pile driving noise at North Hoyle and Scroby Sands

The initial data reported in Nedwell *et al.* (2003) used a straight line GL model to estimate the effective Source Level of pile driving noise during the construction of the North Hoyle and Scroby Sands offshore wind farms. The measurements and subsequent modelling of the noise during the North Hoyle construction indicated Source Level pile driving noise measured at a 5 m depth of 260 dB re 1 μPa @ 1 m, and at 10 m depth of 262 dB re 1 μPa @ 1 m. The corresponding Transmission Loss was given by 22 log (R).

The measurements and analysis conducted at this time highlighted the importance of obtaining measured data both at close range (ideally within 100 m) and at long range as the pile driving noise approaches the level of the ambient sea noise. The later measurements during construction at the Barrow and Burbo Bank sites have attempted to address this, with measurements during the Burbo Bank construction, for example, undertaken over ranges from 100 m to 25 km. Data obtained over these extended ranges highlighted the importance of the aborption factor (α.R – see equations in section 4.3) in modelling the sound level with range from large scale pile driving operations.

Consequently, the data for the North Hoyle offshore windfarm construction programme presented in the earlier report by Nedwell *et al.* (2003) has been re-analysed to incorporate absorption. The unweighted peak to peak sound level with range for the North Hoyle pile driving construction is presented in Figure 4.10. The least sum of squares fit to the measured data indicates a sound level with range for the pile driving operation with 4.0 m diameter piles of the form

$$L_{\text{North Hoyle}} = 249 - 17 \log R - 0.0011 R.$$

The re-analysis of the North Hoyle data for representative species of fish and marine mammal using the dB_{ht} (*Species*) sound level is presented in Figure 4.11. It may be seen that there are considerable differences in the perceived noise for the representative species considered. This highlights the importance of considering the effects of underwater noise on a species basis, and indicates that simple criteria that attempt to characterise the effects of noise by broadband measures of its level are unlikely to provide a realistic assessment.

Species	**Peak-to-peak perceived Source Level (dB_{ht} @ 1 m)**	**Behavioural impact range (based on 90 dB_{ht} peak-to-peak level)**
Cod (*Gadus morhua*)	166	5.5 km
Herring (*Clupea harengus*)	177	11 km
Salmon (*Salmo salar*)	155	2 km
Bottlenose dolphin (*Tursiops truncates*)	185	5.7 km
Harbour porpoise (*Phocoena phocoena*)	191	9 km
Common seal (*Phoca vitulina*)	154	3 km

Table 4.1. Summary of peak-to-peak perceived Source Level noise in dB_{ht} units and behavioural impact range for impact pile driving operations during construction of the North Hoyle offshore windfarm.

Figure 4.12 presents the re-modelling of the peak to peak sound level with range measured during pile driving operations with 4.2 m diameter piles during the construction of the Scroby Sands offshore wind farm. In this case the data is highly scattered, probably due to the rapid depth variations, and shallow water sandbanks in and around the site. In can be seen from the data that the sound level with range trend is not as distinct as that obtained during pile driving operations at North Hoyle. The least sum of squares fit to the Scroby Sands pile driving data indicates a variation in peak to peak sound level with range of the form

$$L_{\text{Scroby Sands}} = 257 - 20 \log R - 0.003 R.$$

It should be noted, however, that there may be considerable error in the modelled data from this construction.

4.5 Measurement of pile driving noise at Kentish Flats

4.5.1 Introduction

The Kentish Flats windfarm, which started generating electricity in October 2005, is located on the southern side of the outer Thames estuary, about 8.5 km off the north Kent coast near Whitstable and Herne Bay. The water depth is about 5 m at this site, and the site is mainly silt and sand deposits. The farm is comprised of thirty 3 MW turbines, each mounted on a 4.3 m diameter monopile driven into the seabed. The hub of each turbine is about 70 m above mean sea level, and each is fitted with a 90 m diameter rotor. For the pile driving the hammer used was an IHC s-600. When pile F4 was driven 3248 blows were required to drive the pile, with an average energy per blow of 344 kJ.

Figure 4.13 is a sketch map showing the location of the windfarm site and the transect along which the measurements were taken.

4.5.2 Unweighted measurements

Figure 4.14 presents the peak-to-peak underwater sound data measured at the Kentish Flats offshore windfarm site during pile driving construction operations with 4.3 m diameter piles.

At a range of 213 m the average peak-to-peak level of the transient pressure wave radiated following hammer impact was 195 dB re. 1 μPa, and it had decreased to a level of 150 dB re. 1 μPa at a range of 7.5 km. At this range the peak subsea noise from the impact pile driving operation was still above the ambient sea noise level.

Modelling of the measured subsea noise during construction of the Kentish Flats windfarm using the GL (linear fit) model indicates a peak-to-peak noise Source Level of 272 dB re. 1 μPa @ 1m, associated with an attenuation constant of 31.7. Analysis using the GL/AL model indicates that the sound propagation during the Kentish Flats pile driving construction operation can be described by the expression

$$L_{\text{Kentish Flats}} = 243 - 20 \log R - 0.002 R.$$

The measured data therefore indicates an unweighted peak-to-peak Source Level of 243 dB re. 1 μPa @ 1 m for the impact pile driving operation with 4.3 m diameter piles at Kentish Flats.

4.5.3 The species perceived sound level in dB_{ht} units for Kentish Flats

The Kentish Flats OWF is sited in very shallow water, with typically a few metres of water covering silt and sand deposits. Consequently, propagation of underwater sound, and particularly the very low frequency components of the underwater sound, is very poor. The measured sound level with range therefore decreased very rapidly at the Kentish Flats site, and the absorption loss factors determined for the receptor species were also correspondingly high. As a result the behavioural impact ranges predicted from the measured data for this impact pile driving operation are considerably shorter than those determined for the other constructions reported here.

Figure 4.15 illustrates the best fits to the dB_{ht} level of the sound measured during the pile driving at Kentish Flats. It may be seen that the perceived level of the noise varies significantly from species to species. For sensitive species, such as the harbour porpoise, the level near to the pile driving is relatively high. By comparison, the level for species with poor hearing, such as the bass, is relatively low. It is interesting to note that the rate at which the level changes with distance from the pile driving varies significantly from species to species; in general, for the marine mammals the level decreases more rapidly than for the fish. This results from the fact that the fish tend to hear at lower frequencies, where the noise from the pile driving tends to propagate better. The seal is an exception to this, however – it may be noted that the seal has good low frequency hearing. It may be seen from the figure that, as a result of the differing propagation losses, the ranges at which a strong avoidance reaction would be expected (a level of 90 dB_{ht}) cluster between about 1 km for the most insensitive species, and 4 km for the most sensitive.

Species	**Peak-to-peak perceived Source Level (dB_{ht} @ 1 m)**	**Behavioural impact range (based on 90 dB_{ht} peak-to-peak level)**
Cod (*Gadus morhua*)	150	1.6 km
Herring (*Clupea harengus*)	173	2.5 km
Salmon (*Salmo salar*)	156	500 m

Bass (*Dicentrarchus labrax*)	143	400 m
Bottlenose dolphin (*Tursiops truncates*)	191	1.6 km
Striped dolphin (*Stenella coeruleoalba*)	190	1.5 km
Harbour porpoise (*Phocoena phocoena*)	201	2.5 km
Common seal (*Phoca vitulina*)	175	2.2 km

Table 4.2. Summary of peak-to-peak perceived Source Level noise in dB_{ht} units and behavioural impact range for impact pile driving operations during construction of the Kentish Flats offshore windfarm.

The Source Level of the transient pressure wave from the impact pile driving operation varies from 201 dB_{ht} (*Phocoena phocoena*) @ 1 m (i.e. for the harbour porpoise, a relatively sensitive marine mammal species), to 143 dB_{ht} (*Dicentrarchus labrax*) @ 1 m (i.e. for the bass, a fish with relatively insensitive hearing).

Table 4.2 presents the perceived noise Source Level and predicted 90 dB_{ht} range within which strong avoidance is likely to occur for various fish and marine mammal species based on underwater noise measurements during construction of the Kentish Flats offshore windfarm.

The level is significantly lower than for the preceding figure in which peak-to-peak levels were presented; this results from the short pulse of intermittent energy from the pile driving strike being spread over the much greater time between pile strikes. From the criteria of section 2.4.2, where the level is lower than 92 dB_{ht} L_{eq}, the noise level is insufficient to create a Noise Dose during a 5 hour pile driving operation that is likely to damage hearing. For instance, it may be seen that the level of the pile driving falls below 92 dB_{ht} L_{eq} at a range of about 250 metres for the harbour porpoise, the most sensitive species. A harbour porpoise could therefore be exposed to the noise during the entire pile driving operation without harm from accumulated Noise Dose, provided that during exposure it was at a range greater than 250 metres.

However, as discussed in section 2.4.3, this analysis assumes that an animal will remain static at that distance. The results were used to calculate the critical distance, that is the distance at and inside which an animal would have to be to receive a hazardous Noise Dose while fleeing from the noise. It was assumed that the animals could swim at 1 m/s which was thought to be a pessimistically low value. In all cases the critical distance was found to be less than 10 metres. Since this is less than the distance at which traumatic hearing injury may occur as a result of a single noise exposure, that is, when exposed to a level of 130 dB_{ht} or more, the important conclusion may be drawn that if an animal is protected from a single traumatic injury, it will be protected from accumulated injury from Noise Dose also.

4.6 Measurement of pile driving noise at Barrow

4.6.1 Introduction

The Barrow windfarm, which started generating electricity in July 2006, is located approximately 7 km south-west of Walney Island, near Barrow-in-Furness in Cumbria. The farm is comprised of thirty 3 MW turbines, each mounted on a 4.7 m diameter monopile which has been driven into the seabed. The hub of each turbine is about 70 m above mean sea level, and each is fitted with a 90 m diameter rotor.

Measurements of pile driving noise were taken in the early hours of the morning of 9 November 2005 (from about 0015 hours to 0330 hours) along a transect towards the north-east from turbine 11, and between 1800 hours and 1930 hours on the same day along a transect towards the south-west from turbine 16. For the first set of measurements the sea was choppy with a low swell, and the wind was blowing at 6 m/s from the west-north-west. For the second set of measurements the sea was choppy with a medium swell and the wind was blowing at between 7 and 10 m/s from the south-south-west.

Figure 4.17 is a sketch map showing the location of the windfarm site and the transects along which the measurements were taken.

4.6.2 Unweighted measurements

Figure 4.18 presents the peak-to-peak levels of unweighted subsea noise for pile driving at Barrow. At a range of 92 m the peak-to-peak noise was measured at a level of 217 dB re. 1 μPa, and at a range of 12.8 km the peak-to-peak sound level had reduced to 174 dB re. 1 μPa.

At this deeper water site there was a consistent variation in sound level with range. The least sum of squares fit to the measured data using the GL/AL model indicates sound propagation that can be described by the expression

$$L_{Barrow} = 252 - 18 \log R - 0.0003 R.$$

The measured data therefore indicates a peak-to-peak Source Level of 252 dB re. 1 μPa @ 1 m, for the impact pile driving operation at the Barrow offshore windfarm, with a geometric spreading loss factor of 18 and an absorption coefficient of 0.0003 dB/m.

4.6.3 The species perceived sound level in dB_{ht} units for Barrow

Figure 4.19 presents the best fit lines for the peak-to-peak dB_{ht} sound levels that would be perceived by a number of typical marine species. The data obtained by this technique indicate a perceived noise Source Level of the transient pressure wave from the impact pile driving operation that varies from 199 dB_{ht} (*Phocoena phocoena*) @ 1 m (i.e. for the harbour porpoise, a relatively sensitive marine mammal species), to 147 dB_{ht} (*Dicentrarchus labrax*) @ 1 m (i.e. for bass, a fish with relatively insensitive hearing). The data indicate that although marine mammals initially hear the underwater sound at higher levels than fish, due to their very high frequency hearing capability, the perceived pile driving noise decreases more quickly with range for marine mammal species as high frequency sound is attenuated more rapidly in deep water. Consequently, for these relatively deep water measurements, low frequency fish hearing specialists such as the herring hear the subsea pile driving noise at ranges comparable with marine mammals.

Based on the data illustrated in Figure 4.19, Table 4.3 presents the predicted 90 dB_{ht} range within which strong avoidance is likely to occur, for various fish and marine mammal species. From the measured data at the Barrow offshore windfarm, the analysis indicates ranges that vary from approximately 2 km for a species of fish with poor hearing, such as the bass, to a range of approximately 22 km for a sensitive hearing fish species, such as the herring. A similar analysis based on the impact pile driving measurements during construction of the North Hoyle offshore windfarm (with smaller 4.0 m diameter piles) (Nedwell *et al.* 2003) reported equivalent ranges for fish of 1.6 km and 5.5 km for the dab and cod respectively, and marine mammal behavioural impact ranges of 4.6 km for the bottlenose dolphin and 7.4 km for the harbour porpoise. The increased ranges at Barrow are probably due partly to the increased pile diameter, but more significantly for the fish species, are a result of better low frequency sound propagation in the Barrow region.

Species	Peak-to-peak perceived Source Level (dB_{ht} @ 1 m)	Behavioural impact range (based on 90 dB_{ht} peak-to-peak level)
Cod (*Gadus morhua*)	158	20 km
Herring (*Clupea harengus*)	175	22 km
Dab (*Limanda limanda*)	156	4 km
Bass (*Dicentrarchus labrax*)	147	2 km
Bottlenose dolphin (*Tursiops truncates*)	203	5 km
Striped dolphin (*Stenella coeruleoalba*)	199	4 km
Harbour porpoise (*Phocoena phocoena*)	199	10 km
Common seal (*Phoca vitulina*)	179	6 km

Table 4.3. Summary of peak-to-peak perceived source level noise and behavioural impact range for impact pile driving operations during construction of the Barrow offshore windfarm.

4.6.4 The species Noise Dose in dB_{ht} L_{eq} units for Barrow

Figure 4.20 presents the dB_{ht} L_{eq} results from the raw time history data of underwater sound recorded during impact pile driving at the Barrow offshore windfarm site. Although the pile is of similar diameter to that at Kentish Flats, the Barrow site is in deeper water (approximately 20 m) and the levels of sound measured at range are considerably higher.

The levels are thus rather higher than for the preceding case of Kentish Flats, and indicate a spread of distances at which a static animal would receive a hazardous Noise Dose, from 27 metres or so for the bass up to just over a kilometre for the harbour porpoise, herring and cod.

The critical distance at which an animal would have to start to receive an unacceptable Noise Dose while fleeing from the noise was found to be 14 metres for a bottlenose dolphin, 84 metres for a harbour porpoise and 17 metres for a herring. For the other cases considered, the critical distance was found to be less than 10 metres. These distances were well below the distance at which the level was 130 dB_{ht}, the level at which it is thought traumatic hearing injury could occur. Therefore, if an animal is protected from a single traumatic injury, it would again be protected from accumulated injury from Noise Dose.

4.7 Measurement of pile driving noise at Burbo Bank

4.7.1 Introduction

The Burbo Bank windfarm, which is under construction, is located in Liverpool Bay at the entrance to the River Mersey. At the time that measurements were taken at this site, in July 2006, the foundation piles were being driven, with installation of the turbines to follow at a later date. When complete, the farm will have twenty five turbines, each sitting atop a 4.7 m diameter monopile driven into the seabed. The location of the windfarm site and the transects along which the pile driving noise measurements were taken are shown in Figure 4.8.

Measurements of pile driving noise were taken between 1915 hours and 2130 hours on 11 July 2006 along a transect to the north-west from turbine B7, ranging from 100 m to 15 km from the pile being driven. The water depth along this transect varied from 7 m in the immediate vicinity of the pile to a depth of 24 m at 15 km. From the pile driving operation to a range of approximately 4 km the water depth was shallower than 10 m. On this night there were high winds, and the construction operation was halted for a period. The sea was choppy with breaking waves and a swell of several metres. Background sea noise measurements taken during non-pile driving periods indicated a mean ambient sea noise level (10 Hz to 150 kHz) of 140 dB re. 1 µPa, the sea noise data being dominated by wind and wave action.

The second set of measurements were taken between 0030 hours and 0230 hours on 16 July 2006 along a transect to the west from turbine B4. Initial measurements were taken at a range of 20 km in a water depth of 29 m. Distinct pile strikes with good signal-to-background noise ratio were recorded, at a peak to peak level of approximately 135 dB re. 1 µPa. The survey vessel was, therefore, moved out to a range of 25 km from the pile driving operation. At this range the individual pile strikes were audible on the instrumentation headphones, but were difficult to identify against the sea noise in the noise time history data. Measurements during non-pile driving periods at this measurement point indicated ambient sea noise levels (10 Hz to 150 kHz) from 110 to 117 dB re. 1 µPa, with a mean sea noise of 115 dB re. 1 µPa. Subsequent measurements were taken along the 270 radial transect at ranges of 15 km, 10 km, 7 km and 5 km, at which point the pile driving ceased.

4.7.2 Unweighted measurements

The unweighted peak-to-peak noise level data with range obtained during this construction operation is shown as 'Transect 1' in Figure 4.21, together with the mean background measured sea noise during non-pie driving periods. At measurement ranges from 100 m to 5 km, there was a high level of signal to noise, and the individual pile strikes can clearly be identified in the noise time history records. The data indicate that the unweighted peak-to-peak noise varied from 207 dB re. 1 µPa at a range of 100 m to approximately 143 dB re. 1 µPa at a range of 5 km. Data were also recorded at ranges of 10 km and 15 km, but with the high background sea noise level on this night the pile strikes were often difficult to distinguish, and the data may therefore be influenced by the background noise. Figure 4.21 indicates that the peak to peak levels of pile driving noise where of similar magnitude to the ambient sea noise level at ranges beyond 7 km.

Using the GL/AL model of sound propagation a least sum of squares fit to the measured data acquired at ranges from 100 m to 5 km indicates that broadband (1 Hz to 175 kHz) sound propagation can be described by the expression

$$L_{BurboBank} = 249 - 21 \log R - 0.0047 R.$$

The measured data from transect 1 therefore indicates a peak-to-peak Source Level of 249 dB re. 1 µPa @ 1 m, with a geometric spreading loss factor of 21 and an absorption coefficient of 0.0047 dB/m.

Figure 4.21 also presents the peak-to-peak levels of unweighted noise measured along transect 2. In order to fit the data to an acoustic model, the data from transect 1 (100 m to 2 km) has been used to approximate the data at closer range. In this case the sound level with range is described by

$$L_{BurboBank} = 250 - 23 \log R - 0.007 R.$$

The measured data from transect 2 at long range therefore indicates a peak-to-peak Source Level of 250 dB re. 1 µPa @ 1 m, with a geometric spreading loss factor of 23 and an absorption coefficient of 0.0007 dB/m.

Although the depth profile of the two radial transects was similar, the broadband sound propagation data indicates a higher level of absorption with range for transect 1 than for transect 2. This becomes apparent for the measured data at ranges greater than 5 km. A possible cause of this variability is the high sea state conditions of the 11 July (transect 1) which may have caused higher levels of sound loss.

4.7.3 The species perceived sound level in dB_{ht} units for Burbo Bank

Species	90 dB_{ht} range
Bass	500 m
Dab	500 m
Cod	2 km
Herring	2.6 km
Harbour porpoise	5 km
Bottlenose dolphin	4 km
Striped dolphin	4 km
Common seal	3 km

Table 4.4. Summary of predicted behavioural avoidance range (based on a 90 dB_{ht} loudness criterion) from measured pile driving noise during construction of the Burbo Bank offshore windfarm.

Figure 4.22 presents the best fit lines of peak-to-peak dB_{ht} level variation with range for several species of fish and marine mammal. The marine mammal species initially hear the pile driving noise at higher loudness levels than the species of fish, but, due to the higher propagation losses at the sound frequencies perceived by marine mammals, the dB_{ht} level decreases more rapidly with range. Based on a 90 dB_{ht} loudness criterion, Table 4.4 indicates the range over which a strong avoidance response is likely to occur, for representative species of fish and marine mammal. These distances vary from 500 metres for the insensitive fish species dab and bass up to 5 km for the relatively sensitive harbour porpoise.

4.7.4 The species Noise Dose in dB_{ht} L_{eq} units for Burbo Bank

Figure 4.23 presents the dB_{ht} L_{eq} results from the raw time history data of underwater sound recorded during impact pile driving at the Burbo Bank offshore windfarm site.

The noise is generally of high level, and the spread of distances at which a static animal would receive an unacceptable Noise Dose range from about 14 metres for a bass up to 320 metres for the harbour porpoise.

The critical distance at which an animal would have to start to receive an unacceptable Noise Dose while fleeing from the noise was found to be less than 10 metres in all cases, apart from the harbour porpoise, for which it was 14 metres. Again, these distances were well below the distance at which the level was 130 dB_{ht}, and an animal protected from a single traumatic injury at this level would again be protected from accumulated injury from Noise Dose.

4.8 Summary of results for pile driving at all the windfarms

4.8.1 Pile driving

Table 4.4 summarises the information on pile driving noise presented in the previous sections. It may be seen that generally there is an increase in the Source Level of the pile driving with increasing pile diameter. It is clear from the data that the propagation terms N and are dominated by geological and bathymetric effects, although they indicate a significant degree of variation. Generally, high values of the loss term are associated with shallow water and low values with deep water, and *vice-versa* for the geometric spreading term N. This may be expected, since in shallow water the pile driving noise may be expected to interact more strongly with the seabed, leading to increased losses.

Data source	Pile diameter (m)	Source Level (dB re 1 Pa @ 1 m)	N	dB/m)	Sound level at 500 m (dB re 1 Pa @ 500 m)	Depth along transect(m)
North Hoyle	4.0	249	17	0.0011	203	10 - 15
Scroby Sands	4.2	257	20	0.0030	202	3 - 30
Kentish Flats	4.3	243	20	0.0020	188	5 - 8
Barrow	4.7	252	18	0.0003	203	10 - 20
Burbo Bank	4.7	249	21	0.0047	192	7 - 24

Table 4.5. Summary of the results of the analysis of unweighted peak-to-peak data for the pile driving operations at the windfarms. Data are also presented of the estimated noise at a range of 500 m based on the measured data from each construction.

The unweighted peak-to-peak Source Levels of the various pile driving operations vary between 243 dB re 1 Pa @ 1 metre, and 257 dB re 1 Pa @ 1 metre, having an average value of 250 dB re 1 Pa @ 1 metre.

Measurements previously undertaken by the authors indicate peak to peak Source Levels that vary from 189 dB re. 1 μPa @ 1 m for a 0.5 m diameter pile, 211 dB re. 1 μPa @ 1 m for a 0.7 m diameter pile, and 201 dB re. 1 μPa @ 1 m for a 0.9 m diameter pile (Parvin *et al.* 2006). Data for a 2.4 m diameter pile has been estimated from the measurements of Abbott and Bing-Sawyer (2002), indicating a Source Level of 242 dB re. 1 μPa @ 1 m. For 4.7 m diameter piles measurements indicate Source Levels of typically 250 to 255 dB re. 1 μPa @ 1 m. This pile driving data therefore indicates a variation of approximately 65 dB in Source Level from piles of different diameter. A recent sensitivity analysis by Parvin *et al.* (2006) highlighted that the pile diameter was the main factor in estimating the noise from an impact piling operation. Other factors such as the seabed type, blow force and water depth may affect the level. However, monopiles are chosen because of the nature of the seabed around shallow water sandbanks being developed for UK OWFs. These tend to be fairly consistent, and composed of compacted sand, mud and silt deposits that allow a pile to penetrate. Where the seabed effects the noise is in relation to the blow force applied to the pile. If the seabed is more compact, the pile has to be hit harder, and vice versa. Measurements by Subacoustech in the Moray Firth (Beatrice OWF), during implementation of a soft start procedure where the blow force was built up slowly from one third force to full blow force, indicated a variation in peak to peak level of 10 dB. A peer review paper is currently being prepared on these data (Bailey *et al.* 2007). In respect of offshore wind farm developments using monopole construction, the seabed affects the blow force required for penetration, but both of these are of secondary consideration to that of the pile diameter.

Generally, the Source Levels are fairly consistent and appear to indicate a small increase in Source Level with increasing pile diameter; however it is apparent that the measurements at Scroby Sands are perhaps rather higher than general, and those at Kentish Flats rather lower. In the case of Scroby Sands, the depth of water varied greatly with range from the pile driving, with successive regions of both very shallow and deep water. As a consequence, while the best fit to the data is presented here (see Figure 4.12), other fits having a lower Source Level and lower transmission losses would also give a fit of nearly the same quality. In the case of Kentish Flats, while the fit was of good quality, the water in the vicinity of the pile driving was very shallow, varying between about 5 and 8 metres, and there was consequently significant absorption in the immediate vicinity of the pile driving, possibly leading to the apparently low Source Level. The measurements from North Hoyle, Burbo Bank and Barrow are all large data sets in relatively constant bathymetric conditions and hence may be regarded as the data that is the simplest to interpret and hence most reliable.

Table 4.5 also presents peak to peak noise levels at a range of 500 m from the pile driving operations. The standard for acoustic measurements is to normalise sound measurements undertaken at various ranges to an apparent or affective Source Level range, that is, the level at a range of 1 metre. In this instance data has also been presented at a range of 500 m by interpolating between the measured pile driving noise data for each wind farm construction. The data at 500 m range indicates very consistent peak to peak levels of 202 to 203 dB re. 1 µPa @ 500 m for the construction operations at the North Hoyle, Barrow and Scroby Sands sites. The Kentish Flats and Burbo Bank data indicate lower levels of noise at a 500 m range. In the case of the Kentish Flats construction this is likely to be due to the increased influence of the water depth and seabed on the sound propagation.

The measurements taken in this work show that the noise from pile driving operations can remain above the ambient noise to a range of 25 km (Burbo Bank data shown in Figure 4.21). However on the previous night the noise was being influenced by background levels at ranges of approximately 10 km. The range to ambient sea noise is, therefore, highly dependent on the background sea noise environment, and hence measurements should always be compared with data from similar sites. The recent study by Thomsen *et al.*, (2006) has probably overestimated these ranges by using unrepresentatively low, deep background sea noise levels. In the case of UK OWFs, noise from construction and operation should be compared with background sea noise and UK coastal sites, and ideally, with measurements conducted at the OWF site prior to construction. In quieter sea noise environments, and/or construction operations with larger diameter piles and better propagation conditions, it has been suggested that pile driving noise may be detected to ranges of the order of 100 km (Parvin *et al.* 2006, Thomsen *et al.* 2006).

4.8.2 Noise dose

The results from Kentish Flats indicate that a harbour porpoise could be exposed to the noise during the entire pile driving operation without harm from accumulated Noise Dose, provided that during exposure it was at a range greater than 250 metres.

In humans, sound levels of 130 dB and above are known to be capable of causing immediate, traumatic and irreversible hearing loss. If this is translated to the harbour porpoise, it is interesting to note that it would experience a peak-to-peak dB_{ht} level of 130 dB_{ht} at a range of about 350 metres. This is a greater range than the 250 metres at which accumulated hearing damage could occur; hence in this case it may be concluded that a criterion based on a maximum level of 130 dB_{ht} would in this instance not only protect the animal against traumatic hearing loss but also against accumulated hearing damage from Noise Dose.

In the case of Barrow, however, the range at which the pile driving noise falls to 92 dB_{ht} L_{eq} exceeds the range at which it falls below 130 dB_{ht}, and in principle this simple criterion would not apply. However, the 92 dB_{ht} L_{eq} limit is based on the simple and unrealistic "static animal" model. If the animal flees the pile driving noise, even at a very low speed, it is able to significantly limit its noise exposure and hence this range will be unrealistically large. Consequently, it may be argued that the 130 dB_{ht} limit may in practice provide adequate protection against the cumulative effects of noise, in terms of the received Noise Dose.

4.8.3 A simplified model for environmental impact of pile driving noise

The conclusions of the measurements presented in the preceding section, when combined with the criteria of section 2.4.2, 2.4.3 and 2.4.4, are important because it simplifies the estimation of the areas around a pile driving operation within which the two key auditory effects of noise will occur. The results indicate that for typical piling operations motile animals within the area bounded by the 130 dB_{ht} level contour may suffer injury, including permanent damage to hearing. Motile animals within the area bounded by the 90 dB_{ht} level contour will strongly avoid the noise.

The criterion suggests two primary regions in which there will be an effect, which may be termed the Noise Injury Zone (NIZ) and the Behavioural Effect Zone (BEZ). The NIZ, bounded by the 130 dB_{ht} contour, defines the area in which hearing injury can occur, and, in addition, the areas in which lethal and physical injury could occur, since the ranges at which these will occur are much less than those for hearing injury. This area typically extends to a few hundred metres from pile driving, and hence is within the range in which marine animals can be detected by marine mammal observers. Most animals would be able to flee this area in a relatively short time, and so soft start procedures, in which the strength of the strike on the pile is gradually brought up to full power, might be effective in reducing any effect.

It should be noted that these considerations do not apply to immotile animals, or those that are constrained in their ability to move away from the noise source, for which the effects of the accumulative effects of noise might have to be considered.

The BEZ, bounded by the 90 dB_{ht} level contour, typically extends from a kilometre up to perhaps ten kilometres or more. Within this area, species are likely to display a strong avoidance reaction to the noise. However, the biological consequences of the noise must be judged by reference to the effects on the species. Moving individuals from one area of sea to another may have no consequence. However, if a migratory route is blocked by the noise the effect may well be significant. The biological significance of the reaction will depend on the consequences for populations, and individuals within the population.

The conclusions of the criterion are thought to be realistic and valuable since they imply that simple mitigation measures could be effective in preventing injury, and offer a simple criterion for the zones within which injury and behavioural effects could occur.

It should be noted that since different marine animals have different hearing sensitivity, the extent of the NIZ and BEZ will be different for differing species.

4.9 Summary of pile driving noise measurements

1. An improved analysis of previously reported pile driving data from North Hoyle and Scroby Sands has been undertaken, on piles of 4 and 4.2 metre diameter respectively. The re-analysis includes the effects of sound absorption losses during propagation.

2. Further measurements of pile driving noise have been undertaken at Kentish Flats during the driving of piles of 4.3 metre diameter, and at Burbo Bank and Barrow during the driving of piles of 4.7 metre diameter.

3. The Source Levels of these five pile driving operations varied between 243 and 257 dB re 1 Pa @ 1 metre, having an average value of 250 dB re 1 Pa @ 1 metre.

4. The Transmission Losses were characterised by values of geometric loss factor *N* of 17 to 21, and absorption factor of 0.0003 to 0.0047 dB/m.

5. The measurements taken in the course of this work have indicated that the noise from pile driving operations can remain above the background underwater noise to ranges of 25 km or more. The range is however highly dependent on the local background underwater noise, and for one set of measurements the pile driving noise was difficult to detect at ranges of 10 km.

6. Consequently, estimates of the range at which piling noise falls to background noise should always be compared with the actual background noise measured at the site, or where this is not possible, background noise from acoustically similar shallow coastal sites.

7. Analysis of the measurements using a Noise Dose criterion indicate that a static harbour porpoise at a typical range of 250 metres could be exposed to the noise during the entire

pile driving operation without harm. However, if the animal flees the pile driving noise, even at a very low speed, it is able to greatly limit its noise exposure and hence this range will be unrealistically large.

8. The results further indicates that the distance from piling within which the level exceeds 130 dB_{ht}, and hence is capable of causing traumatic hearing injury, exceeds this value. Therefore, this criterion serves to protect the animal against both traumatic hearing loss and accumulated hearing damage from Noise Dose.

9. The results therefore simplify the estimation of the areas around a pile driving operation within which the two key auditory effects of noise will occur. Provided animals are free to flee the noise, those within the area bounded by the 90 dB_{ht} level contour, or Behavioural Effect Zone, will strongly avoid the noise. Animals within the area bounded by the 130 dB_{ht} level contour, or Noise Injury Zone, may suffer injury, including permanent damage to hearing.

4.10 Figures

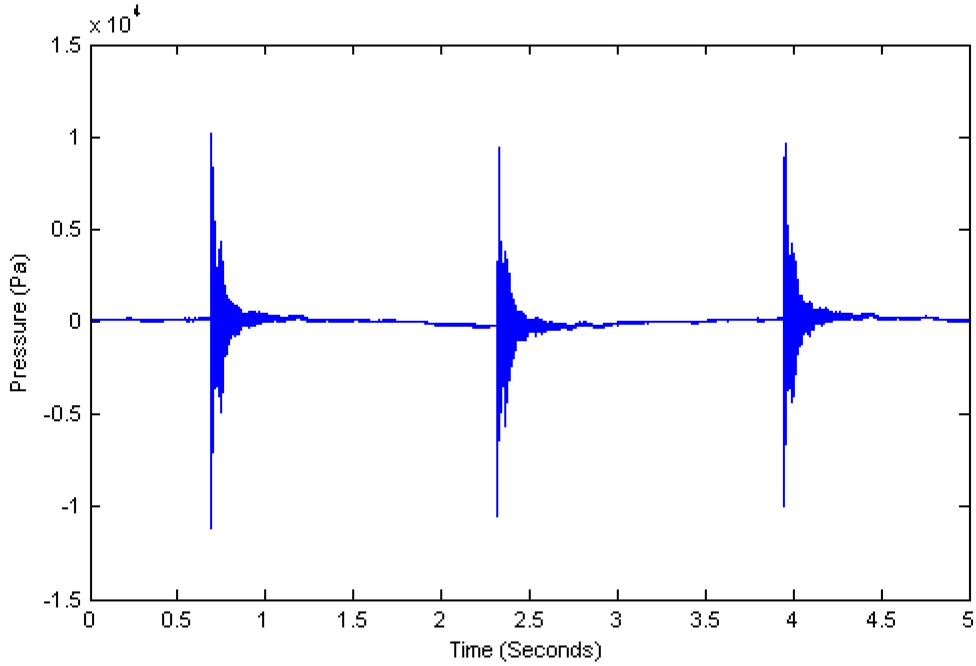

Figure 4.1. Example of a pressure~time history – taken during pile driving operations at Burbo Bank, at 100 m from the pile.

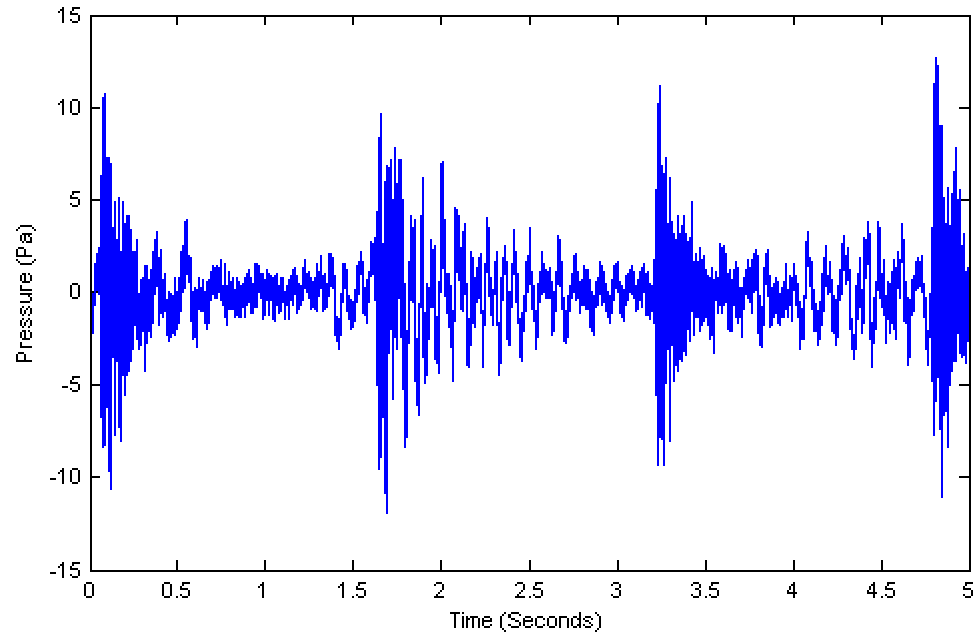

Figure 4.2. Example of a pressure~time history – taken during pile driving operations at Burbo Bank, at 10 km from the pile.

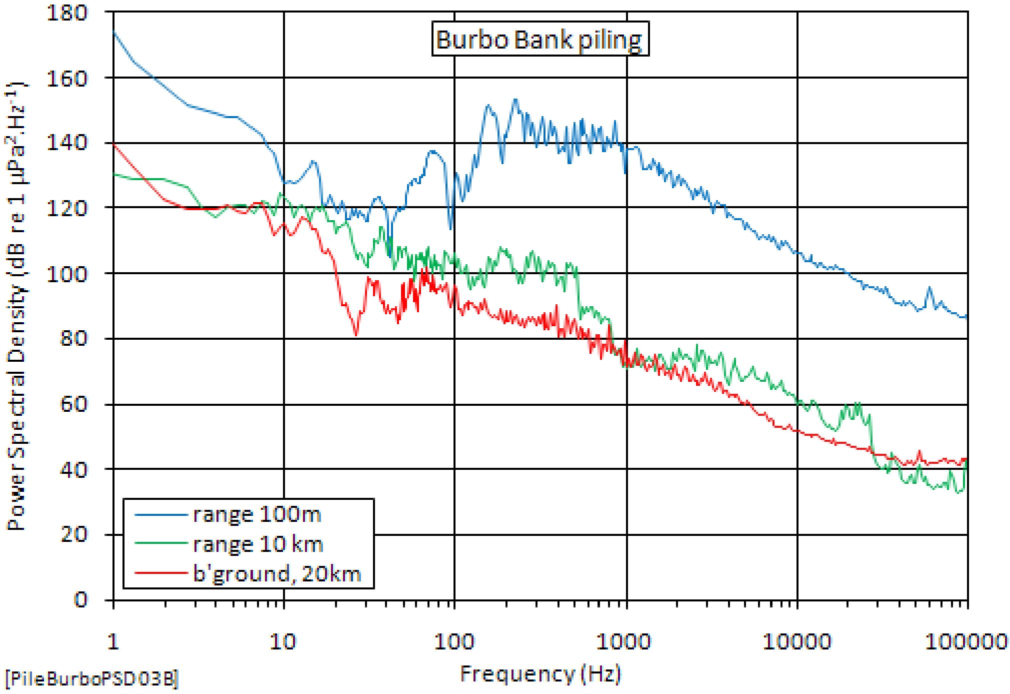

Figure 4.3. Spectra of the preceding two time histories, and a background time history taken at 20 km when no pile driving was occurring.

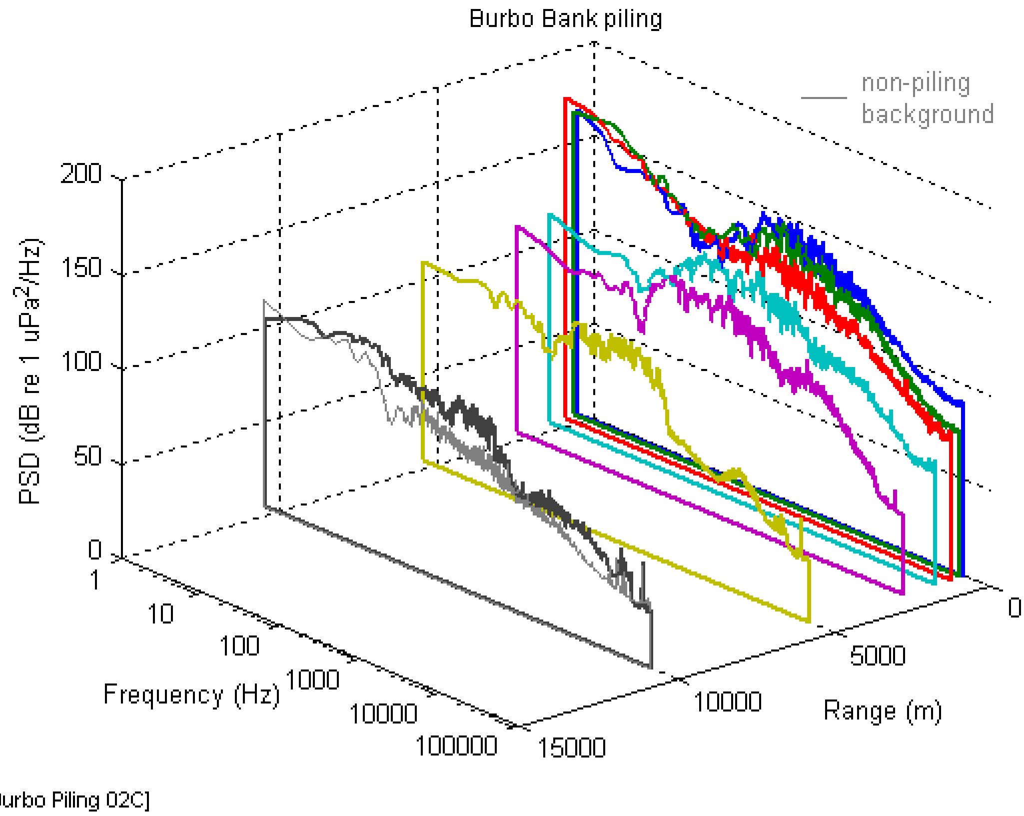

Figure 4.4. Spectra at selected ranges from the pile being driven; Burbo Bank windfarm. (Note: range is shown on a linear scale).

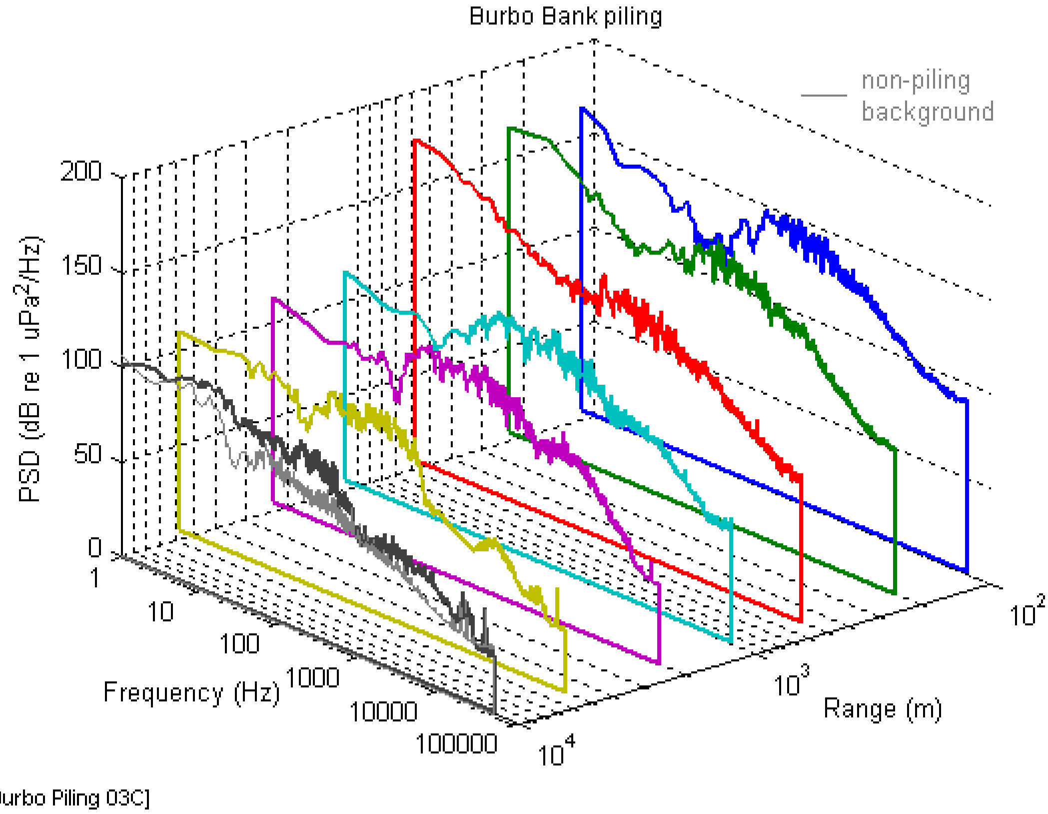

Figure 4.5. Spectra at selected ranges from the pile being driven; Burbo Bank windfarm. (Note: same data as preceding figure; range is shown on a logarithmic scale).

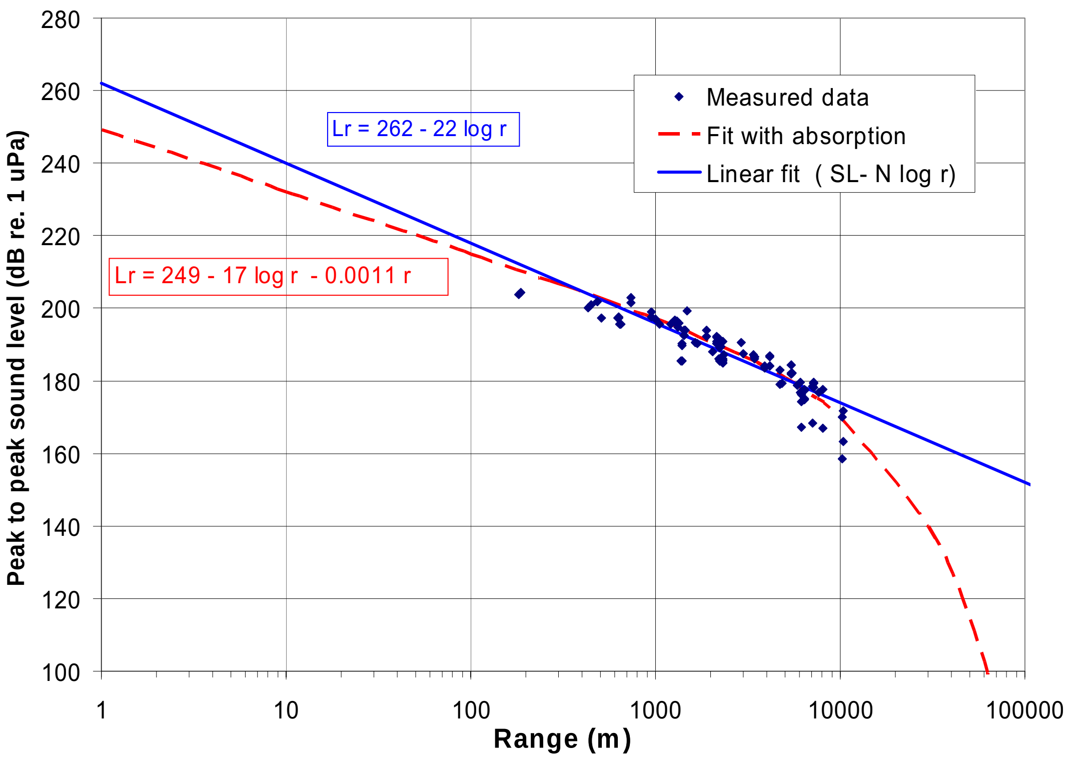

Figure 4.6. An example of a GL/AL model fitted to the peak-to-peak noise during impact pile driving operations to construct the North Hoyle offshore windfarm.

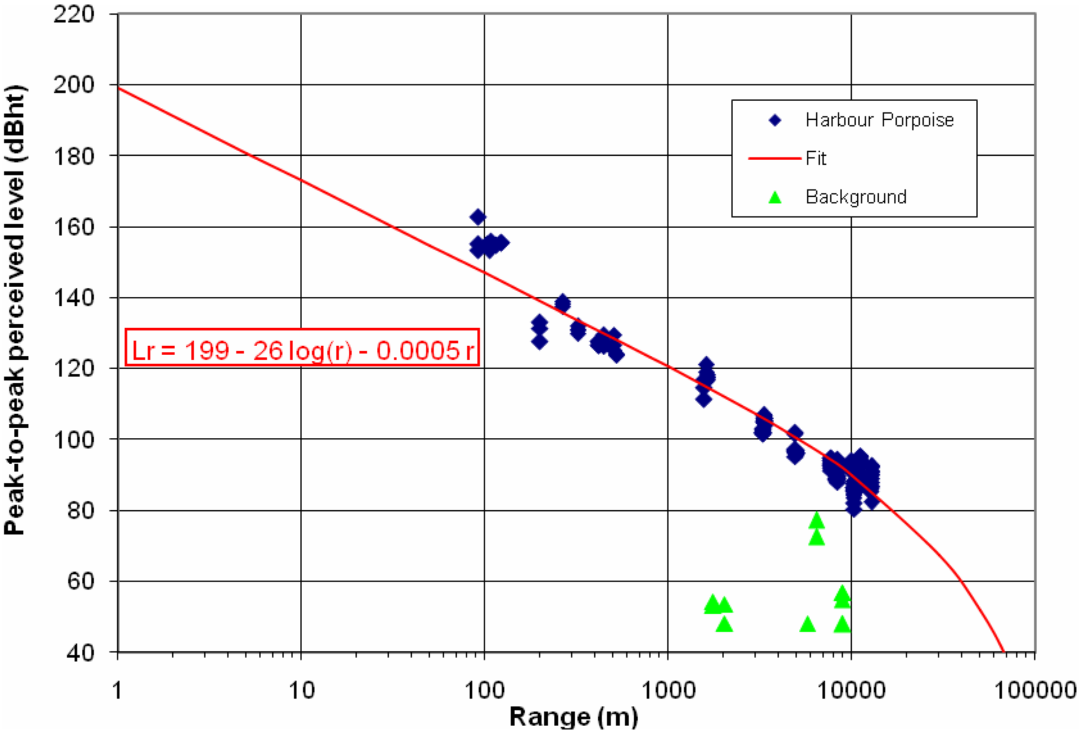

Figure 4.7. An example of a GL/AL model fitted to the peak-to-peak harbour porpoise perceived sound level in dB_{ht} (*Phocoena phocoena*) units during impact pile driving operations to construct the Barrow offshore windfarm.

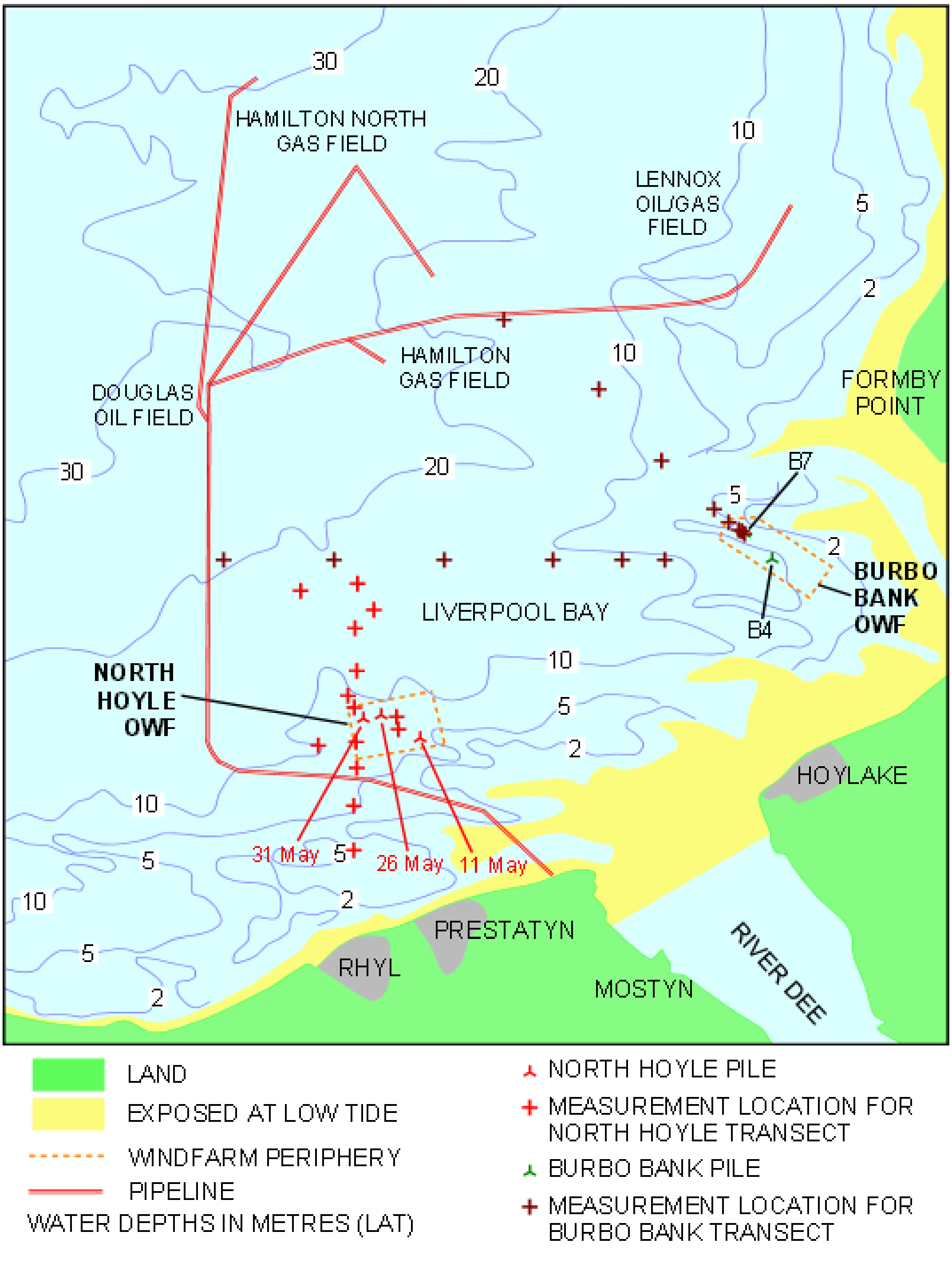

Figure 4.8. Sketch map showing the locations of the North Hoyle and Burbo Bank windfarm sites and the transects along which pile driving noise measurements were taken.

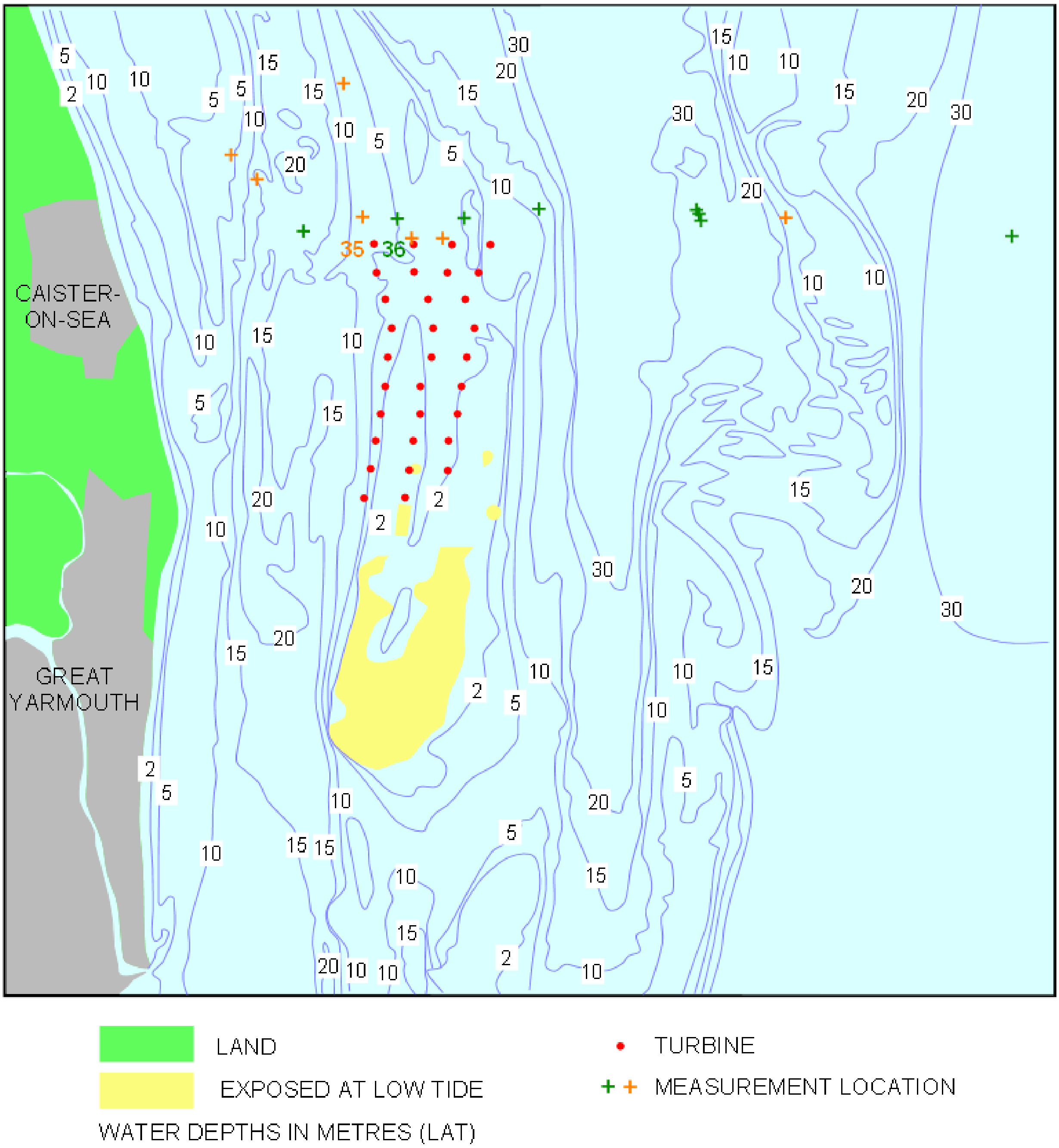

Figure 4.9. Sketch map showing the location of the Scroby Sands windfarm site and the transects along which pile driving noise measurements were taken.

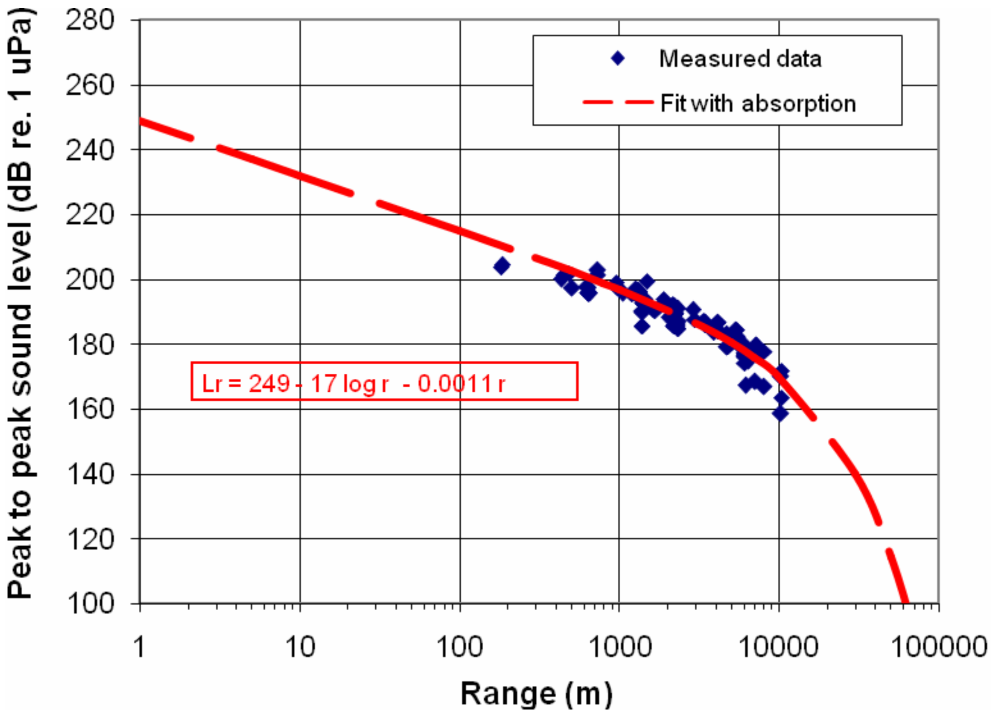

Figure 4.10. Variation of the unweighted peak-to-peak sound level with range during construction of the North Hoyle offshore windfarm (4.0 m diameter piles in shallow water).

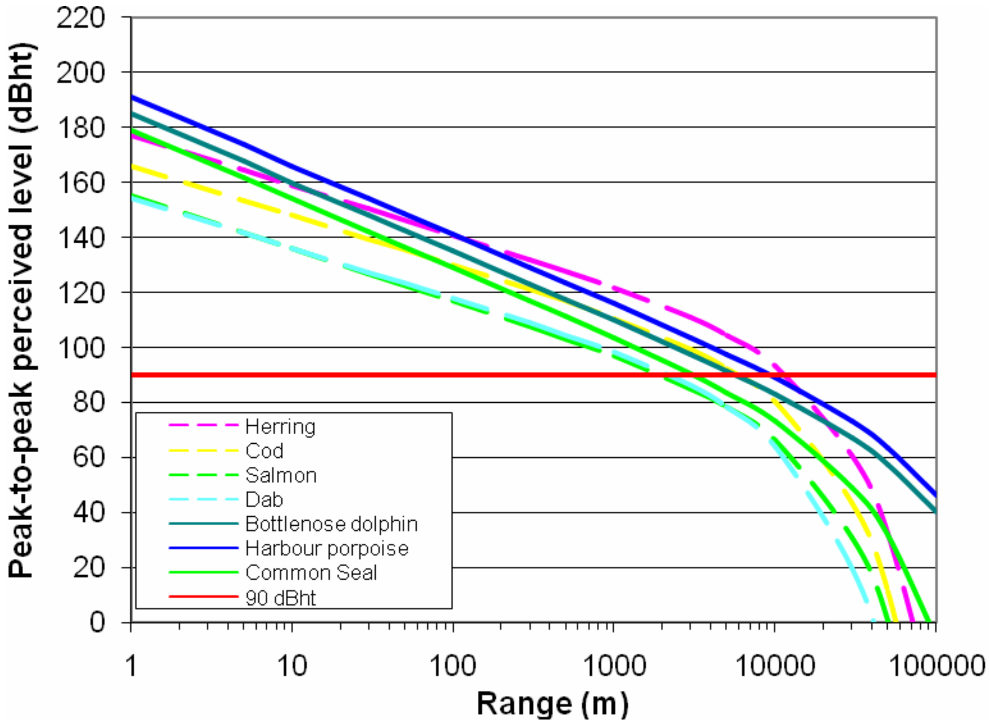

Figure 4.11. Variation of the perceived peak-to-peak sound level (dB_{ht}) with range for various marine species during impact pile driving operations to construct the North Hoyle offshore windfarm.

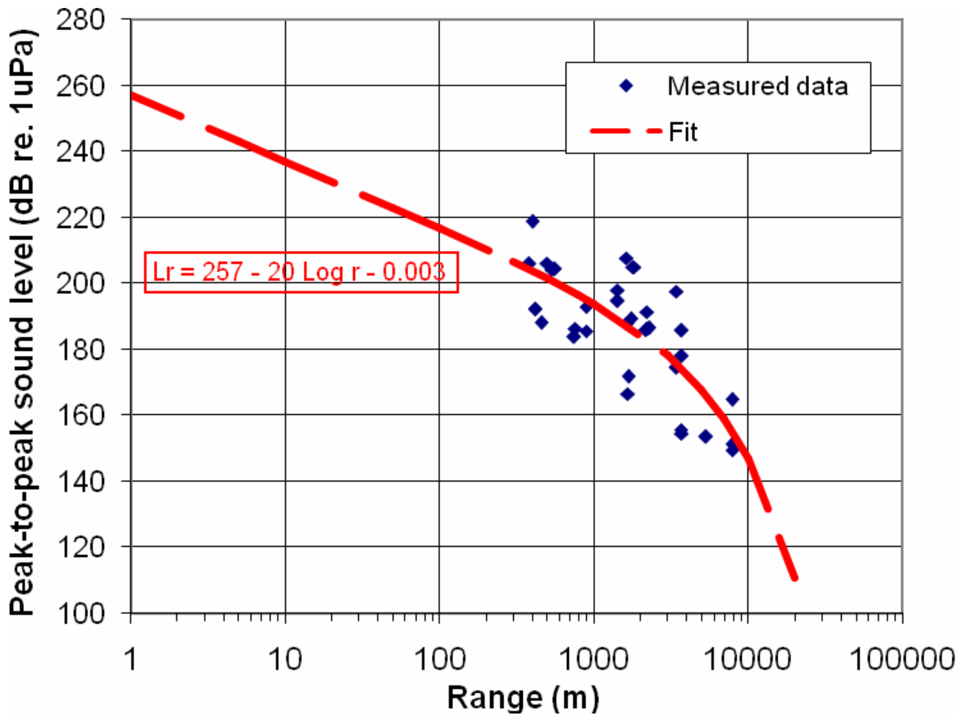

Figure 4.12. Variation of the unweighted peak-to-peak sound level with range during construction of the Scroby Sands offshore windfarm (4.2 m diameter piles in shallow water).

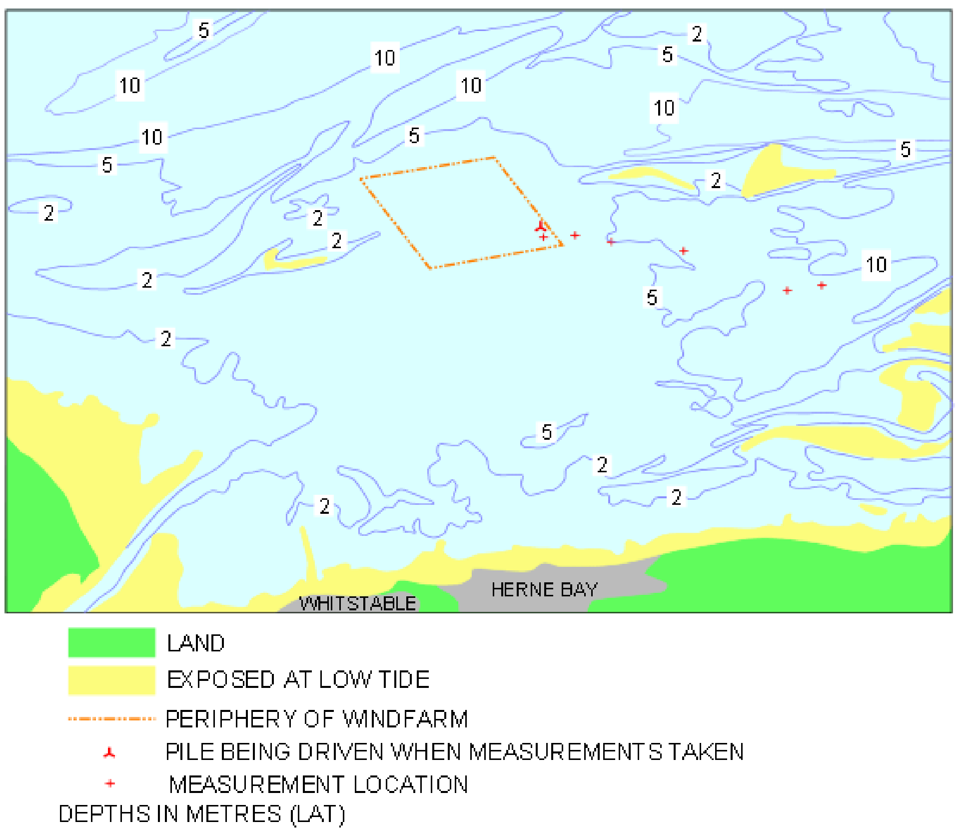

Figure 4.13. Sketch map showing the location of the Kentish Flats windfarm and the transect along which pile driving noise measurements were taken.

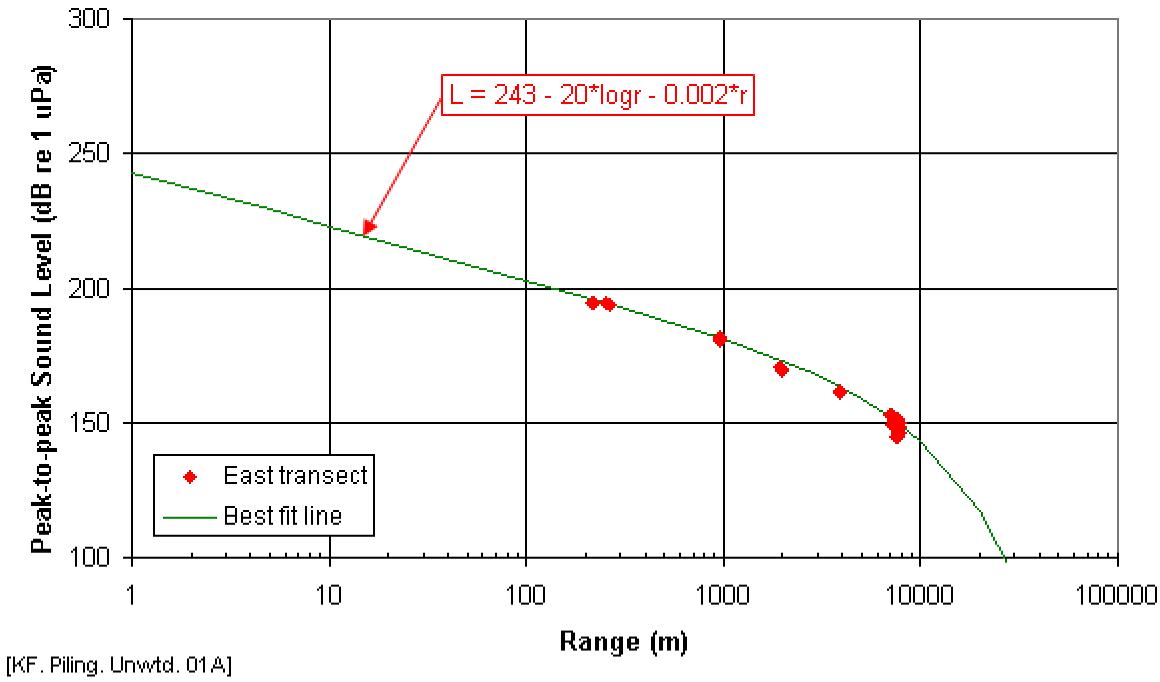

Figure 4.14. Variation of the unweighted peak-to-peak sound level with range during construction of the Kentish Flats windfarm (4.3 m diameter piles in very shallow water).

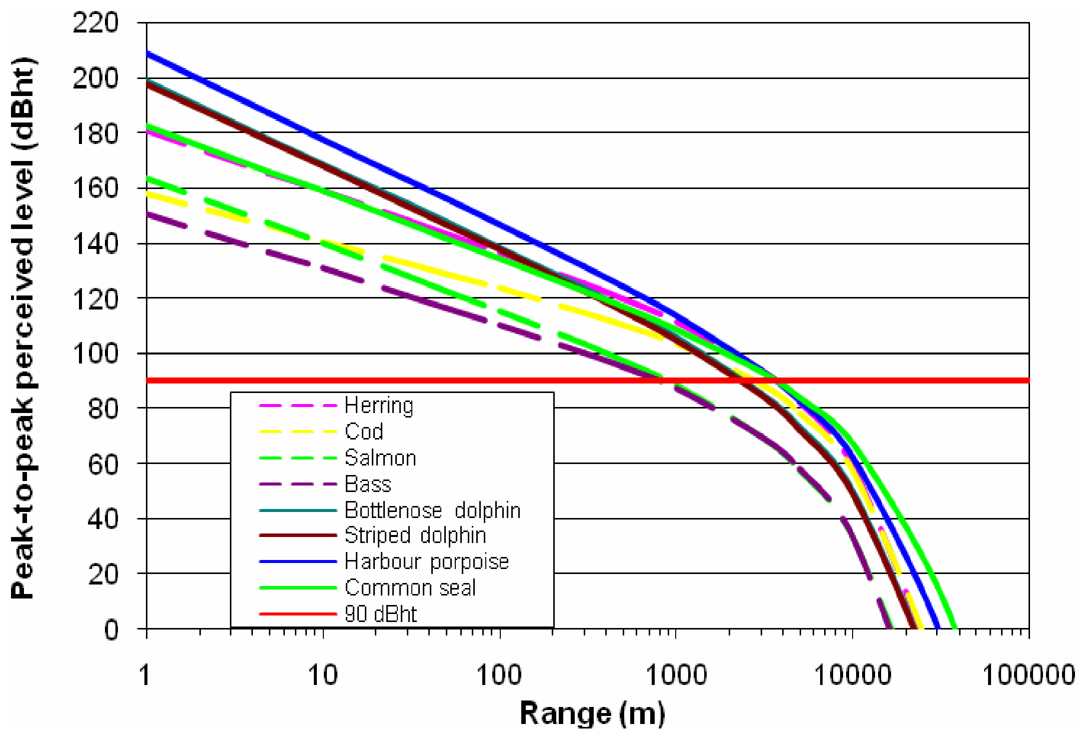

Figure 4.15. Variation of the perceived peak-to-peak sound level (dB_{ht}) with range for various marine species during impact pile driving operations to construct the Kentish Flats offshore windfarm.

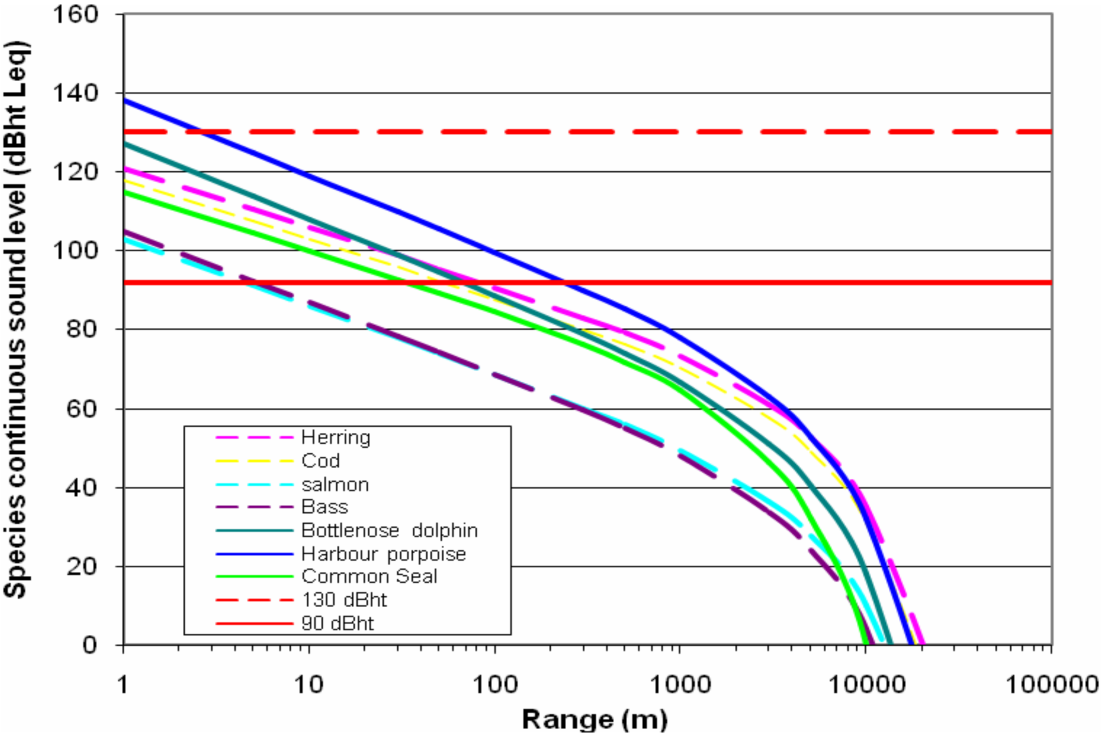

Figure 4.16. Best fit curves for the variation with range of the species continuous perceived sound level in dB_{ht} units during impact pile driving operations during construction of the Kentish Flats offshore windfarm.

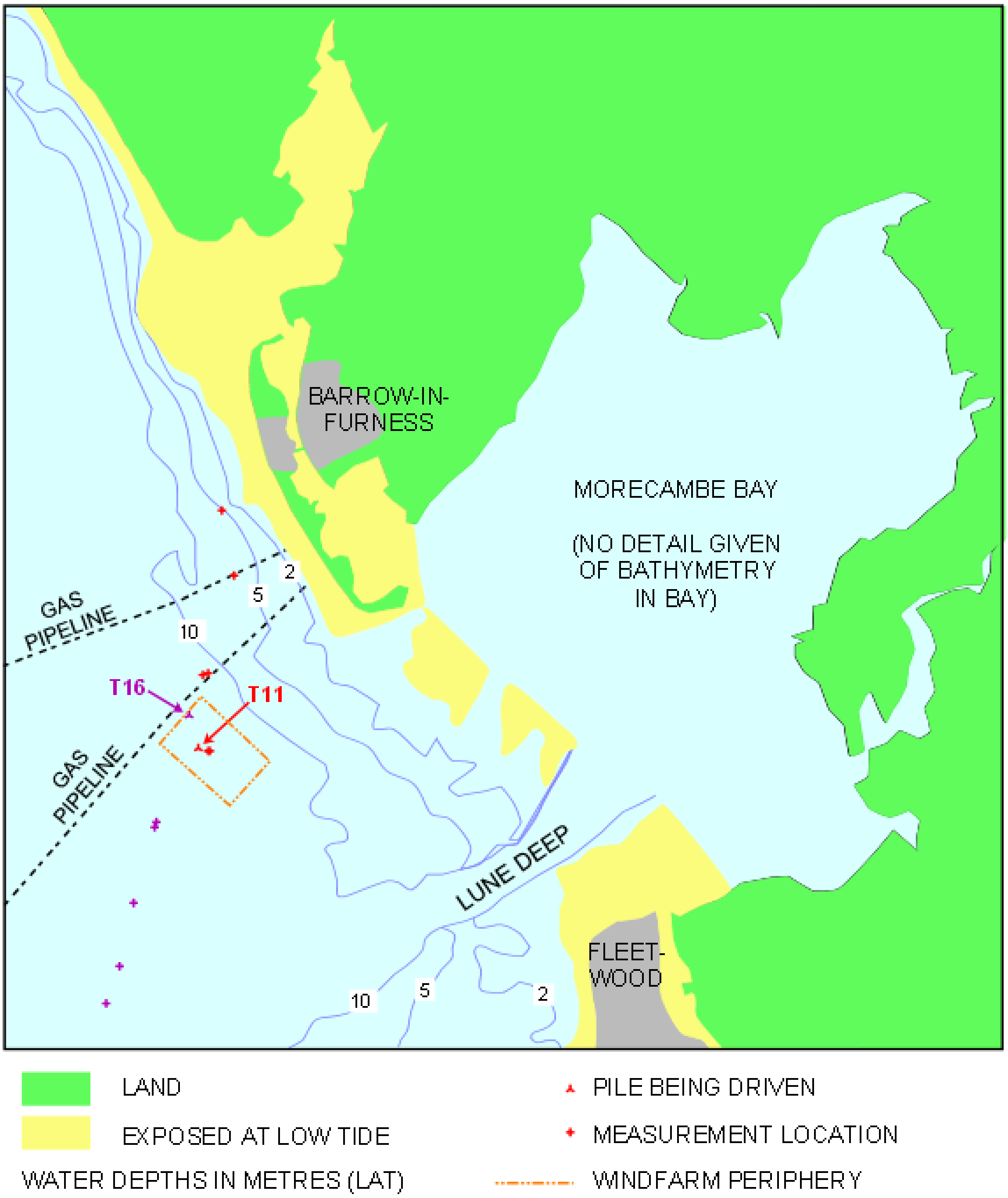

Figure 4.17. Sketch map showing the location of the Barrow windfarm site and the transects along which pile driving noise measurements were taken.

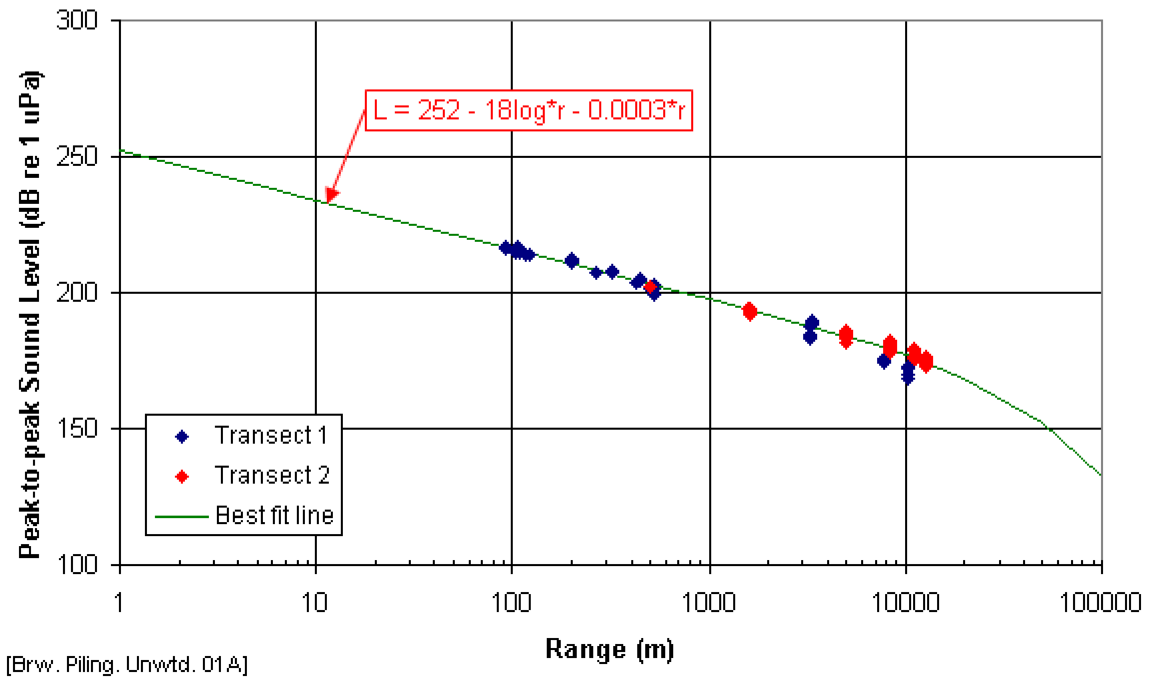

Figure 4.18. Variation of the unweighted peak-to-peak sound level with range during construction of the Barrow windfarm (4.7 m diameter piles in deep water).

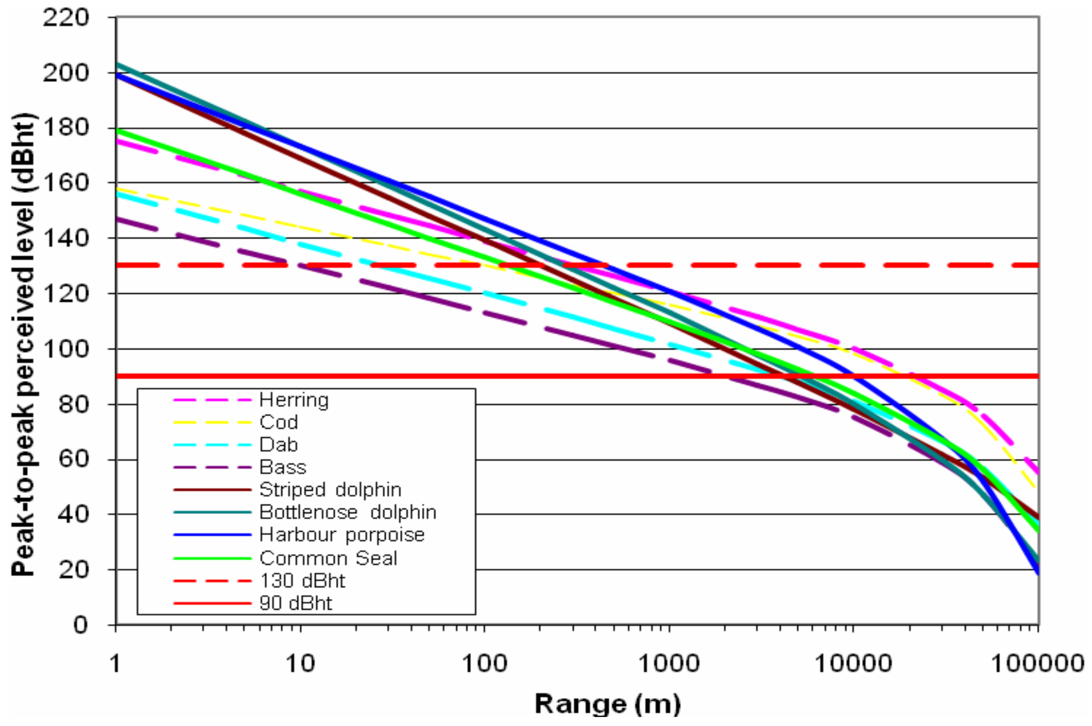

Figure 4.19. Variation of the perceived peak-to-peak sound level (dB_{ht}) with range for various marine species during impact pile driving operations to construct the Barrow offshore windfarm.

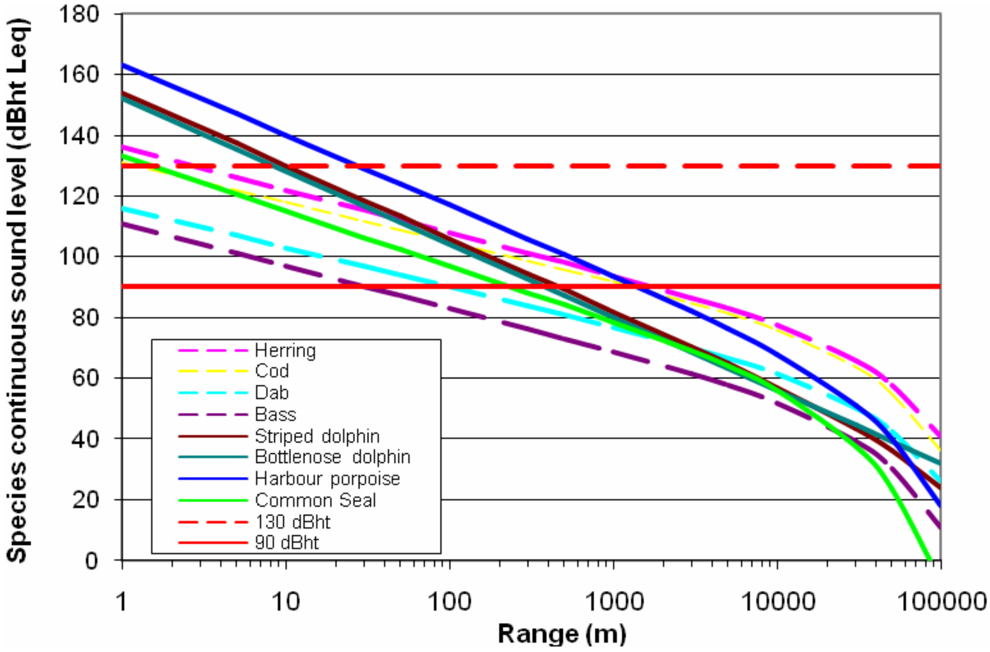

Figure 4.20. Best fit curves for the variation with range of the species continuous perceived sound level in dB_{ht} units during impact pile driving operations during construction of the Barrow offshore windfarm.

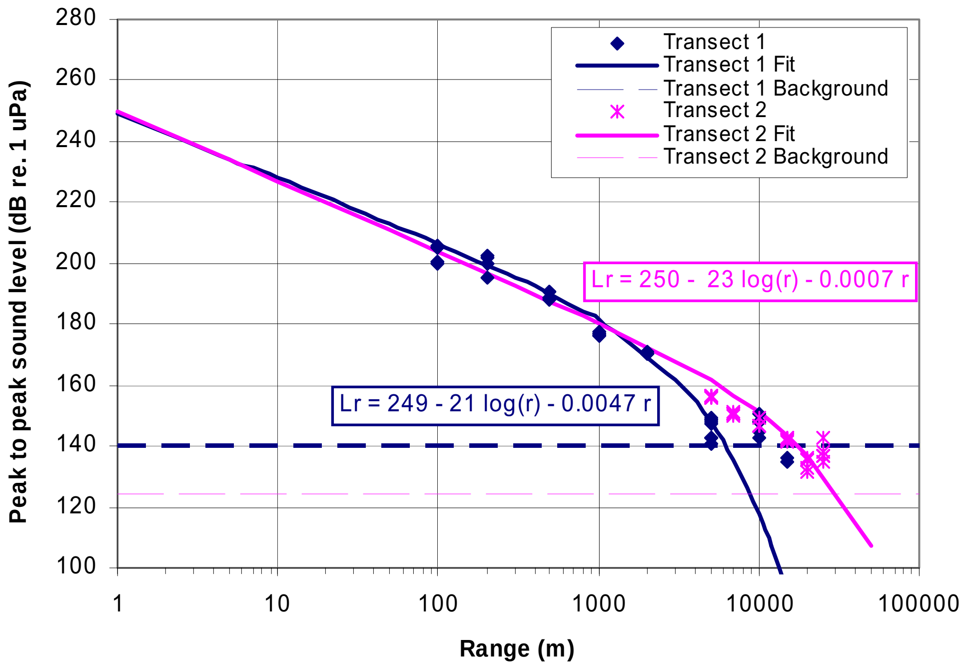

Figure 4.21. Variation of the unweighted peak-to-peak sound level with range during construction of the Burbo Bank windfarm.

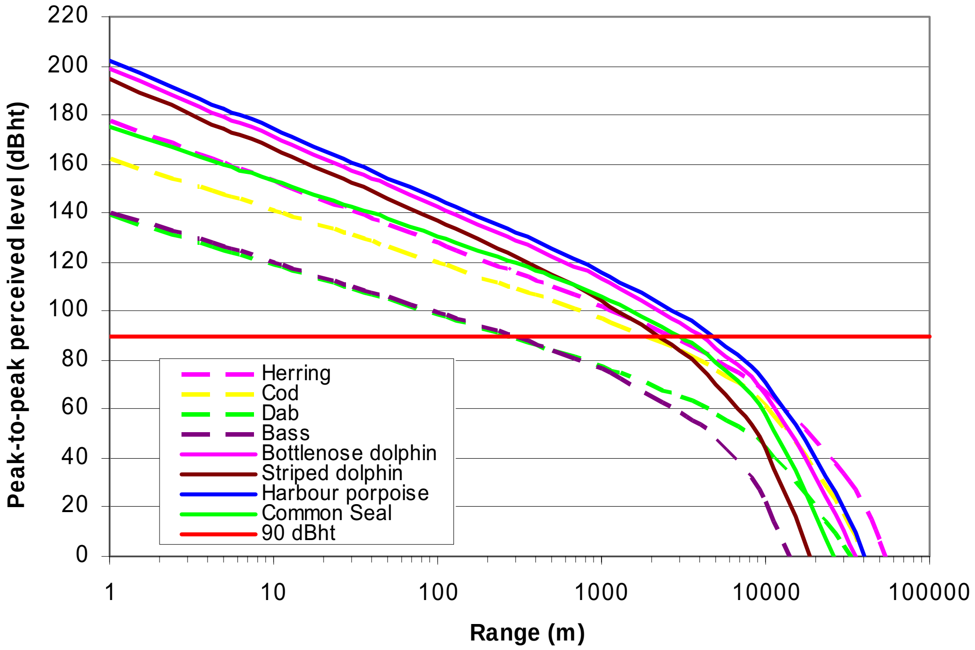

Figure 4.22. Variation of the perceived peak-to-peak sound level (dB_{ht}) with range for various marine species during impact pile driving operations to construct the Burbo Bank offshore windfarm.

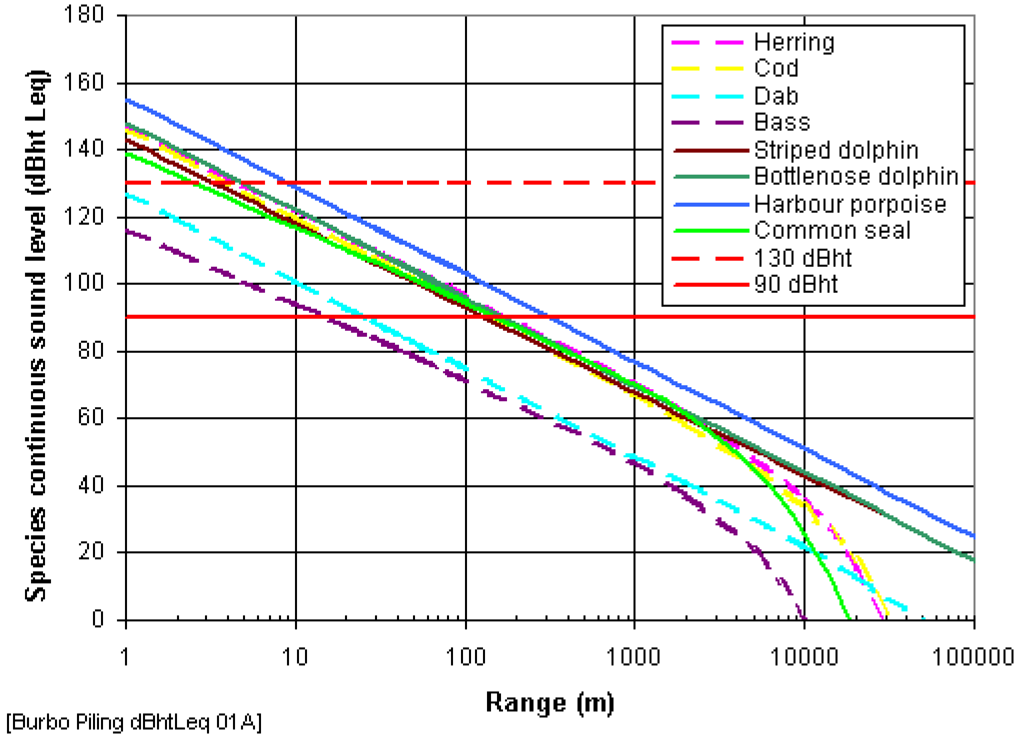

Figure 4.23. Best fit curves for the variation with range of the species continuous perceived sound level in dB_{ht} units during impact pile driving operations during construction of the Burbo Bank offshore windfarm.

5 Measurements of operational noise

5.1 Measurements of operational noise at North Hoyle

5.1.1 Introduction

When a windfarm is operational, the main source of underwater noise will be mechanically generated vibration from the the turbines transmitted into the sea through the structure of the support pile and foundations (Nedwell *et al.* 2003). The available data indicate that the noise generated by a working turbine is much lower than the noise created during construction by piling. However, while construction noise may only span a period of a few months, operational noise will span the lifetime of the windfarm. There is consequently interest in whether operational noise may have long term effects, such as excluding species from the vicinity of the windfarm.

The requirements for accurate measurement of the noise from operational windfarms are, if anything, more stringent than those for measurement of construction noise. The noise may be near to the natural background noise level, and hence easily contaminated by extraneous or electronic noise. In seawater, in the vicinity of working turbines, large circulatory currents normally occur and electronic "hums" are readily induced in the sensitive equipment used to measure sound, which will register as a spurious peak in the noise spectrum and an artificially high level of noise. It may be noted that at least one measurement of windfarm noise available in the public domain is dominated by spectral peaks characteristic of mains induced noise.

In the spectral domain, mechanical noise generally presents as a set of "swathes", or peaks of a few Hz or tens of Hz bandwidth. However, contamination by mains noise is readily recognised by narrow peaks at mains frequency and its third harmonic (50 Hz and 150Hz). As a consequence, the spectra of the measurements of operational noise in this section have been presented as narrowband spectra. The reader is therefore able to make this assessment for themselves. It may be commented that no evidence of such contamination was found in the measurements presented here.

5.1.2 Unweighted measurements and spectra for North Hoyle

Measurements of noise of the operational North Hoyle windfarm were taken on 3 March 2005 between 0900 hours and 1600 hours. On this day all the turbines, with the exception of WTG05, WTG06 and WTG10, were operating. The wind was from the north to north-west, at Force 4 at the start of the taking of the measurements, but falling soon to Force 3 and then decreasing to Force 2 and Force 1 during the day. The sea state was initially choppy with a low swell, but it declined to a smooth state with a low swell for most of the time that measurements were taken.

Figure 5.1 illustrates the locations where measurements were taken within and around the operational North Hoyle windfarm. The data presented in this section have been selected from Drift 3, during which the measurement boat drifted from a position just over a kilometre to the north-west outside the windfarm, passing onwards a further kilometre within the windfarm.

Measurements were taken at intervals of a few hundred metres along the course of the drift. The time histories obtained were analysed into spectra, illustrating the frequency components of the signal. Figure 5.2 illustrates the spectra obtained along Drift 3. The figure illustrates the Power Spectral Density of the sound on a frequency scale from 1 Hz to 100 kHz. A total of nine spectra are plotted; these illustrate the spectra of the sound at various positions on the drift. These are presented as the distance from the north-western-most turbine; it may be seen that the drift passed close to this turbine on entering the turbine array and continued onwards between the turbines in roughly the same direction.

It may be seen that generally the spectral levels are similar, with no great increase as the measurements enter the active turbine array that would indicate the presence of a dominant source of noise. The spectral measurements comprise three regions. Between 1 Hz and 20 Hz the level is roughly constant and is probably dominated by noise created by wave action. Between about 20 Hz and 80 Hz there is a small broad peak or "swathe" in the spectra. It is possible that this corresponds to noise from local shipping, although it is possible that there is a contribution from rotational noise from the windfarm. At the higher frequencies, from 100 Hz upwards, there is a broad featureless skirt in the noise, which may correspond to wind generated noise.

In one case, for the measurement at 227 metres inside the farm, there is an increase in high-frequency broadband noise from 30 Hz to the highest frequencies measured; it is likely that this results from a short local increase in wind speed and hence in surface generated noise. In the case of the measurement taken 483 metres inside the windfarm, there is also an increase in the spectral level, but in this case in the swathe from 20 Hz to 80 Hz. While it is possible that this arises from the operation of the windfarm, there was no equivalent measurement taken elsewhere in the windfarm array. It is therefore more probable that this results from noise external to the windfarm, perhaps from the movement of distant shipping during the recording.

Figure 5.3 illustrates the same data as in the preceding figure. In this case it has been presented as an isometric plot, with the spectral level presented as a function of both the frequency and range from the north-western turbine. No obvious contribution to the noise field from the turbines of the windfarm can be detected.

5.1.3 The species perceived sound level in dB_{ht} units for North Hoyle

The measurements indicate that the level of noise created by the North Hoyle windfarm is low and insufficient to cause environmental effects. The noise was only above the ambient noise in the immediate vicinity of the windfarm turbines. Under these circumstances, as the levels of noise were low in comparison with the background sea noise environment in shallow water, it was found that the measurement methods used to quantify the effects of pile driving noise (the distance within which a certain effect might be noted) were not appropriate. Therefore, to quantify the contribution of the windfarm to the noise field, a statistical approach has been used. The noise levels were averaged over the measurements made within the windfarm, and an equivalent number made at distance from the same windfarm (generally in excess of 1 km). Table 5.1 illustrates the level of noise in unweighted and dB_{ht} units within and outside the North Hoyle windfarm.

It may be seen from the second row that the unweighted level was 128 dB re 1 Pa within the windfarm, and 120 dB re 1 Pa outside the windfarm. On average, therefore, the region within and in the immediate vicinity of the windfarm was 8 dB noisier than was the case further away.

The same averaged levels are presented for five species of fish and three marine mammals in rows 4 to 11 of the table. It may be seen that there is a significant variation in the results; this may be expected as, in some species, the noise from the windfarm may coincide with the most sensitive hearing range of that species. It is interesting to note that the increase is greater with fish than with marine mammals; this may be because fish are low frequency hearers and the spectrum of the windfarm's noise is predominantly low frequency. The results have been averaged across the fish species and the marine mammal species in the final three rows of the table; it may be seen that the level is 9.4 dB higher on average for the fish species whereas it is only 6.3 dB higher for the marine mammals. While it might be concluded that the effects of the noise would tend to be more significant for the fish than the marine mammals, it should be noted that the difference in level is comparable with the variations that naturally occur as a result of varying sea conditions. It is thought very unlikely that the slightly higher levels within the windfarm have any significance for fish and marine mammal populations.

Windfarm: North Hoyle	**Inside farm**	**Outside farm**	**Difference**
Unweighted (dB re. 1μPa)	128	120	8
Species	**Species Perceived Level (dB_{ht})**		
Bass	15	9	6
Cod	38	27	11
Dab	22	9	13
Herring	41	35	6
Salmon	16	5	11
Bottlenose Dolphin	46	39	7
Harbour Porpoise	55	48	7
Common Seal	39	34	5
Average difference - marine mammals species			6.3
Average difference - fish species			9.4
Average difference - all species			8.25

Table 5.1. Average values of unweighted and of dB_{ht} levels for various species for operational noise at the North Hoyle windfarm.

5.2 Measurements of operational noise at Scroby Sands

5.2.1 Introduction

Measurements of the noise of the operational Scroby Sands windfarm were taken on 12 March 2005 between 0845 hours and 1245 hours. On this day twenty five of the turbines were operating (turbines WTG2, WTG5, WTG25, WTG31 and WTG38 were out of action). The wind was from the north-west, initially at 8 m/s but increasing by 1100 hours to between 10 and 11 m/s. The sea state was choppy and with a medium swell throughout the time that measurements were taken. During this time the water depth varied from 4 to 12 m.

Figure 5.4 shows the tracks of the survey vessel for three of the drifts along which measurements were taken.

5.2.2 Unweighted measurements for Scroby Sands

5.2.2.1 Background measurements

Five measurements were taken of noise to the west of the windfarm. Three measurements were taken at a nominal ½ nautical mile (925 m) range, and two measurements were taken at a nominal 1 nautical mile (1850 m) range from the windfarm site. These two measurement locations are shown in Figure 5.4. At these locations the water depth was measured at 20 m.

The spectra for the five sets of background noise measurements are shown in Figure 5.5, together with the mean (average) background spectrum. It may be seen that the spectra may be divided into four bands. At frequencies of about 8 Hz and below, the spectrum is relatively flat and probably dominated by pressure changes caused by the passage of waves. There are two peaks in the spectrum at frequencies of about 7 Hz and 10 Hz. There is also a broad peak or swathe in the spectrum at frequencies from about 20 Hz to 70 Hz. It is probable that all three of these peaks are caused by the sound from distant shipping. At frequencies above 80 Hz or so, and up to the highest frequencies recorded at 100 kHz, there is a relatively broad band of sound, probably mainly associated with wind-generated noise. Despite being spaced some distance apart, and taken at different times, it may be seen that the spectra for the background noise are relatively constant.

These spectral levels have been used to provide an indication of the ambient background sea noise (as if no windfarm were present) in the windfarm region, and are typical of the levels that have been measured previously by the authors in coastal waters. For instance, a summary of about 500 individual measurements of background noise at shallow costal windfarm sites is presented in Nedwell *et al.* (2003). The measurements of overall rms sound pressure level, which were made over a wide frequency range of 10 Hz to 120 kHz, indicated a mode of about 116 dB dB re. 1 μPa at the North Hoyle windfarm site, associated with range of levels from about 90 – 158 dB re. 1 μPa. This report also presented previous measurements of noise at the Scroby Sands site, taken in 2003. The levels, which were found to have a mode of about 120 dB re. 1 μPa, associated with range of levels from about 100 – 135 dB re. 1 μPa, are consistent with background sea noise levels measured during the pile driving noise surveys.

Compared with quoted ambient noise levels for deep water, the waters around the Scroby Sands site appear relatively noisy. However, it should be noted that most measurements of background noise presented in the literature have been measured over very limited frequency ranges, often terminating at an upper limit 10 kHz or so. Such measurements do not include any contribution from noise above that frequency, which may be substantial, particularly in and around sandbanks and shallow coastal water regions.

5.2.2.2 Noise within the windfarm array

During the subsea noise survey underwater sound recordings were undertaken throughout the windfarm array. Figure 5.6 shows a noise time history of 30 seconds of a typical underwater noise recording. The noise is relatively featureless with no tonal components, or transients, that characterise high levels of anthropometric noise. Throughout the measurement period the overall Sound Pressure Level in and around the windfarm array varied from 122 to 147 dB re. 1 μPa (ie. RMS pressures from approximately 1 to 20 Pa).

5.2.2.3 Measurements from a single wind turbine

A series of recordings were taken at increasing range from a single operational wind turbine (turbine 13). Figure 5.7 compares the spectral levels of the underwater noise at increasing range from the turbine. The figure presents the power spectral density of the sound in dB re 1 μPa^2 per Hertz, versus the frequency.

It may be seen that the levels recorded at the windfarm are in most cases rather higher than the background noise levels presented in the previous section which were recorded in deeper water further away from the windfarm. However, there is little correlation between the proximity of the turbine and the level of the spectrum, and hence it may well be that the background noise itself is rather higher, perhaps as a result of the shallower water. This tends to be reinforced by the observation that the spectra are relatively featureless, without the sharp peaks that tend to be associated with rotating machinery.

It may be noted that, even when in close proximity to an operational wind turbine, the spectral levels of the underwater noise are no more than 20 dB above the ambient background levels measured at distance from the windfarm array.

Figure 5.8 (a) illustrates the same information, but in this case as an isometric plot. The figure presents the spectral level of the sound, as a function of the range from wind turbine 13. The level is plotted over a low frequency range from 10 Hz to 100 Hz. The intention of the analysis was to detect peaks in the spectra caused by rotating machinery. Figure 5.8 (b) presents the same information, but in this case the spectrum has been connected as a surface to make changes in the level more apparent.

If the spectra in close proximity to the turbine are inspected it may be seen that the level is slightly higher in the frequency range from about 20 Hz to 60 Hz. There are broad peaks in the spectra rising a few dB above the general level. However, these are not in a constant position, and therefore it must be concluded that they are an artefact of natural processes, rather than a feature of noise from the wind turbine.

In summary, it is therefore apparent that the wind turbines measured create low levels of noise, that are only possibly discernible from existing background noise within the immediate vicinity of the windfarm, and certainly do not contribute to the background noise at any great distance. The underwater noise emissions are greatly below the level that might cause lethal or physical injury to marine species. None of the spectra obtained indicate narrowband tonal components that would characterise mechanical or electrical noise emissions from the operational wind turbines. The spectra may represent a general increase in low frequency noise due to tidal water flow around the turbine monopiles, or alternatively, it may indicate the natural increase in flow noise and the concentration of underwater noise in the very shallow waters at Scroby Sands compared with that in deeper water (approximately 20 m) to the west.

5.2.3 The species perceived sound level in dB_{ht} units for Scroby Sands

Table 5.2 indicates the average level of sound that would be perceived by various species in the vicinity of the Scroby Sands windfarm, and at distance from it. The table illustrates that there is a considerable variation in the perceived level of noise for different marine species. In general, it may be seen that for species with poor hearing, such as the salmon, the perceived level of sound is low, despite the background noise in the shallower water being higher than that in deeper water. For the most sensitive species, such as the porpoise, the perceived levels are rather higher. However, none of the dB_{ht} levels within the windfarm exceed the 90 dB_{ht} level, at which a strong avoidance, or even the 75 dB_{ht} level, at which a mild behavioural avoidance, for marine species might be expected. It should be noted that the closest measurements were taken at a range of only 15 m from an operational wind turbine.

The second row indicates the unweighted level of noise; it is interesting to note that the level is actually lower within the windfarm than outside it. Turning to the results for the various species, it may be seen that in general the levels are slightly lower within the windfarm than outside it. It is possible that these results have been caused by rougher wave conditions outside the windfarm creating higher levels of noise. Whatever the cause, it indicates that the increase in noise level within the windfarm is within the limits of natural variability.

Windfarm: Scroby Sands	**Inside farm**	**Outside farm**	**Difference**
Unweighted (dB re. 1µPa)	130	132	-2
Species	**Species Perceived Level (dB_{ht})**		
Bass	33	36	-3
Cod	56	54	2
Dab	34	35	-1
Herring	50	51	-1
Salmon	21	23	-2
Bottlenose Dolphin		51	N/A
Harbour Porpoise	56	56	0
Common Seal	40	42	-2
Average difference - marine mammals species			-1
Average difference - fish species			-1
Average difference - all species			-1

Table 5.2. Average values of unweighted and of dB_{ht} levels for various species for operational noise at the Scroby Sands windfarm.

5.3 Measurements of operational noise at Kentish Flats

5.3.1 Introduction

Measurements of the noise of the operational Kentish Flats windfarm were taken on 24 and 25 May 2007, on the former day from about 0915 hours to about 1630 hours, and on the latter day from about 1200 hours to about 1830 hours. On both days the wind speed was very low, and for most of the time the turbines were not turning, or only very slowly. Towards the end of the second day, at about 1720 hours, the wind picked up and started blowing at 6 to 8 m/s, and measurements were taken along two transects, from the western and northern edges of the farm.

Figure 5.9 is a sketch of the drift paths along which measurements were taken.

5.3.2 Unweighted measurements for Kentish Flats

Figure 5.10 illustrates spectra from time histories recorded as the survey vessel drifted away from the windfarm, from turbine A3. The figure presents the power spectral density in dB re 1 Pa^2 per Hertz, versus the frequency. Spectra are plotted for measurements at ranges from 105 m at closest to just over 2 km at the greatest range.

The spectra divide into three bands. At the lowest frequency, from 1 Hz to about 10 Hz, the spectrum is generally relatively featureless and is probably mainly associated with hydrodynamic pressure changes resulting from the passage of waves and turbulence. From 10 Hz to about 300 Hz there is a band in which there is significant tonal noise. From 300 Hz to about 10 kHz there is a band of broadband noise, although in some cases there does appear to be some structure in the noise, in some cases presenting as a "comb"-type spectrum.

Figure 5.11 presents the same information, but in this case as an isometric plot. The figure illustrates the power spectral density in dB re 1 Pa^2 per Hz of the noise, versus the frequency on one axis and the distance from turbine A3 on the other. The colours in which each of the time histories of the plot are illustrated have been chosen to be the same as those of the preceding plot of Figure 5.10. It may be seen from this figure that there are possibly three distinct noise regions or mechanisms in the second band. At the lower frequencies in the band from 30 Hz to about 100 Hz, the strong band of noise may be detected at the greatest distance from the turbine that sound was measured, of about 2 km. There is a second band, at about 200 to 800 Hz, which may be clearly seen for measurements in the vicinity of the wind turbine and out to about 1 km, where the individual peaks in the band are lost. It appears that in this band there is also a generally high level of broadband noise, possibly caused by flow or wind noise. Finally, for the closest measurements, at around 100 m, there is a tonal band from about 2 kHz to 8 kHz; these components cannot however be seen in any of the measurements at greater range.

It cannot be ascertained at the current state of research where these tonals arise, although it may be commented that audibly there is a clear sound of rotating machinery on the recordings. It is possible that the lower frequencies arise from meshing noise within gearboxes of the windfarm turbines. However, in view of the relatively constant level of the sound in the lowest frequency band, it is thought more likely that it arises from a source external to the windfarm array, perhaps from a distant ship. It may be commented that the Thames shipping lane was adjacent to the windfarm, and while no recordings were taken with shipping in close proximity to the windfarm, in general there was always shipping within 5 or 10 km. Audibly, the recordings sounded similar to shipping noise.

By contrast, at the higher frequencies of about 200 to 800 Hz, the level of the tonals falls off rapidly with range and hence they can be ascribed with reasonable confidence to the wind turbines. In the case of these higher frequencies it may be commented that, where power convertors are used, such frequencies may arise from the high frequency transformers and other electronics used in the conversion process.

Figures 5.12 and 5.13 present the same information, but in this case for a different drift, from turbine D1. Measurements were taken at distances from about 100 m up to just over 1 km. In general, the form of the spectra is very similar to that of the preceding set of measurements. There is strong evidence of tonal noise in the band from about 30 Hz to 800 Hz; however, in this case, there is no clear evidence of tonal noise at the higher frequencies that were observed in the preceding case. Similarly to the preceding case, however, the lower frequency tonal noise may be seen to be clearly evident at the greatest range that measurements were made, of 1 km. Indeed, there is little difference in the spectra at all of the ranges measured and hence it may be assumed that even at the closet range measured, of about 100 m, there is no evidence of the wind turbines contributing to the background noise level.

5.3.3 The species perceived sound level in dB_{ht} units for Kentish Flats

Table 5.3 indicates the average level of sound that would be perceived by various species in the vicinity of the Kentish Flats windfarm, and at distance from it. The table again illustrates that there is a considerable variation in the perceived level of noise for different marine species.

The unweighted level is very slightly higher in the windfarm than outside it, by 1 dB. The results for dB_{ht} levels for the marine animals indicate that the perceived noise levels are slightly higher in the windfarm than outside, by a few dB. Again, however, the perceived level of sound is low, such that no effect on marine species might be expected.

It may be concluded that the contribution to noise from the windfarm is insignificant, even in its immediate vicinity.

Windfarm: Kentish Flats	**Inside farm**	**Outside farm**	**Difference**
Unweighted level (dB re. 1µPa)	114	113	1
Species	**Species Perceived Level (dB_{ht})**		
Bass	8	5	3
Cod	29	26	3
Dab	15	12	3
Herring	34	31	3
Salmon	8	5	3
Bottlenose Dolphin	37	37	0
Harbour Porpoise	48	50	-2
Common Seal	38	29	9
Average difference - marine mammals species			2.3
Average difference - fish species			3
Average difference - all species			2.75

Table 5.3. Average values of unweighted and of dB_{ht} level for various species for operational noise at the Kentish Flats windfarm.

5.4 Measurements of operational noise at Barrow

5.4.1 Introduction

Measurements of the noise of the operational Barrow windfarm were taken on 30 January and 1 February 2007.

On the first day measurements were taken between 0945 hours and 1300 hours while the vessel drifted in the farm between turbines, and along a transect starting at turbine WTG11 (C5) and out towards the north-west. When measurements were taken along this transect turbines C5 and C7 were operating, but turbine C6 was not rotating. The wind gradually increased from 8 m/s to 11 m/s during the time that measurements were taken, and wave height increased from 0.4 m to 0.9 m.

On the second day measurements were taken between 0945 hours and 1400 hours along transects out to the north-east from turbine WTG29 (A2), to the south-east from turbine WTG15 (C1), and to the south-west from turbine WTG6 (D3), and while drifting between turbines within the farm. The wind speed was about 5 m/s for most of the time, increasing to 7.5 m/s over the last third of the measurement period. During this time the wave height was 0.4 m all the time.

Figure 5.14 is a sketch of the locations where measurements were taken in and around the windfarm.

5.4.2 Unweighted measurements for Barrow

Figure 5.15 illustrates the spectra from time histories recorded as the measurement vessel drifted away from turbine C5, on the first drift. The figure presents the power spectral density in dB re 1 Pa^2 per Hertz, versus the frequency. Spectra are plotted for measurements at ranges from 5 m at closest to 500 m at the greatest range. Figure 5.16 presents the same information as an isometric plot of power spectral density in dB re 1 Pa^2 per Hz of the noise, versus the frequency on one axis and the distance from turbine C5 on the other. The colours of the spectra of the plot are the same as those of the preceding figure.

At the lowest frequencies, from 1 Hz to about 10 Hz, the spectra are generally relatively featureless and, in common with the measurements of the previous section, are probably mainly associated with hydrodynamic pressure changes resulting from the passage of waves. It may be noted, however, that there is a small increase in this band in the vicinity of the turbine; it is thought likely that this arises from increased turbulence levels around the turbine. Narrowband analysis of the data did not reveal any structure, such as for instance low frequency tonal components characteristic of blade rate noise.

From 10 Hz to about 200 Hz there is a band in which there is significant tonal noise. It may be noted that for the measurements closest to the turbine there is a significantly increased level of tonals in this band. The recordings audibly indicated machinery noise, modulated heavily by propagation through a highly time-variant channel. It was evident from the recordings that the modulation was caused by wave action in the shallow water, probably due to the consequent changes in depth. It has been noted that the attenuation of waterborne sound increases greatly as the water depth decreases.

From 200 Hz to above 10 kHz there is a band of broadband noise. It is probable that this arises from wind noise, caused by wind interaction with the rough water surface. It is possible to demonstrate that noise in this band does not arise at the turbine. For instance, it may be noted that in the case of the closest measurement, at 5 m, the level in this band is actually the lowest recorded, whereas in the case of the measurement at 250 m the level is actually rather high.

Since there is no consistent relationship between distance and level, it may be assumed that the noise does not arise at the turbine.

Figures 5.17 and 5.18 present the same information, but in this case for the second drift that was undertaken, which commenced at turbine C2 and terminated near to turbine C3. From 10 Hz to about 200 Hz there is again significant tonal noise. The levels generally appear to decrease as the distance from the turbine, but increase for the measurement at 500 m from the turbine; however this latter measurement was in close proximity to turbine C3. The levels are lowest for the measurements at 200 and 330 m, which were furthest from any turbine. The recordings again audibly indicated machinery noise with heavy modulation.

The broadband noise band from 200 Hz to above 10 kHz again indicates no consistent relationship between distance and level, and is thought to be due to wind noise.

Further sets of measurements were taken outside the windfarm, on transects to the north-west, north-east and south-east. The purpose of these measurements was to identify the distance over which the windfarm contributed to the background noise field. As for the previous results, the spectra from these measurements are presented in pairs. The first figure of each pair presents the power spectral densities of the measurements in dB re 1 Pa^2 per Hz, versus the frequency, and the second figure an isometric plot of power spectral density in dB re 1 Pa^2 per Hz of the noise, versus the frequency on one axis and the distance from turbine at the start of the transect on the other.

Figures 5.19 and 5.20 present the results for the transect to the north-west. The first three recordings, which were made at distances of 100, 200 and 400 m from turbine C5, are all within the windfarm, and additionally are all in reasonably close proximity to working turbines. It may be seen that, for these measurements, there is a high level of tonal noise in the band from 20 Hz to 200 Hz, due to machinery noise from the turbines. For the measurements at 1000 and 2000 m, the level of the tonals has decreased significantly. These results are consistent with the tonal noise arising from the windfarm. It may be seen that the broadband noise, at 200 Hz and above, is also consistently higher in the vicinity of the windfarm.

Figures 5.21 to 5.24, for the transects to the south-east and north-east, generally show similar features. However, in the case of the transect to the north-east, the level of the broadband noise at 200 Hz and above is relatively constant. It may be that this is because the water depth, in this case only, gradually reduced along the transect.

5.4.3 The species perceived sound level in dB_{ht} units for Barrow

Table 5.4 indicates the average level of sound that would be perceived by various species inside and in close proximity to the Barrow windfarm, and at distance from it. Once more, there is a considerable variation in the perceived level of noise for different marine species, but again the perceived level of sound is low, such that no effect of the noise on marine species might be expected.

The unweighted level is higher in the windfarm than outside it, by 2 dB.

The results for dB_{ht} levels for the marine animals indicate that the perceived noise levels are generally slightly higher in the windfarm than outside, by a few dB. There is a small difference between the results for fish and marine mammals, being 2 dB higher in the windfarm on average for the marine mammals, but only 1 dB on average for fish.

In common with the preceding results for the other windfarms, it may be concluded that the contribution to noise from the windfarm is insignificant.

WindFarm: Barrow	**Inside farm**	**Outside farm**	**Difference**
Unweighted (dB re. 1μPa)	124	122	2
Species	**Species Perceived Level (dB_{ht})**		
Bass	17	16	1
Cod	40	39	1
Dab			
Herring	43	42	1
Salmon	19	18	1
Bottlenose Dolphin	41	39	2
Harbour Porpoise	49	47	2
Common Seal	39	37	2
Average difference - marine mammals species			2
Average difference - fish species			1
Average difference - all species			1.4

Table 5.4. Average values of unweighted and of dB_{ht} levels for various species for operational noise at the Barrow windfarm.

5.5 Discussion of results of subsea operational noise at the four offshore windfarms

In general, the level of noise from operational windfarms was found to be very low. The noise could be recognised by the tonal components caused by rotating machinery, and by its decay with distance. Typically, even in the immediate vicinity of the wind turbines, the noise from the windfarm turbines only dominated over the background noise in a few limited bands of frequency. Even within this range, the noise was usually only a few dB above the background noise. In some cases, the tonal noise caused by the windfarms was dominated by the tonal noise from distant shipping.

An important issue is whether the operational noise from windfarms has the capacity to modify the behaviour of animals in their vicinity. To assess this, the analysis has included an evaluation of the average level of noise measured within the windfarm, compared with the level that was recorded during the measurements well outside the wndfarm (i.e. at a range whereby there was no contribution to the noise from the windfarm). In order to assess the effect that this noise might have on marine animals, the levels have been calculated in dB_{ht} units, which indicate the level of noise that the various species would perceive.

In no case (*i.e.* for none of the windfarms, and for none of the species assessed), did the levels of noise within the windfarm exceed either the level of 90 dB_{ht} at which a strong avoidance behaviour might be exhibited, or the level of 75 dB_{ht} at which a mild avoidance behaviour would be expected. In general, the levels were found to be low and consistent with the levels of pre-existing background noise that the animals would normally live in.

In some cases, such as North Hoyle and Kentish Flats, the level of noise measured within the windfarm was slightly greater, by up to 10 dB or more, than that measured outside. However, in other cases, such as Barrow and Scroby Sands, the level of noise measured within the windfarm was actually lower than that measured outside. When averaged across all of the windfarms, across all of the main mammals considered, the noise environment of a windfarm was found to be about the same as the surrounding area for marine mammals. When averaged the same way across all of the fish species considered, the noise within the windfarm was found to be just over 2 dB higher than the surrounding area The variations in level are well within the spatial and temporal variations that are typically encountered in background noise, and hence it may be concluded that, while there might be a small net contribution to noise in the immediate vicinity of the windfarm, this is no more than is routinely encountered by marine animals during their normal activity.

In conclusion, no evidence was found of noise levels within operational windfarms that might have the capacity to cause marine animals to avoid the area.

5.6 Summary of underwater noise measurements from operational windfarms

Measurements of the underwater noise within and around four operational windfarms have been taken and analysed. The conclusions drawn from the analysis of these measurements indicates that:

1. In general, the level of underwater noise created by operational windfarms was found to be very low. Even in the immediate vicinity of operational turbines few of the measurements were above the background sea noise level.

2. When analysed in terms of sound perception by species of fish and marine mammals using dB_{ht} analysis, the measurements indicated a maximum increase in the immediate vicinity of operational turbines of 8 dB_{ht} at the North Hoyle site, 3 dB_{ht} at the Kentish Flats site and 1 dB_{ht} at the Barrow Offshore Wind Farm site. No difference in levels was found at the Scroby Sands site.

3. These increases in level were no greater than natural variations in background level that may occur as an animal moves or climatic conditions change.

4. An average across all of the operational windfarm measurements indicates that the environment of an offshore windfarm is no noisier for marine mammals, and 2 dBht noisier for fish, than the waters surrounding the windfarm site.

5. On the basis of these findings, the small increase in noise in the immediate vicinity of turbines at operational windfarm sites is very unlikely to cause a behavioural response in the species of marine mammals and fish considered.

5.7 Figures

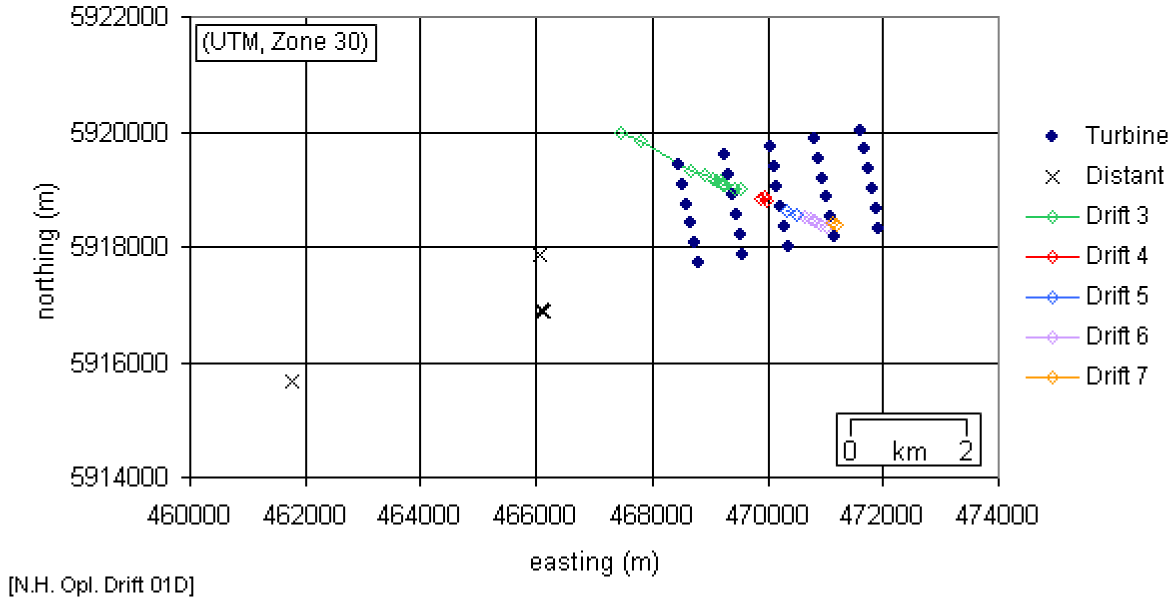

Figure 5.1. Sketch map showing the tracks of the measurement vessel when taking measurements of operational noise at the North Hoyle windfarm.

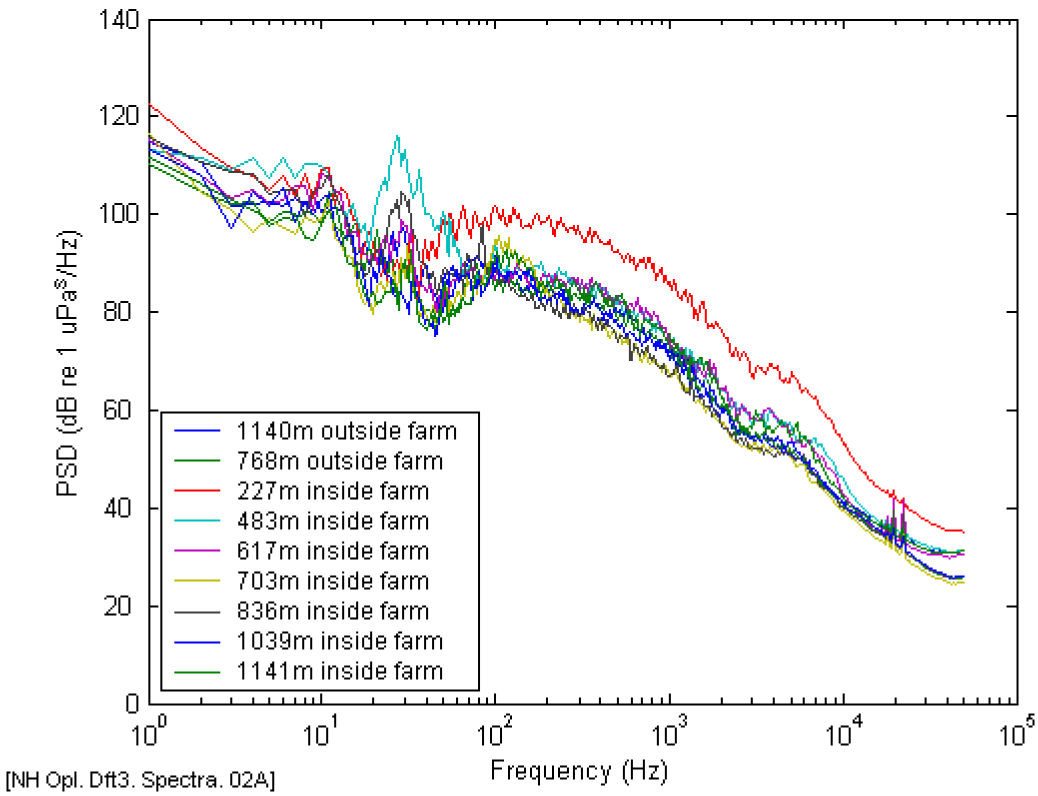

Figure 5.2. Spectra at various locations along Drift 3 at the North Hoyle windfarm.

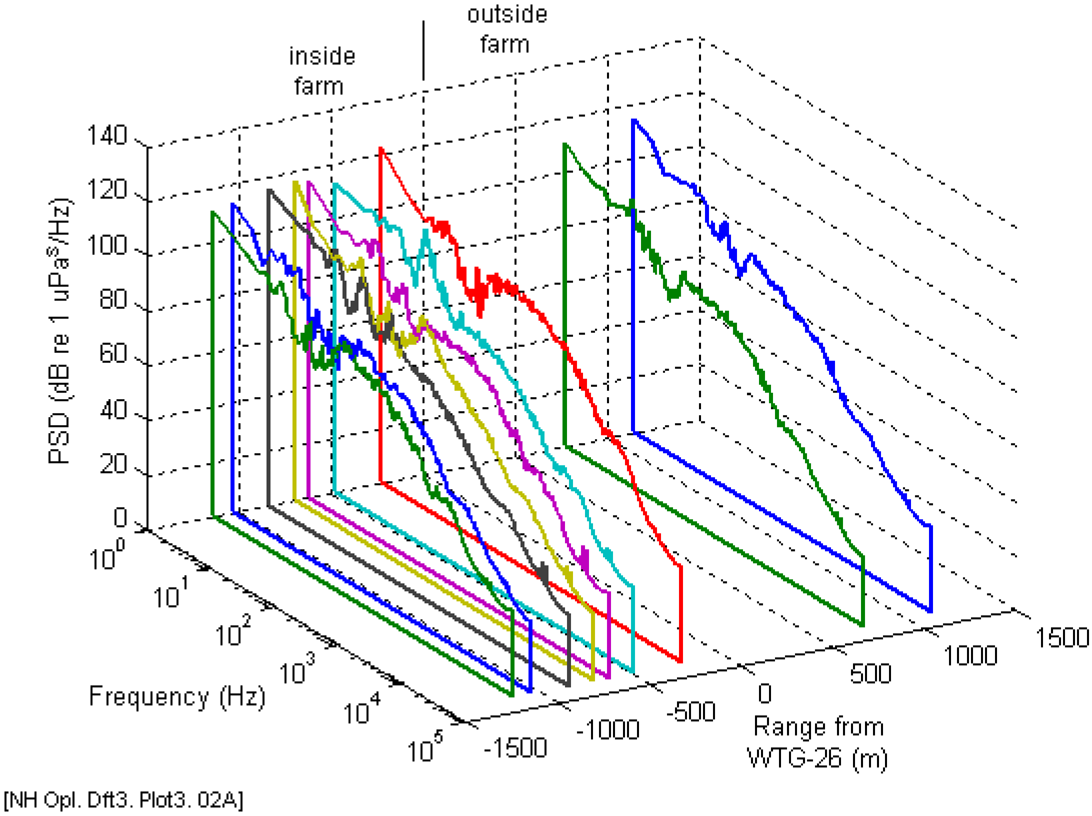

Figure 5.3. Spectra at various locations along Drift 3 at the North Hoyle windfarm (same data as preceding figure).

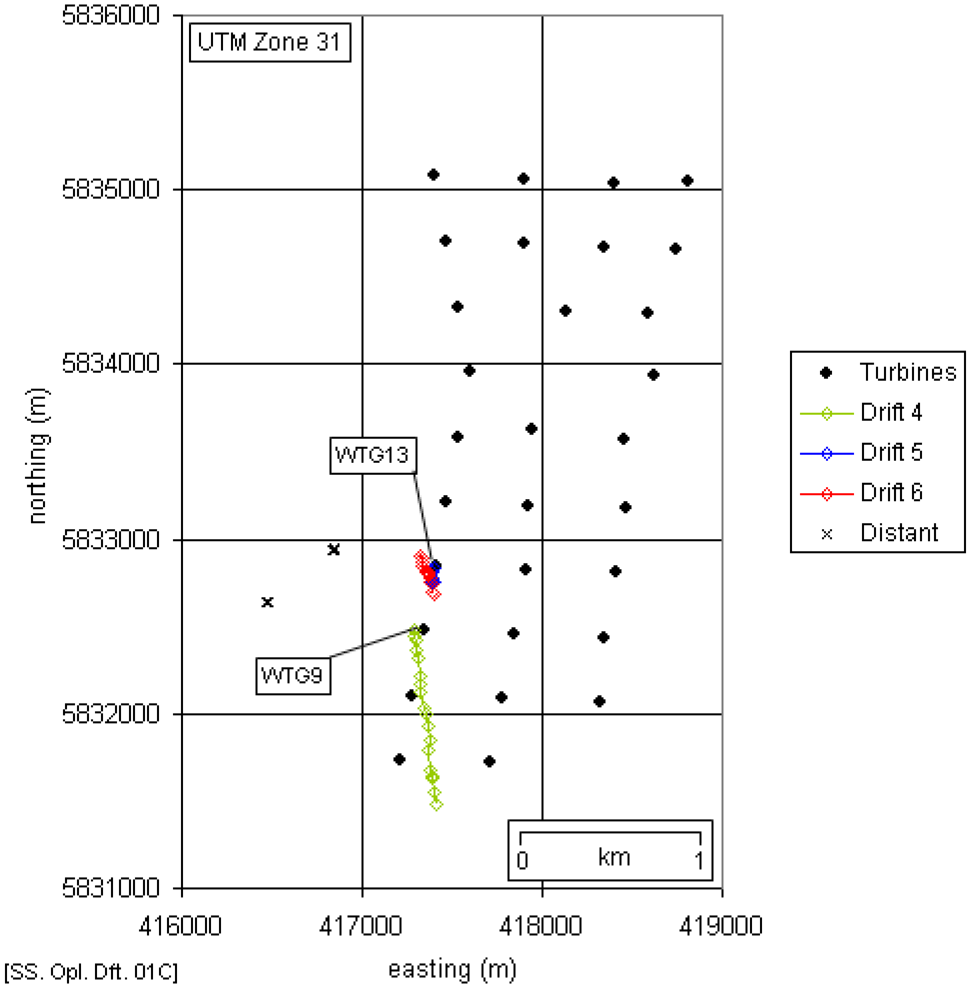

Figure 5.4. Sketch map showing the tracks of the measurement vessel when taking measurements of operational noise at the Scroby Sands windfarm.

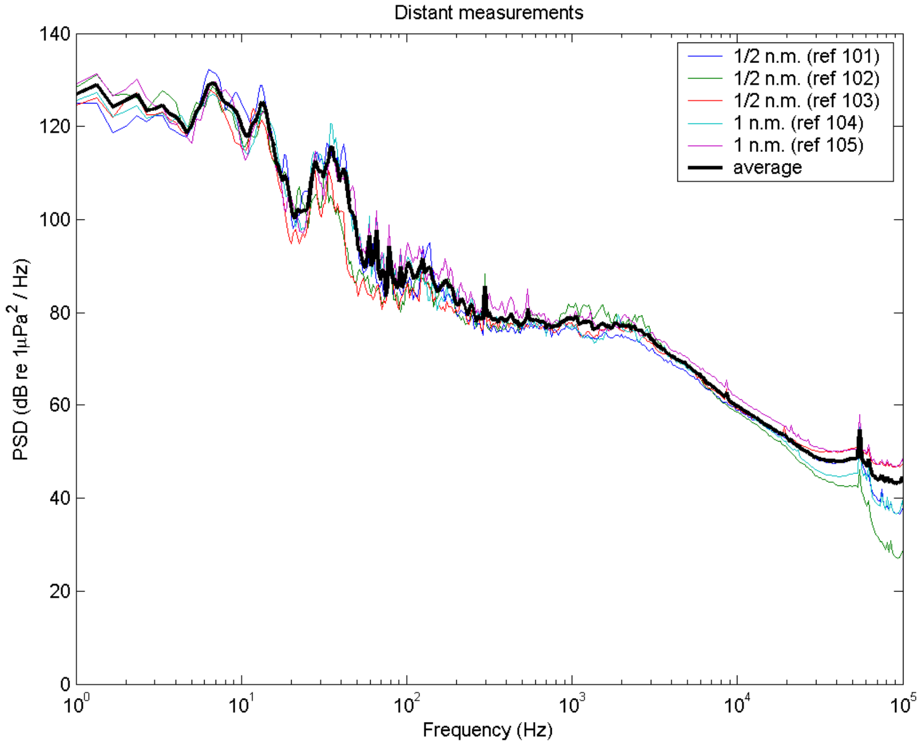

Figure 5.5. Background spectral levels taken ½ and 1 nautical mile to the west of the Scroby Sands windfarm site.

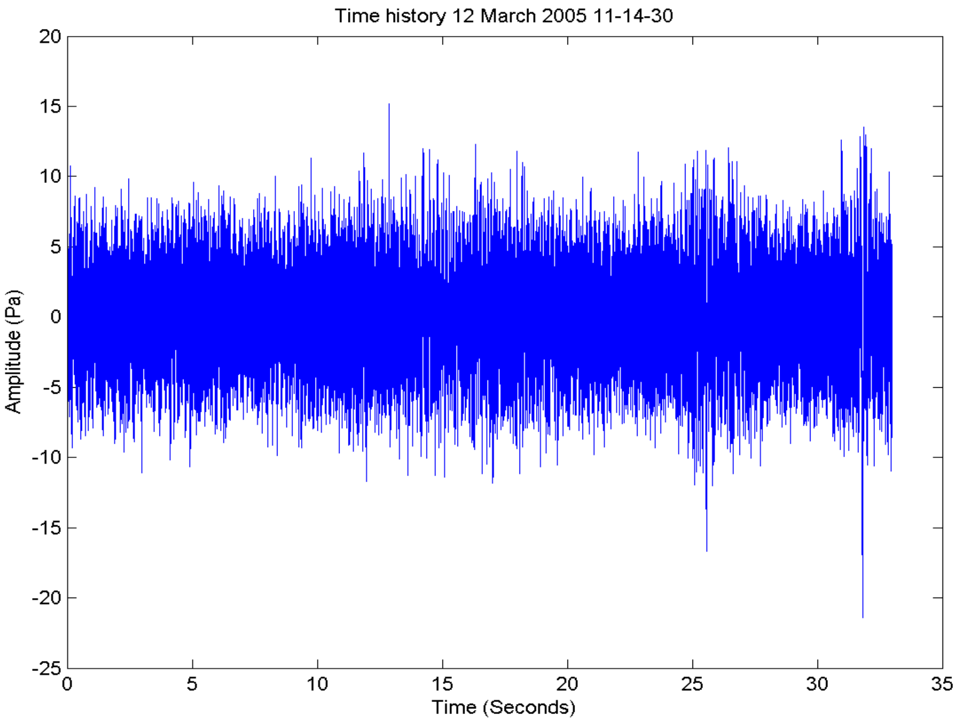

Figure 5.6. A noise time history illustrating the variation in underwater sound at the Scroby Sands windfarm.

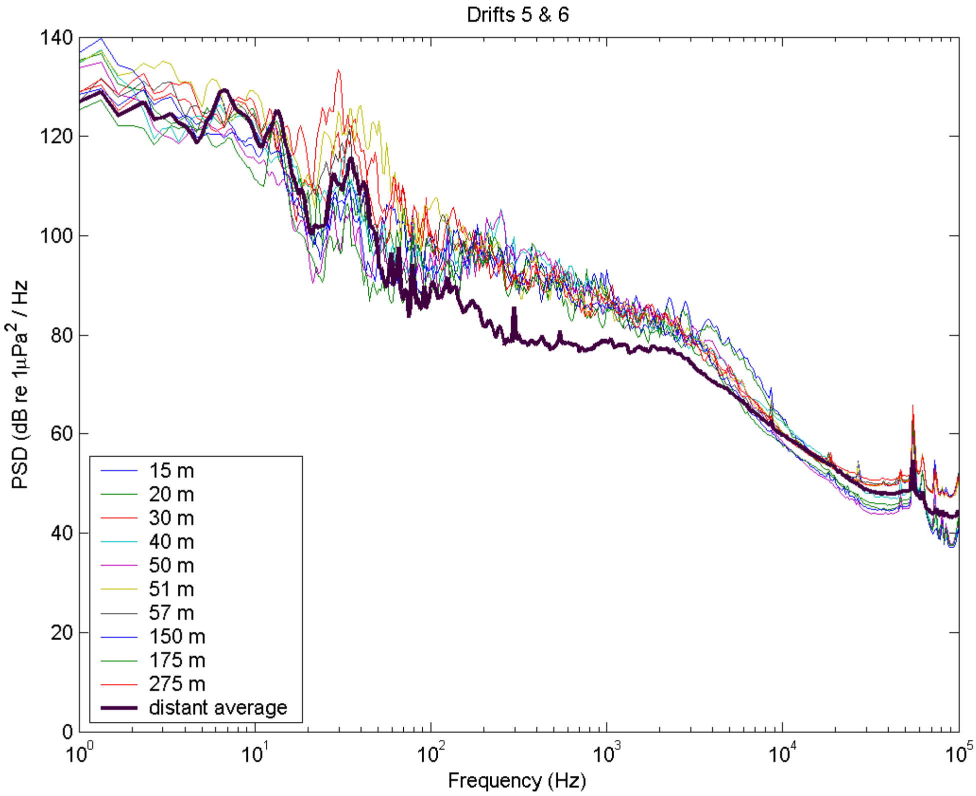

Figure 5.7. Spectral levels of underwater noise at increasing range from a single operational wind turbine (Turbine 13) at the Scroby Sands windfarm.

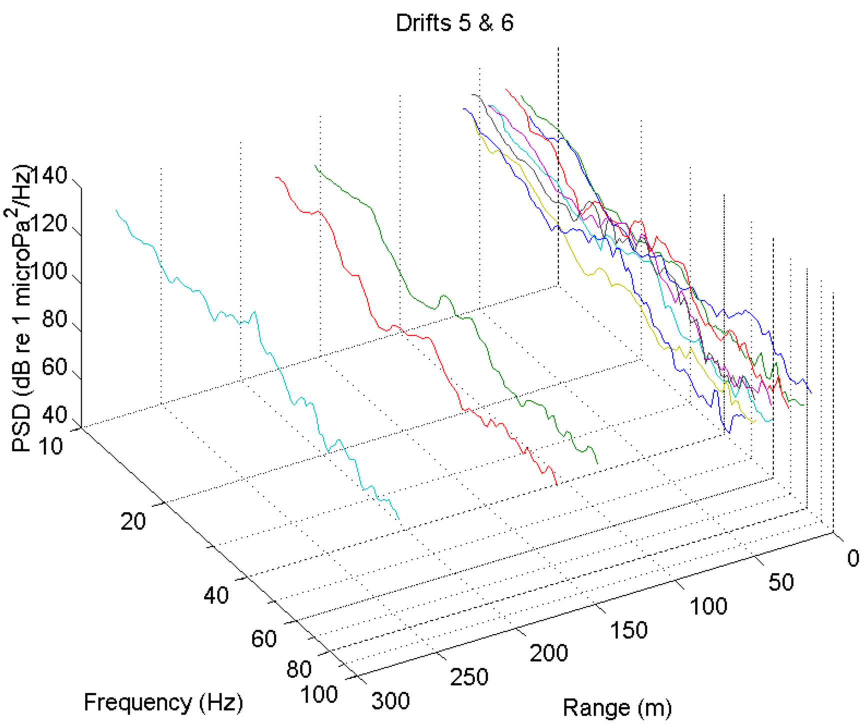

Figure 5.8 (a). Comparison of spectral levels for very low frequency underwater noise (10 to 100 Hz), at increasing range from wind turbine 13 at the Scroby Sands windfarm.

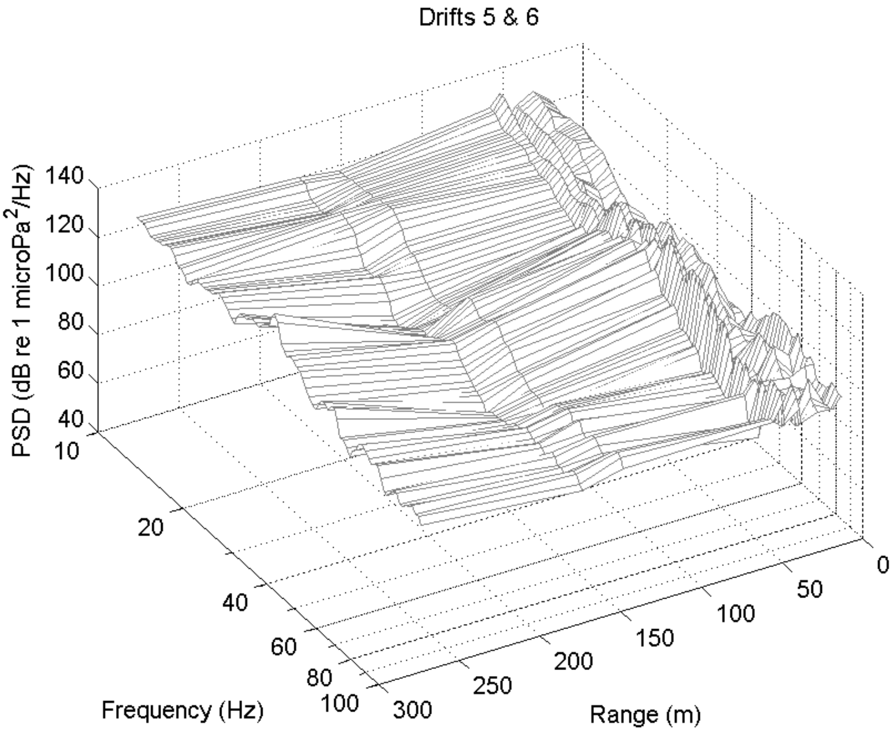

Figure 5.8 (b). Comparison of spectral levels for very low frequency underwater noise (10 to 100 Hz), at increasing range from wind turbine 13 at the Scroby Sands windfarm.

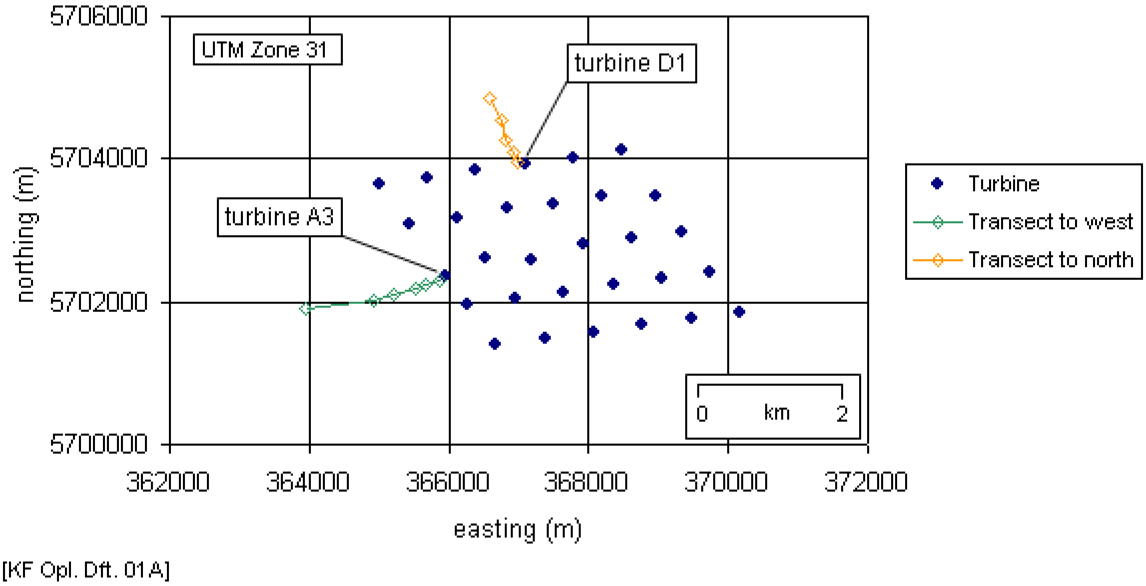

Figure 5.9. Sketch map showing the tracks of the measurement vessel when taking measurements of operational noise at the Kentish Flats windfarm.

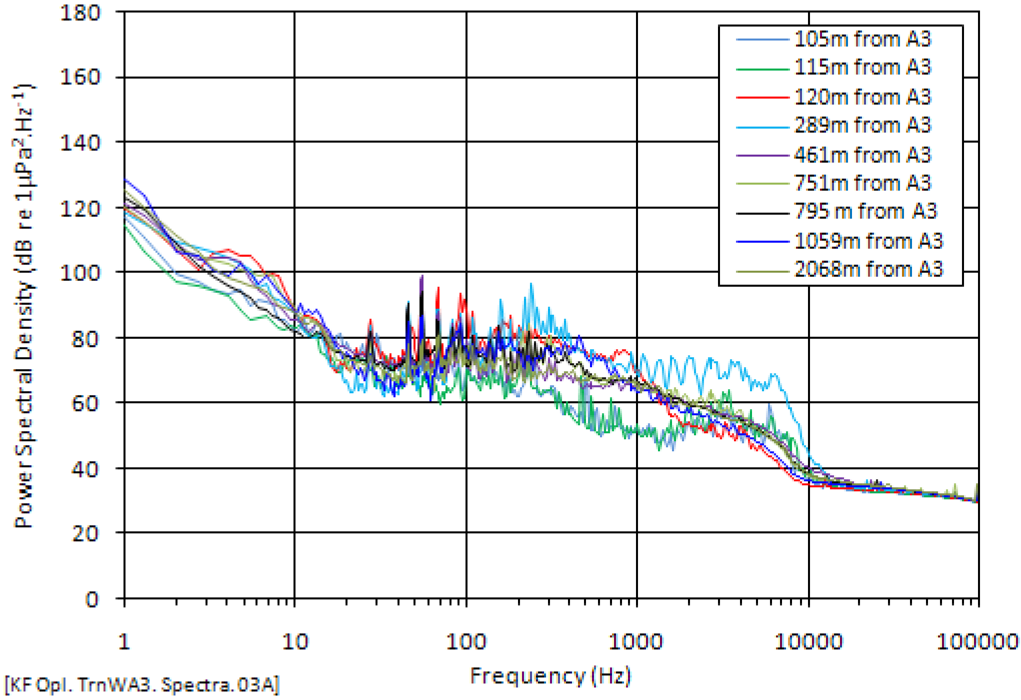

Figure 5.10. Spectra along the transect to the west from turbine A3, Kentish Flats windfarm.

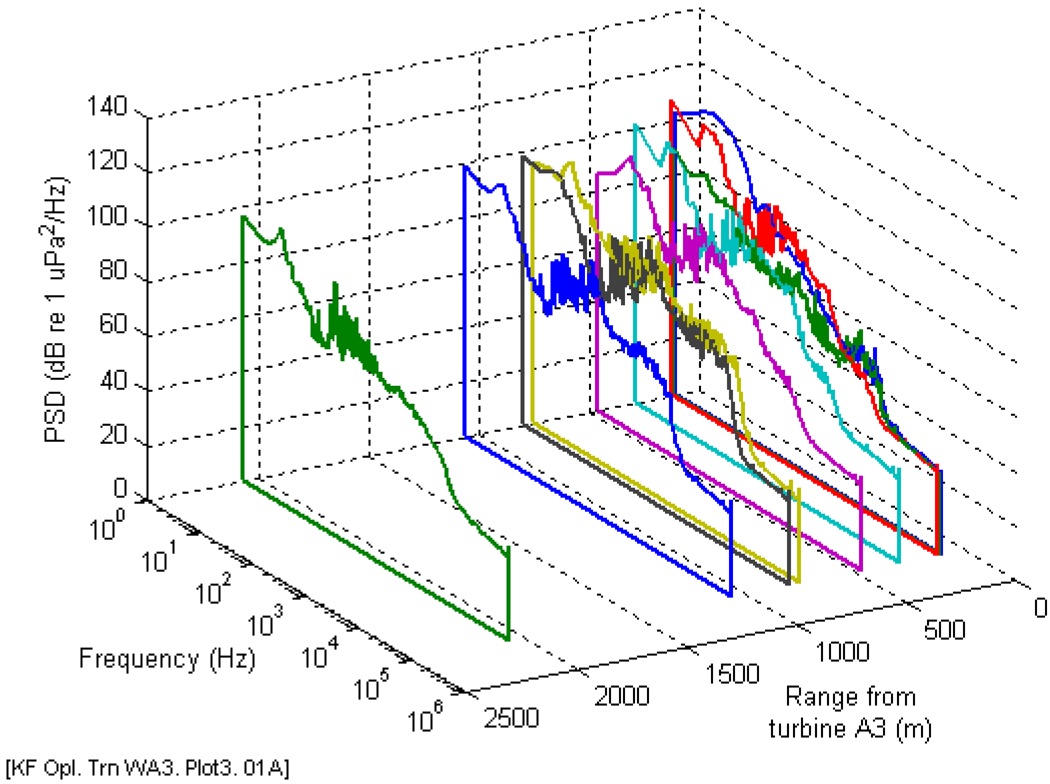

Figure 5.11. Spectra along the transect to the west from turbine A3 (same data as preceding figure).

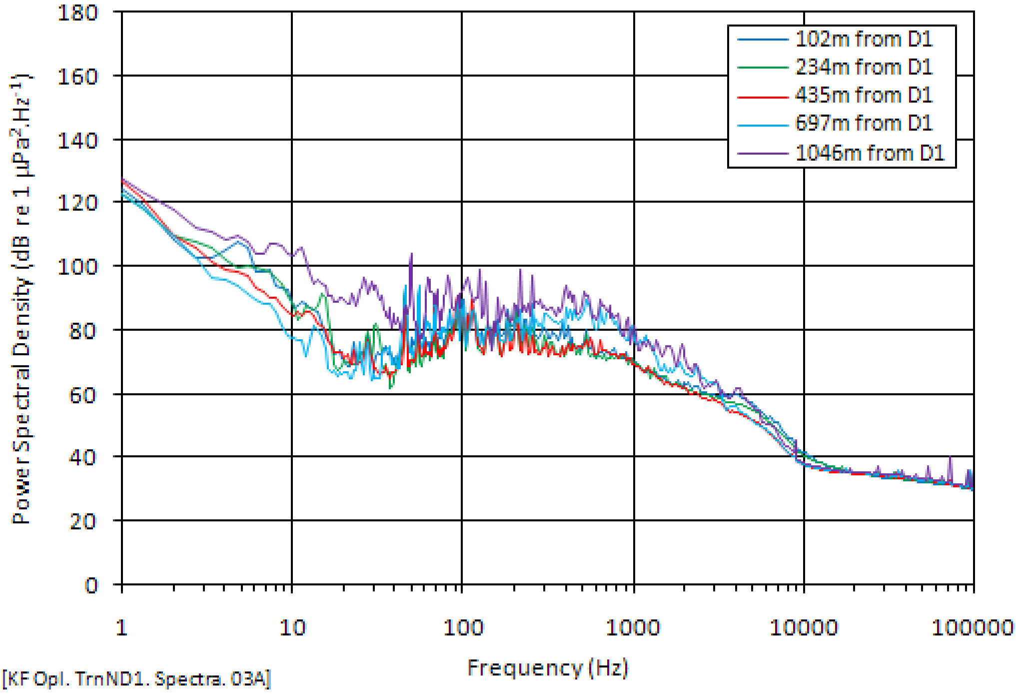

Figure 5.12. Spectra along the transect to the north from turbine D1, Kentish Flats windfarm.

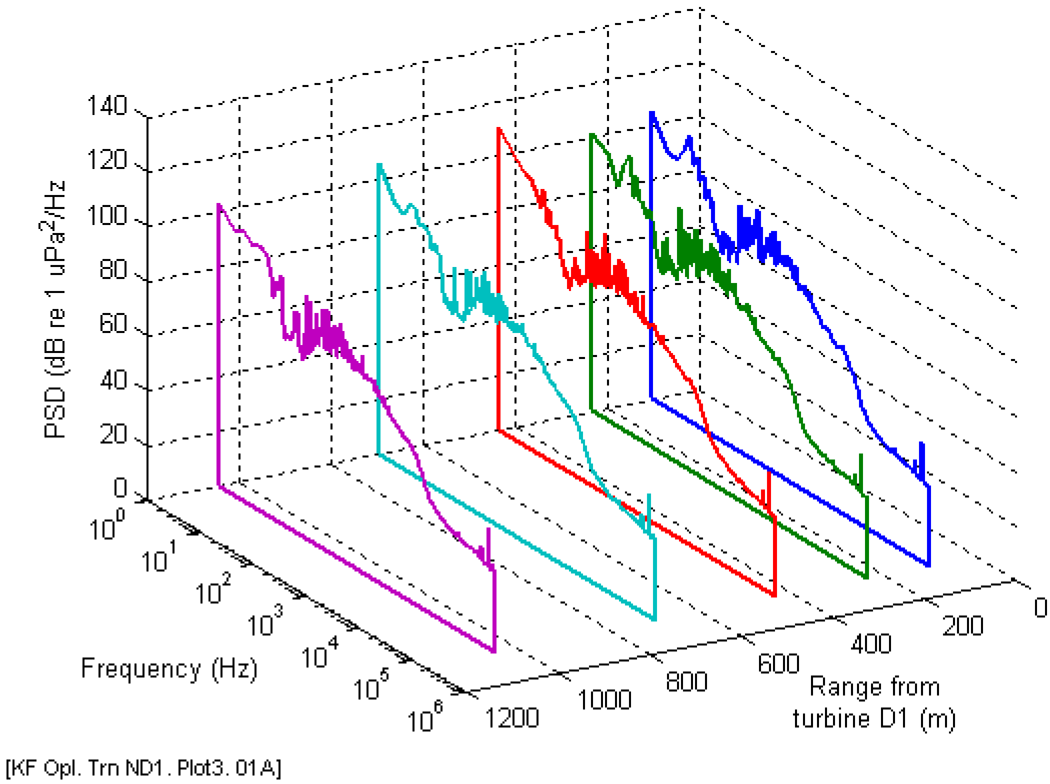

Figure 5.13. Spectra along the transect to the north from turbine D1 (same data as preceding figure).

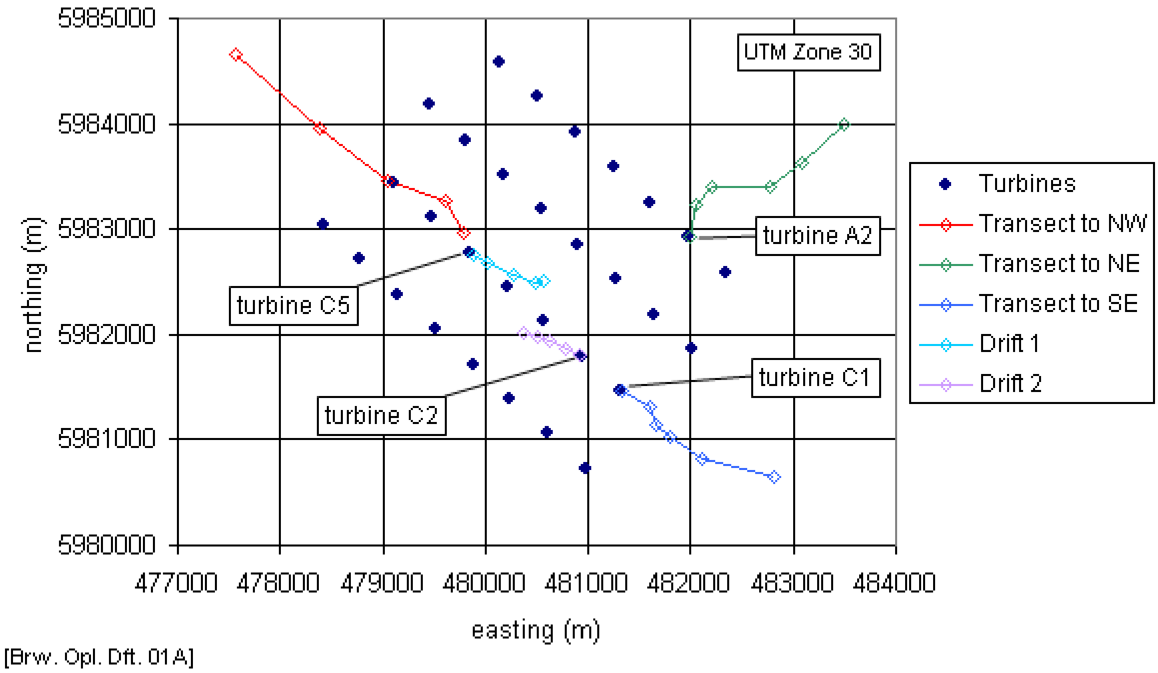

Figure 5.14. Sketch map showing the tracks of the measurement vessel when taking measurements of the operational noise at the Barrow windfarm.

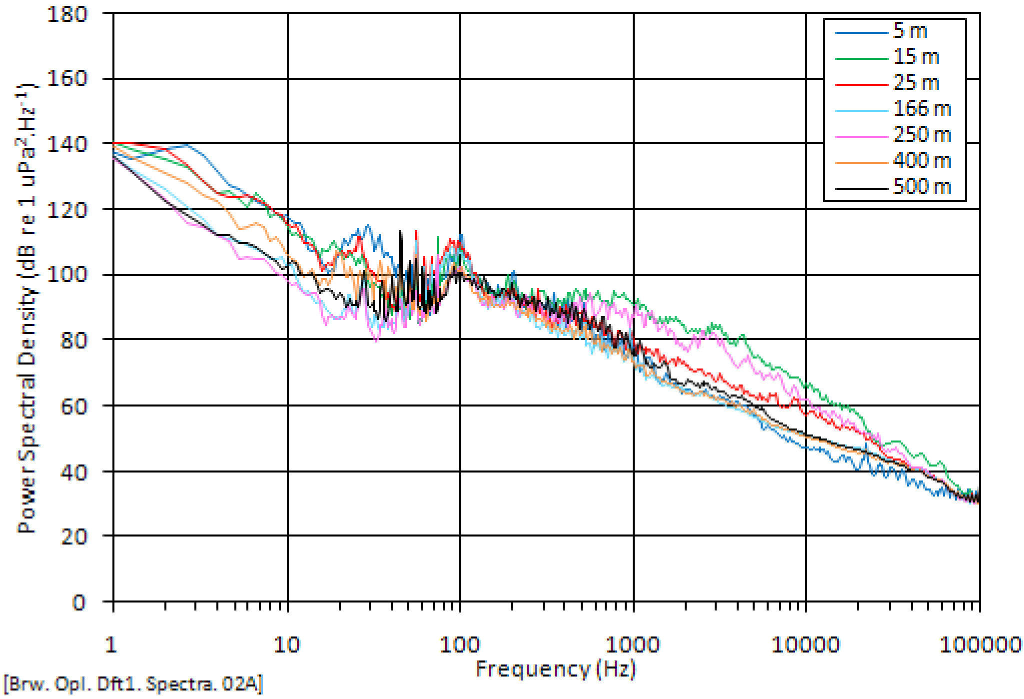

Figure 5.15. Spectra for Drift 1, from turbine C5, Barrow windfarm.

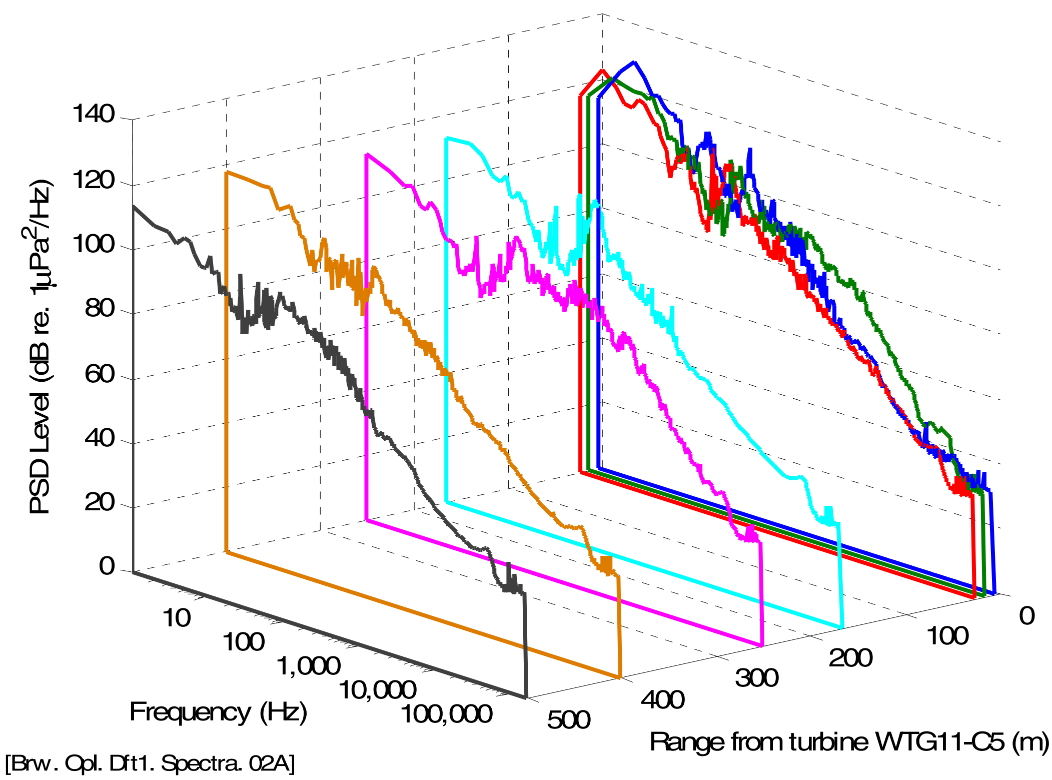

Figure 5.16. Spectra for Drift 1, from turbine C5 (same data as preceding figure).

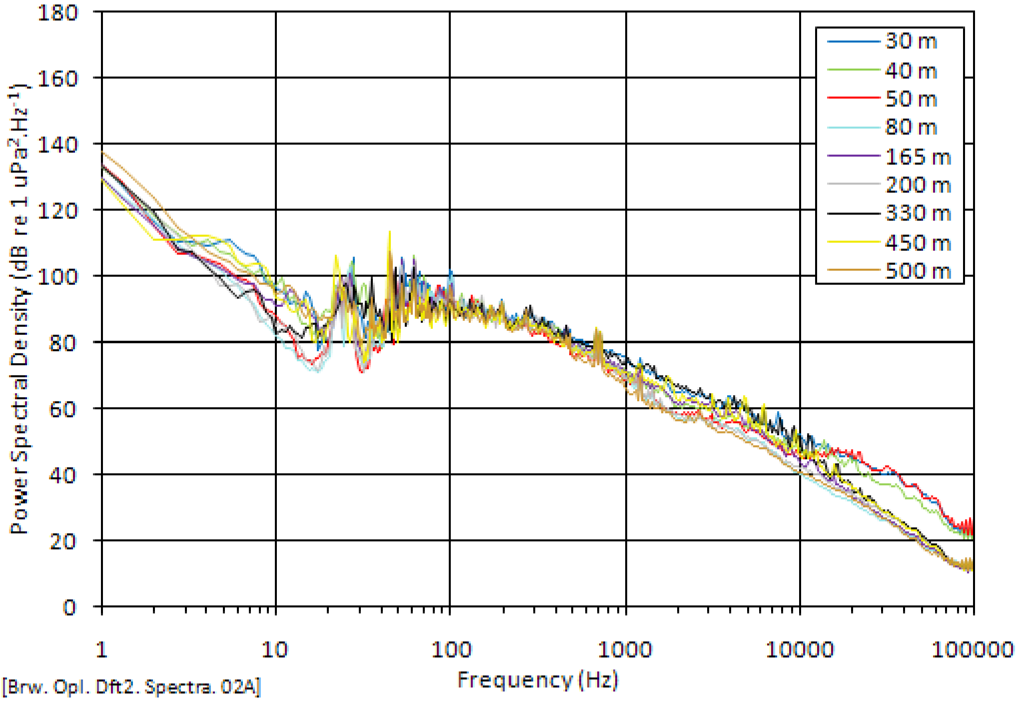

Figure 5.17. Spectra for Drift 2, from turbine C2, Barrow windfarm.

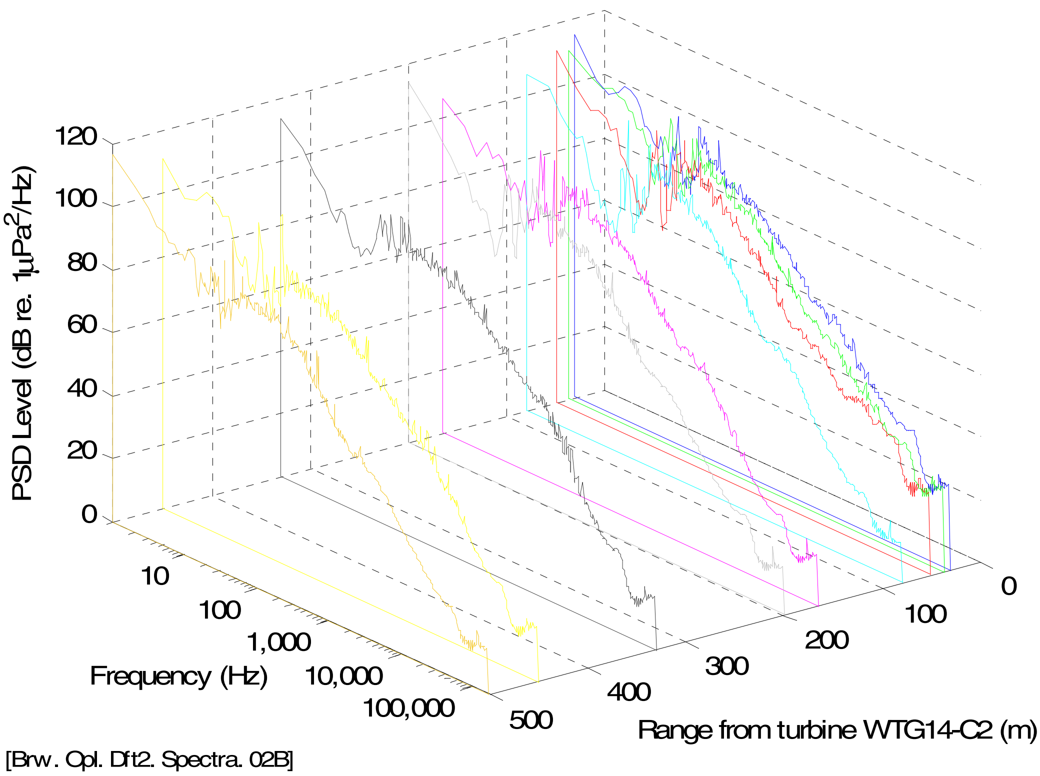

Figure 5.18. Spectra for Drift 2, from turbine C2 (same data as preceding figure).

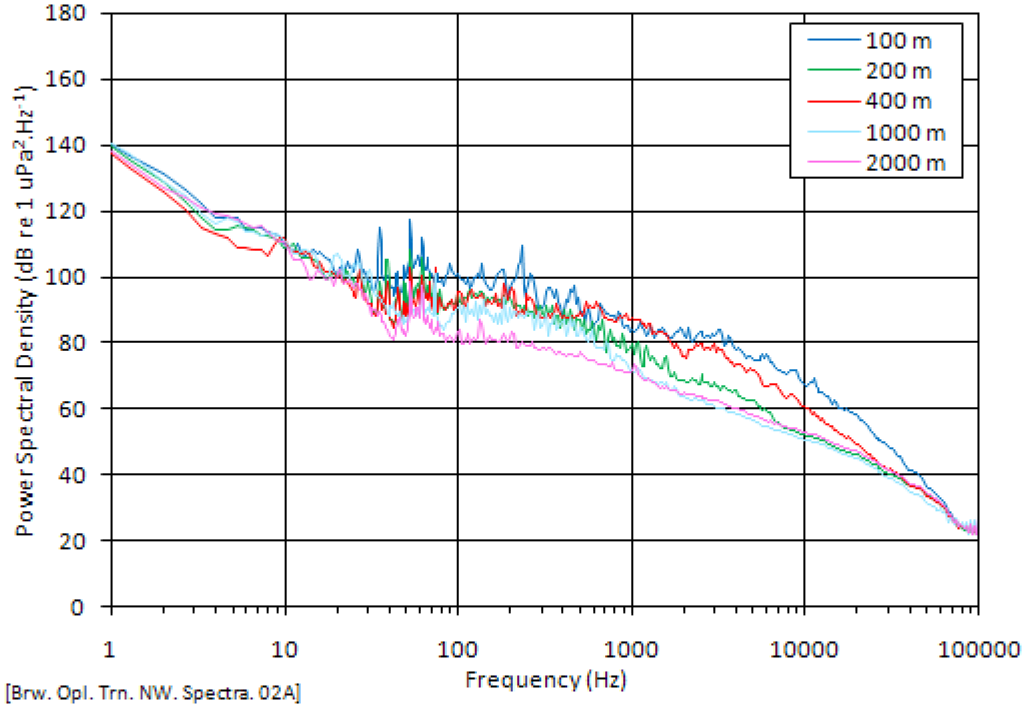

Figure 5.19. Spectra along the transect to the north-west from turbine C5, Barrow windfarm.

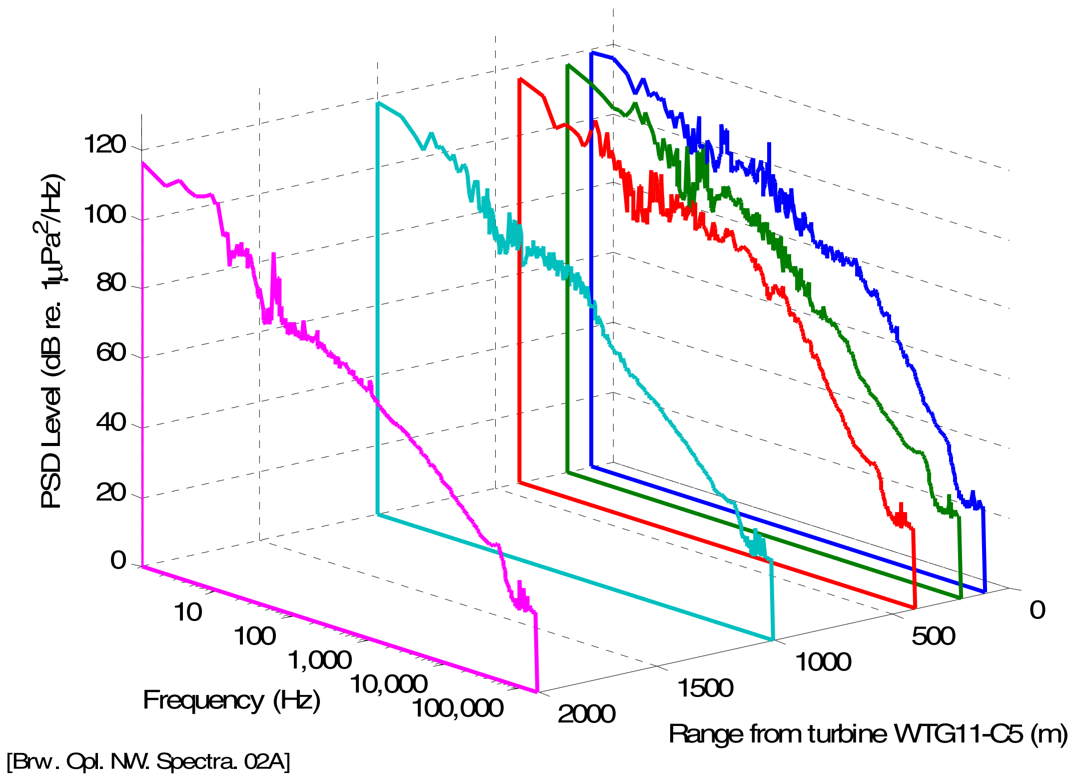

Figure 5.20. Spectra along the transect to the north-west from turbine C5 (same data as preceding figure).

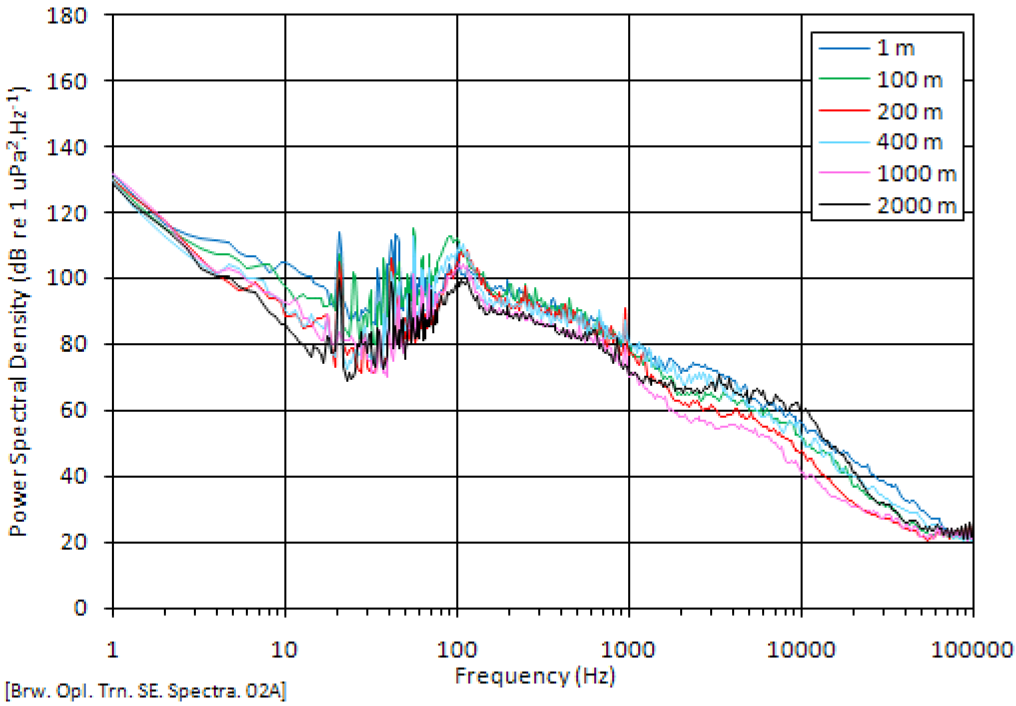

Figure 5.21. Spectra along the transect to the south-east from turbine C1, Barrow windfarm.

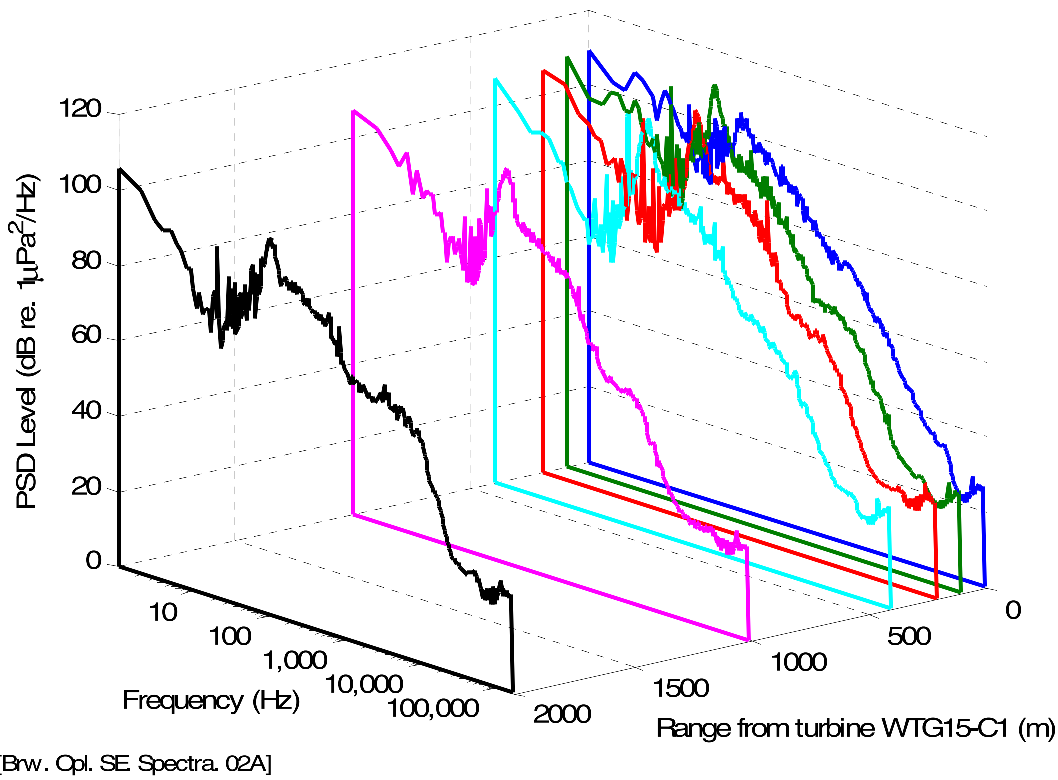

Figure 5.22. Spectra along the transect to the south-east from turbine C1 (same data as preceding figure).

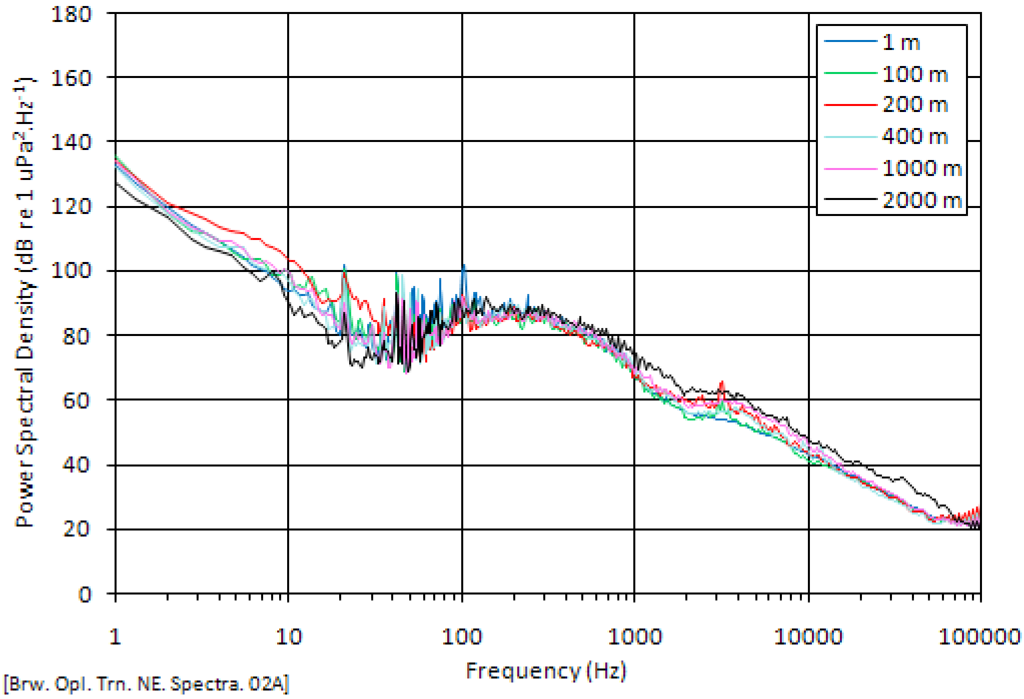

Figure 5.23. Spectra along the transect to the north-east from turbine A2, Barrow windfarm.

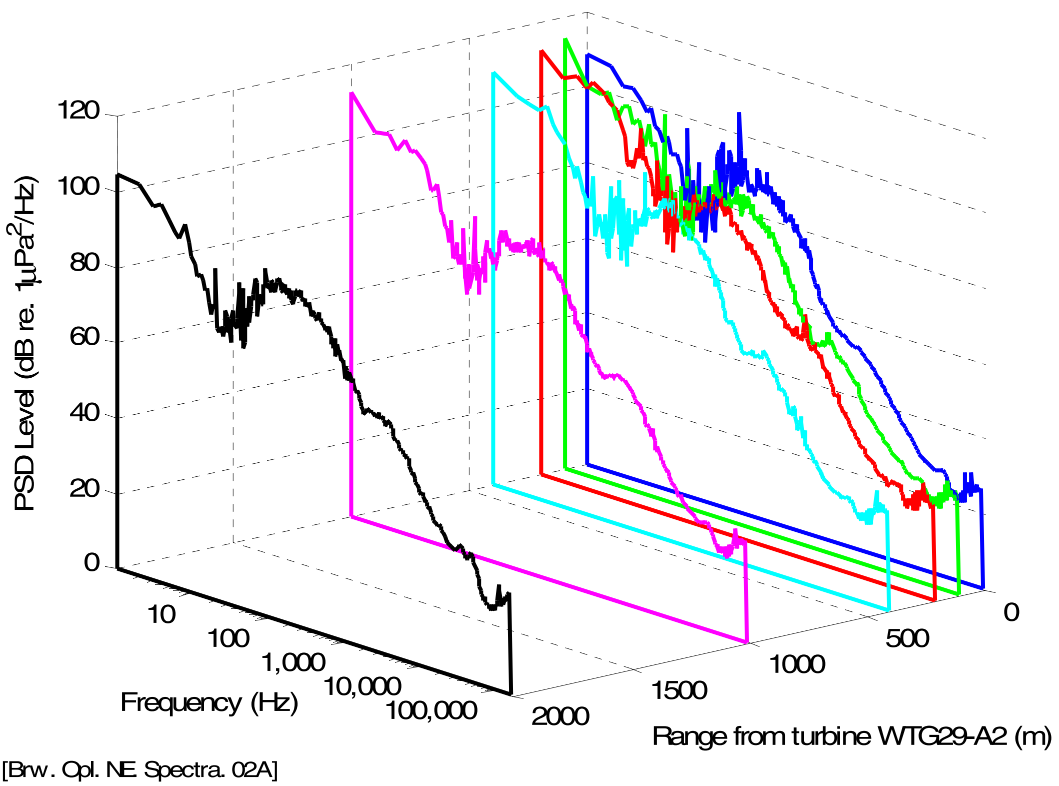

Figure 5.24. Spectra along the transect to the north-east from turbine A2 (same data as preceding figure).

6 Conclusions

The conclusions of the programme of work may be summarised as follows:

1. A substantial set of measurements have been taken of the underwater noise generated by offshore windfarms during pile driving operations for construction, during the operation of the windfarm, and of the background noise in their vicinity.

2. Measurements of the underwater noise during pile driving were taken on five windfarms, at North Hoyle, Scroby Sands, Kentish Flats, Barrow and Burbo Bank. Previous reports have established that pile driving during windfarm construction creates high levels of underwater noise; the measurements indicate that the Source Levels of these five pile driving operations varied between 243 and 257 dB re 1 Pa @ 1 metre, having an average value of 250 dB re 1 Pa @ 1 metre. The Transmission Losses were characterised by values of geometric loss factor N of 17 to 21, and absorption factor of 0.0003 to 0.0047 dB/m.

3. The noise from pile driving operations can remain above the background underwater noise to ranges of 25 km or more. The range is however highly dependent on the local background underwater noise, and for one set of measurements the pile driving noise was difficult to detect at ranges of 10 km. Consequently, estimates of the range at which piling noise falls to background noise should always be compared with the actual background noise measured at the site, or where this is not possible, background noise from acoustically similar shallow coastal sites.

4. A criterion has been used of 90 dB_{ht} for the level of noise above which strong avoidance reaction is likely to occur. On this basis, the results indicate strong avoidance of piling noise by insensitive species such as salmon and bass within ranges of a few hundred metres from piling, up to strong avoidance within ranges of a few kilometres by sensitive species such as harbour porpoise. It should however be noted that avoidance in a decreasing proportion of individuals may occur at greater ranges.

5. The Noise Dose metric used to model the cumulative effects of noise on humans has been adapted to marine animals using the dB_{ht} metric, and indicates that a Noise Dose equivalent to exposure at a level of 90 dB_{ht} for eight hours, or exceeding a peak level of 130 dB_{ht}, is likely to cause hearing damage.

6. This criterion when applied to the measurements indicates that a static harbour porpoise could be exposed to the noise during an entire pile driving operation at a typical range of 250 metres without harm. However, an animal which elects to flee the pile driving noise, even at a very low speed, greatly limits its noise exposure such that the range within which a fleeing animal would have to be in order to receive a hazardous Noise Dose decreases to a few tens of metres.

7. However, the results also indicate that the range from the piling within which the level exceeds 130 dB_{ht}, significantly exceeds this value. Therefore, this latter criterion serves to protect the animal against both traumatic hearing loss and accumulated hearing damage from Noise Dose.

8. The results therefore simplify the estimation of the areas around a pile driving operation within which the two key auditory effects of noise will occur. In summary, provided animals are free to flee the noise, those within the area bounded by the 90 dB_{ht} level contour, or Behavioural Effect Zone, will strongly avoid the noise. Animals within the area bounded by the 130 dB_{ht} level contour, or Noise Injury Zone, may suffer injury, including permanent damage to hearing. The injury ranges indicated by the measurements using this criterion do not exceed a few hundred metres.

9. The underwater noise generated during the operation of the North Hoyle, Scroby Sands, Kentish Flats and Barrow windfarms was measured and found to be very low. The noise was not greatly above the level of background noise, even in the immediate vicinity of wind turbines.

10. The environment within these operational windfarms was found to be on average about 2 dB noisier for fish, and no noisier for marine mammals, than the surrounding area. This is no more than variations which might be encountered by these animals during their normal activity. No evidence was found of noise levels that might have the capacity to cause marine animals to avoid the area.

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Appendix A: Measuring and assessing underwater sound

A.1 Introduction

Sound travels much faster in water (approximately 1500 m/s) than in air (340 m/s). Since water is a relatively incompressible, dense medium the pressures associated with underwater sounds tend to be much higher than in air. Background levels of about 130 dB re. 1 µPa for coastal waters are common (Nedwell *et al.* 2003) This level equates to about 100 dB re. 20 µPa in the units that would be used in air. Such levels in air would be considered to be hazardous, however, marine animals have evolved to live in this environment and are thus insensitive to sound compared with terrestrial mammals.

A.2 Units of measure

Sound measurements underwater are usually expressed using the deciBel (dB) scale, which is a logarithmic measure of sound. A logarithmic scale is used because rather than equal increments of sound having an equal increase in effect, typically a constant ratio is required for this to be the case, that is, each doubling of sound level will cause a roughly equal increase in "loudness".

Any quantity expressed in this scale is termed a "level". If the unit is sound pressure, expressed on the dB scale, it will be termed a "Sound Pressure Level". The fundamental definition of the dB scale is given by

$$\text{Level} = 10 \times \log 10 \, (Q/Q_{ref}) \qquad (1)$$

where Q is the quantity being expressed on the scale, and Q_{ref} is the reference quantity. The dB scale represents a ratio and, for instance, 6 dB really means "twice as much as….". It is therefore used with a reference unit, which expresses the base from which the ratio is expressed. The reference quantity is conventionally smaller than the smallest value to be expressed on the scale, so that any level quoted is positive. For instance, for sound in air a reference quantity of 20 Pa is usually used, since this is the threshold of human hearing.

A refinement is that the scale when used with sound pressure is applied to the pressure squared, rather than the pressure. If this were not the case, if the acoustic power level of a source rose by say 10 dB the Sound Pressure Level would rise by 20 dB. So that variations in the units agree, the sound pressure must be specified in units of RMS pressure squared. This is equivalent to expressing the sound as

$$\text{Sound Pressure Level} = 20 \times \log 10 \, (PRMS/Pref) \qquad (2)$$

For underwater sound, typically a unit of one microPascal (µPa) is used as the reference unit; a Pascal is equal to the pressure exerted by one Newton over one square metre. One microPascal equals one-millionth of this.

A.3 Ways of expressing sound measurements

Sound may be expressed in several ways, which include:

Root Mean Square (RMS) level. For continuous sound, or sound that varies in level, the RMS is used as an "average" value when calculating the level. The time over which the mean is calculated has to be quoted. For instance, in the case of a pile strike lasting say a tenth of a second, the mean taken over a tenth of a second will be ten times higher than the mean taken over one second.

Peak level. The peak level is calculated using the maximum level of the acoustic pressure, usually for positive pressures. It is often used in blast where there is a clear positive peak following the detonation of explosives.

Peak-to-peak level. The peak-to-peak level is usually calculated using the maximum variation of the pressure from positive to negative within the wave. Where the wave is symmetrically distributed in positive and negative pressure, the peak-to-peak level will be twice the peak level, and hence 6 dB higher.

Source Level. Where there is a single and well-defined source of noise, underwater sound pressure measurements may be expressed as dB re 1 µPa @ 1m, which represents the apparent level at a distance of one metre from the source. In fact, since the measurements are usually made at some distance from the source, and extrapolated back to the source, the true level at one metre may be very different from the Source Level. The Source Level may itself be quoted in any of the measures above, for instance, a pile driving source may be expressed as having a "peak-to-peak Source Level of 200 dB re 1 µPa @ 1 metre".

Particle velocity. Particle velocity is another quantity that may be used to measure sound. It defines the movement of the particles of water under the influence of the sound wave. Although there are relationships between the pressure of a sound wave and its particle velocity, these cannot generally be used in shallow water and hence it must be directly measured.

The use of particle velocity as an alternative or complement to sound pressure has been advocated for sound measurements. There is strong evidence that many species of fish are sensitive to particle velocity rather than pressure (Hawkins 1981).

It should be noted that particle velocity is a vector quantity, and hence it must be quoted appropriately, say as a magnitude only or in vertical and horizontal components. It is common to quote the level referenced to the particle velocity of a 1 µPa plane wave. For deep water this has the advantage that the level of the sound is the same whether quoted in particle velocity or pressure.

Appendix B: Calibration charts

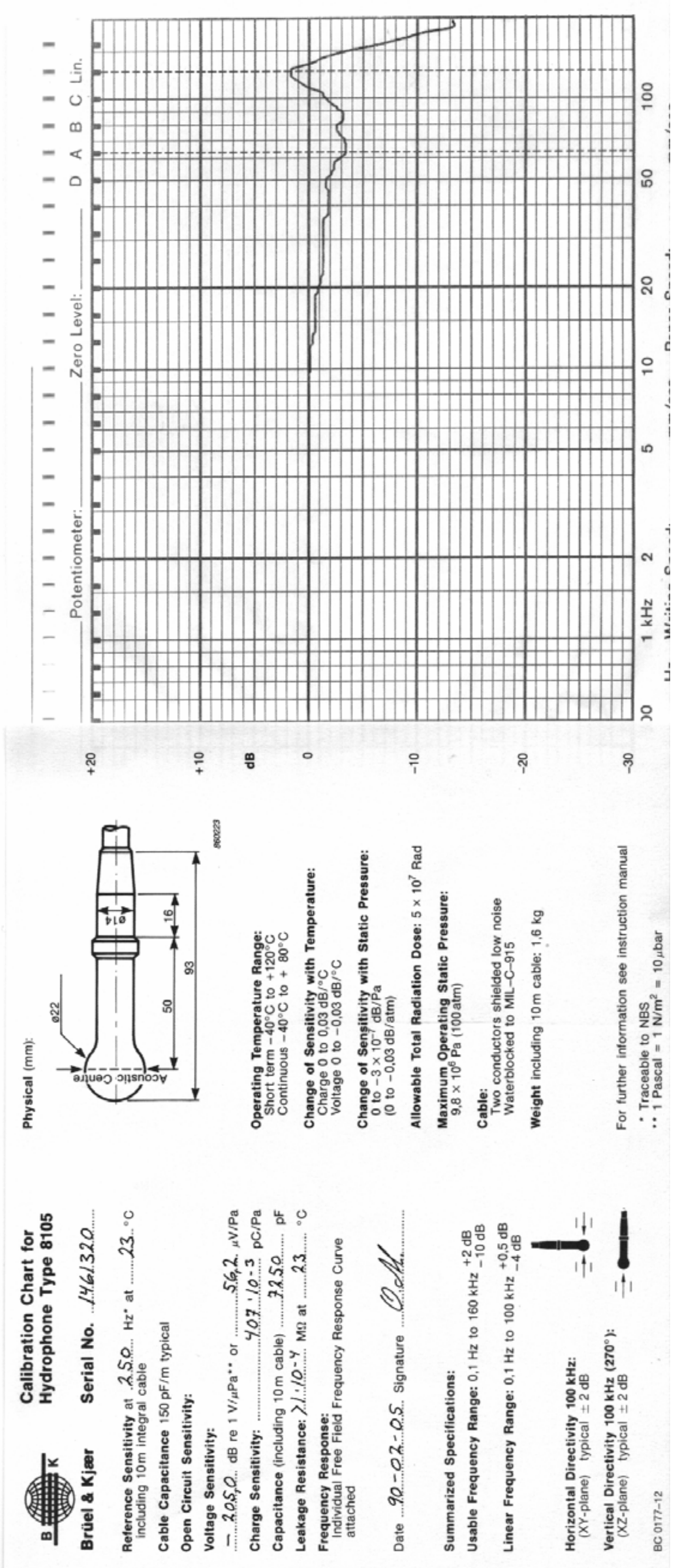


Figure B1. Calibration chart for the B&K Type 8105 hydrophone used.

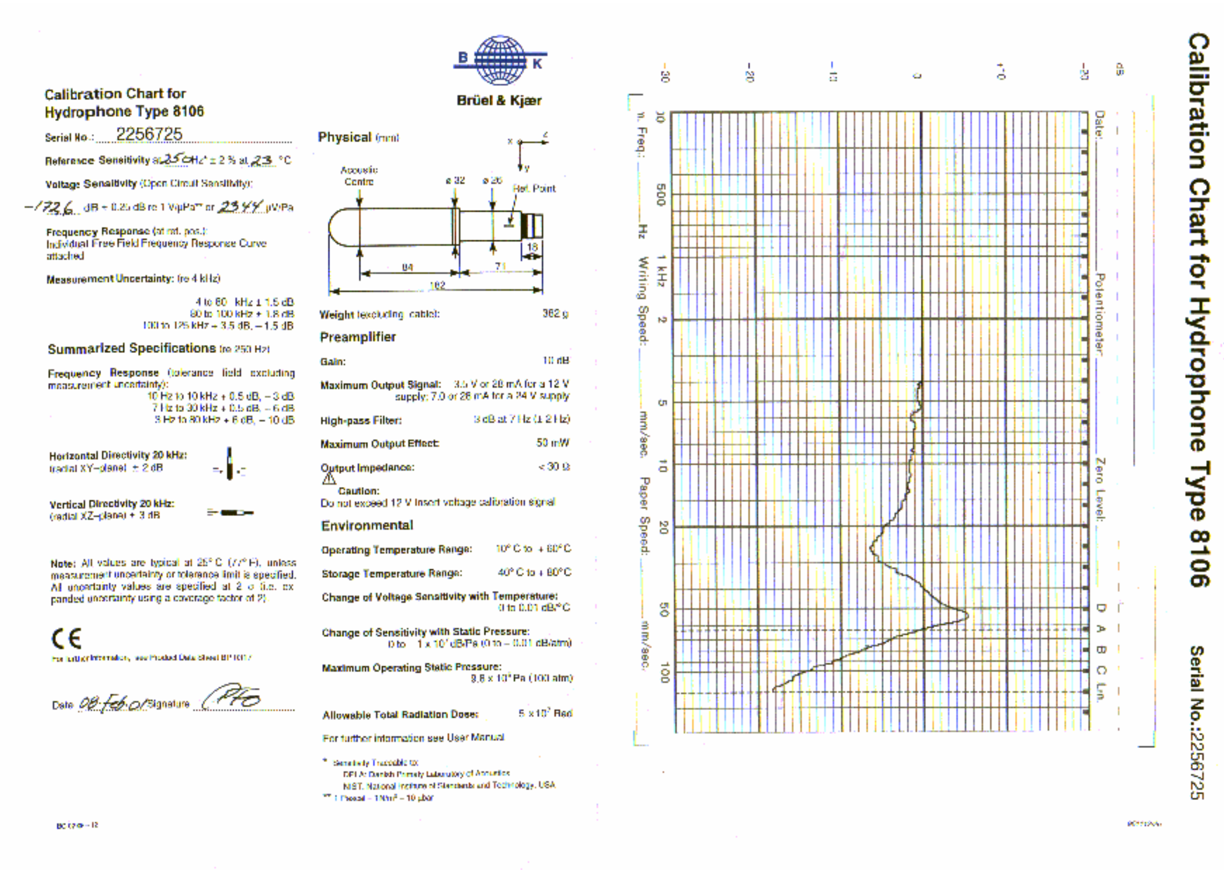
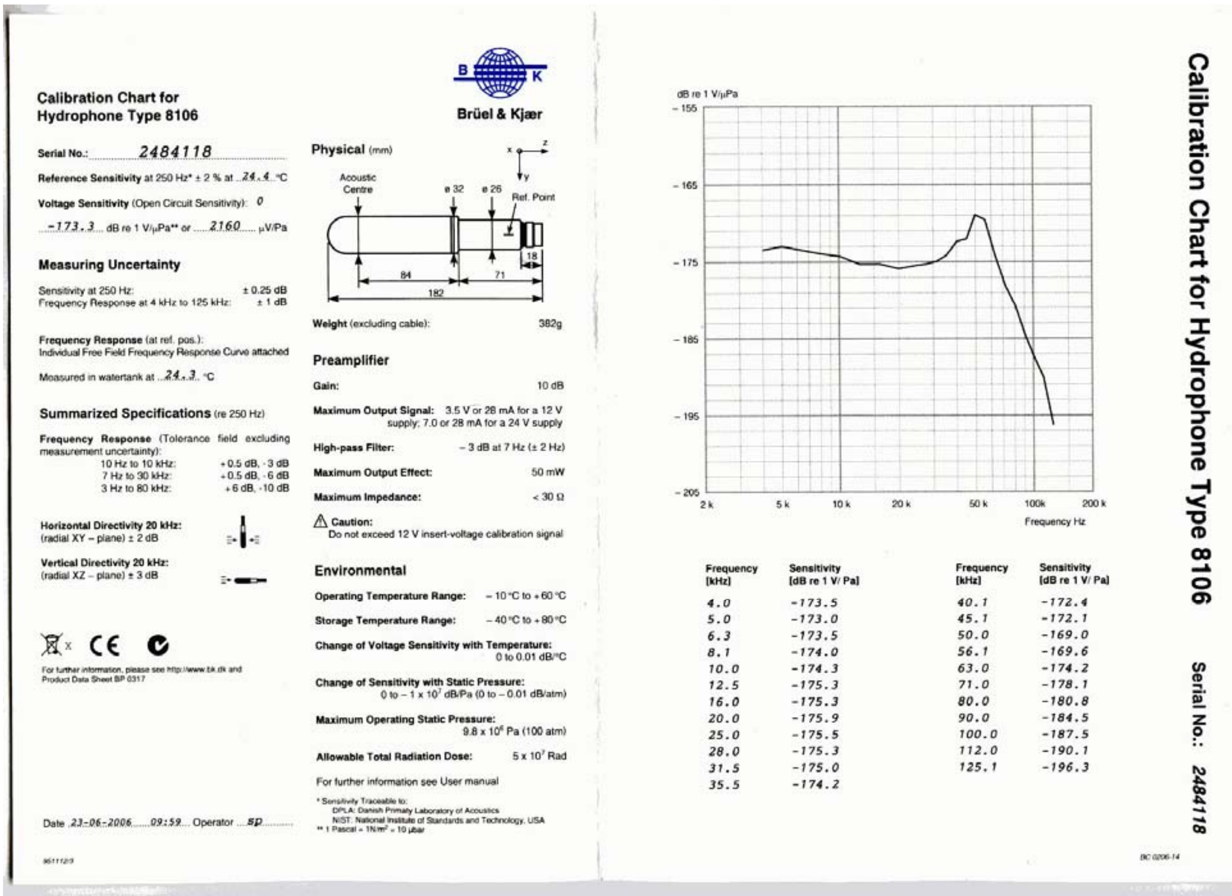


Figure B.2. Calibration chart of the B&K Type 8106 hydrophone, S/N 2256725, used.



Calibration Chart for
Hydrophone Type 8106

Serial No.: 2484118

Reference Sensitivity at 250 Hz* ± 2 % at 24.4 °C

Voltage Sensitivity (Open Circuit Sensitivity): 0

-173.3 dB re 1 V/μPa** or 2160 μV/Pa

Measuring Uncertainty

Sensitivity at 250 Hz: ± 0.25 dB
Frequency Response at 4 kHz to 125 kHz: ± 1 dB

Frequency Response (at ref. pos.):
Individual Free Field Frequency Response Curve attached

Measured in watertank at 24.3 °C

Summarized Specifications (re 250 Hz)

Frequency Response (Tolerance field excluding measurement uncertainty):
10 Hz to 10 kHz: +0.5 dB, -3 dB
7 Hz to 30 kHz: +0.5 dB, -6 dB
3 Hz to 80 kHz: +6 dB, -10 dB

Horizontal Directivity 20 kHz:
(radial XY – plane) ± 2 dB

Vertical Directivity 20 kHz:
(radial XZ – plane) ± 3 dB

For further information, please see http://www.bk.dk and Product Data Sheet BP 0317

Date 23-06-2006 09:59 Operator SP

Brüel & Kjær

Physical (mm)

Acoustic Centre
ø 32
ø 26
Ref. Point
18
84
71
182

Weight (excluding cable): 382g

Preamplifier

Gain: 10 dB

Maximum Output Signal: 3.5 V or 28 mA for a 12 V supply; 7.0 or 28 mA for a 24 V supply

High-pass Filter: – 3 dB at 7 Hz (± 2 Hz)

Maximum Output Effect: 50 mW

Maximum Impedance: < 30 Ω

Caution:
Do not exceed 12 V insert-voltage calibration signal

Environmental

Operating Temperature Range: – 10 °C to + 60 °C

Storage Temperature Range: – 40 °C to + 80 °C

Change of Voltage Sensitivity with Temperature: 0 to 0.01 dB/°C

Change of Sensitivity with Static Pressure: 0 to – 1 x 10⁷ dB/Pa (0 to – 0.01 dB/atm)

Maximum Operating Static Pressure: 9.8 x 10⁶ Pa (100 atm)

Allowable Total Radiation Dose: 5 x 10⁷ Rad

For further information see User manual

* Sensitivity Traceable to:
DPLA: Danish Primary Laboratory of Acoustics
NIST: National Institute of Standards and Technology, USA
** 1 Pascal = 1N/m² = 10 μbar

Calibration Chart for Hydrophone Type 8106 Serial No.: 2484118

Frequency [kHz]	Sensitivity [dB re 1 V/ Pa]	Frequency [kHz]	Sensitivity [dB re 1 V/ Pa]
4.0	-173.5	40.1	-172.4
5.0	-173.0	45.1	-172.1
6.3	-173.5	50.0	-169.0
8.1	-174.0	56.1	-169.6
10.0	-174.3	63.0	-174.2
12.5	-175.3	71.0	-178.1
16.0	-175.3	80.0	-180.8
20.0	-175.9	90.0	-184.5
25.0	-175.5	100.0	-187.5
28.0	-175.3	112.0	-190.1
31.5	-175.0	125.1	-196.3
35.5	-174.2		

Figure B.3. Calibration chart of the B&K Type 8106 hydrophone, S/N 2484118, used.

Appendix C: Record of changes

1. This is a controlled document.
2. Additional copies should be obtained through the Subacoustech Librarian.
3. If copied locally, each document must be marked "Uncontrolled Copy".
4. Amendment shall be by whole document replacement.
5. Proposals for change to this document should be forwarded to Subacoustech.

Issue	Date	Details of changes
544R0701	25/6/2007	First draft by JRN.
544R0732	5/9/2007	Draft issued for comments.
544R0735	23/11/2007	Second draft for comments.
544R0735	3/12/2007	Reviewer's comments incorporated and reissued
544R0738	21/12/2007	Further reviewer's comments addressed and reissued
544R0739	22/2/2008	Issue of Final Draft

1. Originator's current report number	544R0739
2. Originator's Name & Location	J.R.N., Subacoustech
3. Contract number & period covered	544; April 2003 to Nov. 2007
4. Sponsor's name & location	COWRIE for the Crown Estate
5. Report Classification & caveats in use	COWRIE proprietary
6a. Date written	November 2007.
6b. Pagination	Cover + iv + 79.
6c. References	77
7a. Report Title	Measurement and Interpretation of Underwater Noise during Construction and Operation of Windfarms
7b. Translation / Conference details	
7c. Title classification	UNCLASSIFIED
8. Authors	JR Nedwell, SJ Parvin, B Edwards, R Workman, AG Brooker, JE Kynoch
9. Descriptors / Key words	Underwater, noise, windfarm, pile driving, operational.
10a Abstract	Underwater sound measurements were taken around five offshore windfarms around the U.K. (North Hoyle, Scroby Sands, Kentish Flats, Barrow and Burbo Bank) Measurements of pile driving noise were taken at all five, and operational noise at the first four. For the pile driving operations, variation with range of the unweighted peak-to-peak levels, the species perceived levels (dB_{ht}), and the equivalent species perceived levels (dB_{ht} L_{eq}) were established. The unweighted peak-to-peak Source Level averaged 250 dB re 1 Pa @ 1 m. It was found that, especially where the sound propagated in shallow water, account needed to be taken of absorption of the sound when extrapolating results to large distances. Transmission Losses were characterised by values for N (geometric loss factor) of 17 to 21, and for α (absorption factor) of 0.3 to 4.7 dB/km. For the operational windfarms the noise level was found to be very low, with the level within the farm on average no more than 2 dB above the surrounding area for fish, and no higher for marine mammals.
10b. Abstract classification	UNCLASSIFIED; UNLIMITED DISTRIBUTION.