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Controlled exposure tests to establish the effects of noise produced by Trailing Suction Hopper Dredgers on common seals

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1 Introduction

Subacoustech Ltd has been requested by Stichting La Mer on behalf of Rijkswaterstaat to undertake a feasibility study into an experiment investigating the possible effects of noise produced by Trailing Suction Hopper Dredgers (TSHDs) on the harbour (common) seal (*Phoca Vitulina*) during sand extraction. In order to investigate this, it is proposed that a controlled playback experiment will be performed on live harbour seals. This report represents the first phase of the project in which the possibility and logistics of performing such a test have been investigated. This is a precursor to the second phase in which the experiment will be installed and tested and the final third phase during which testing will be performed on the live subjects.

2 Summary

It has been found that the noise produced by Trailing Suction Hopper Dredgers is capable of invoking an avoidance reaction in the common seal with the associated potential ecological impacts. A comparison of a harbour seal audiogram with TSHD noise reveals that this species is likely to be able to hear a range of frequencies between 35 and 40000 Hz with a peak in perception between 200 Hz and 10 kHz. Any measurements taken using sound recording equipment must at least cover this range. However, initial observations on noise levels from TSHD suggest that the distance at which there will be an adverse reaction is a relatively small one.

Investigations have revealed that licences are required in order to perform playback experiments on live seals. These licences depend on the country in which the tests are being performed.

Modelling has been carried out by Subacoustech to assess the necessary sound field and transducer array design. Initial modelling suggests that it is possible to produce the appropriate sound field and level necessary to recreate the noise of an operational TSHD with an appropriately sized and positioned transducer array. It was found that to achieve conditions similar to exposure to a distant source, a transducer array must be placed at about 40m from the subject. It was also found that an acoustic field characteristic of a TSHD at distance cannot be generated in a confined area such as a water tank.

Several types of experiment and experimental conditions are discussed in this report along with costs and feasibility. These are: a pool based procedure involving a transducer deployed in a quiet pool, a net cage in a controlled area in open water with arrays of transducers in place either side of the net, a calibrated feeding station where the seals are deflected from a normal feeding route by a test noise from an array of sound projectors, acoustic location of calling males with a towed array of sound projectors, and tagged seals chased with a towed array of sound projectors. In addition, there are observational techniques presented which may be used to gauge the subjects' reaction to the noise both in terms of position of the subject and also physiological indicators. Each option has been ranked based on markers such as cost effectiveness and likelihood of achieving satisfactory results.

3 Underwater sound measurements

3.1 Introduction

The purpose of this section is to review the means by which sound can be measured underwater.

The significance of the means by which sound is measured lies in the mechanism by which marine animals perceive sound. The science of measuring noise and relating it to its effects on humans, and the use of metrics (scales) such as the dB(A) is well established. It should be noted that these are based on the measurement of the pressure of the sound wave in air, since it is this quantity (the sound pressure) that humans sense.

By comparison with human effects, the effects of noise on marine species are not well understood. It is thought possible that some species may respond to the particle velocity ("vibration") of the water caused by the noise rather than the pressure. It is important to understand this effect because the appropriate quantity describing the noise must be related to its effects. For instance, if an animal perceives particle velocity, and encounters a noise field having a high level of this quantity, it may react to the noise, even where a measurement of noise pressure would indicate the level was too low to create a response.

3.2 Sound Pressure Level

The *Sound Pressure Level,* or SPL, is defined as

$$SPL = 20\log\left(\frac{P}{P_{ref}}\right)$$

Where P is the sound pressure to be expressed on the scale and P_{ref} is the reference pressure, which for underwater applications is 1 μPa (1 micropascal).

Sound pressure is in principle easily measured underwater by the use of a hydrophone. However, it should be noted that there are several effects that can severely compromise the quality of a measurement. First, it should be noted that the frequency range over which marine animals hear is much wider than that conventionally measured in air, and spans from say 10 Hz to at least 100 kHz. Any measurements made of noise underwater that do not cover this range are hence of little value for general analysis in terms of their environmental effects on particular species.

Second, a major limiting factor that is generally ignored is the dynamic range of the measurement. In general, the levels of noise in the ocean are much lower at high frequencies than at low frequencies, that is, the spectrum is highly sloped. Marine animals have evolved to match this environment, and those that have evolved to make use of the high frequencies tend to be very sensitive to them. Consequently, relatively low levels of underwater noise at high frequencies have the capacity to create an adverse effect.

However, consider recording these high frequencies. The level may be 50 – 100 dB below the level of the low frequency noise. Since the dynamic range of typical recording systems is perhaps 60 – 70 dB at best, the high frequency noise may be buried in the noise floor of the recording equipment. Any analysis of the information for high-frequency hearing animals will hence be meaningless. This effect is particularly difficult to avoid, and in the case of the author's work has been minimised by the use of spectral pre-emphasis techniques.

3.3 Particle velocity level

It has been recognised by many authors (Blaxter, 1980; Turl, 1993) that both fish and marine mammals are sensitive to not only sound pressure level but also the velocity of the particles as the sound is transferred through a medium. Thus it is important that this quantity is measured along with the SPL during the experimental phases of the research.

The particle velocity refers to the actual displacement of water under the influence of a sound field. The Particle Velocity Level (PVL) is defined for the purposes of this study as

$$PVL = 20\log\left(\frac{V}{P_{ref}/\rho c}\right)$$

where V is the particle velocity in metres per second, ρ is the density of water and *c* is its sound speed. The definition effectively expresses particle velocity relative to that of a 1 μPa plane wave, and has the advantage that for many sound waves that may be approximated as near to plane, the PVL and the SPL will actually be the same. However, in reactive fields, such as in the presence of pressure-release materials and at the water surface, the SPL and the PVL may be very different. The two values together thus give an indication of the “reactiveness” of an acoustic environment.

Attempts have been made to use accelerometers in “neutral buoyancy” waterproof cylinders to measure the particle velocity of water. This approach is not appealing, since there is no evidence that the cylinder follows the water vibration, the frequency response of the accelerometers is limited, and the flexural modes of the cylinder will be superimposed on the response.

An alternative approach is to measure the pressure gradient in the water. The gradient may be shown by consideration of Euler’s equation to be given by

$$\frac{\partial p}{\partial x} = -\rho\frac{\delta V}{\partial t}$$

Where x is the direction in which the sound energy flows and *V* is the displacement of water as the sound wave passes. Now consider an estimate of the gradient made using two hydrophones at two adjacent points to measure sound pressures P_1 and P_2 at a spacing of Δx. The particle velocity may be estimated as

$$V = -\frac{1}{\rho}\int\frac{(P_1 - P_2)}{\Delta x}dt$$

Thus, the pressure measured using two hydrophones may be interpreted to yield the particle velocity along the line connecting the hydrophones. It may be noted that the approach is based on an assumption of linearity between the points, however it may be shown that this is adequate if the spatial frequency of the wave is adequately low. This is generally satisfied for propagating waves when the hydrophones are separated by significantly less than a wavelength at the highest frequency recorded.

The approach is appealing in that, provided the hydrophones are calibrated and offer an accurate measurement of sound, as will generally be the case, the estimate of particle velocity will also be accurate. Thus, the measurement may, for instance, be readily related to International Standards for measurement of sound pressure.

It may be noted however that there are several practical considerations when implementing this approach. The differential pressure (P_1-P_2) is typically formed by using a differencing amplifier to subtract one estimate of pressure from another; the result will generally be much smaller than each of the individual pressures. If there is an error in the measurement of either pressure, it may easily dominate the result. Thus, it is critically important that the hydrophones are well matched in both the magnitude and phase of their sensitivity. Note, also, that this implies that this calculation cannot be performed digitally after digital acquisition of the signal, due to the limitations of dynamic range caused by the convertor.

The authors use a purpose-built differencing amplifier in conjunction with high-quality phase matched hydrophones to measure particle velocity, and in general this approach has been found to be reliable.

3.4 The dB_{ht} and its use

The underwater sound measurements in this project are generally presented as linear unweighted Sound Pressure Levels (SPL). However, the use of the dB_{ht} has been an essential tool in designing the experiment, and hence some discussion of the method is required here.

The dB_{ht} scale incorporates the concept of "loudness" for a species. The metric incorporates hearing ability by referencing the sound to the species' hearing threshold, and hence evaluates the level of sound a species can perceive. Experimental evidence indicates that the scale provides an objective rating of the effects of underwater noise on marine animals. It may be considered to be analogous to, or an extension of, the dB(A) scale that is used for human noise exposure.

Since any given sound will be perceived differently by different species (since they have differing hearing abilities) the species name must be appended when specifying a level. For instance the same sound may have a level of 70 dB_{ht}(Gaddus morhua) for a cod and 110 dB_{ht}(*Phoca vitulina*) for a common seal.

The perceived noise levels of sources measured in dB_{ht}(Species) are usually much lower than the unweighted levels, both because the sound will contain frequency components that the species cannot detect, and also because most marine species have high thresholds of perception of (i.e. are relatively insensitive to) sound. If the level of sound is sufficiently high on the dB_{ht}(Species) scale, then an avoidance reaction or hearing impediment might occur. Linear unweighted SPL data does not allow the underwater sound to be assessed in this biologically significant manner. To determine the dB_{ht}(Species) sound level, high quality (1 Hz to 150 kHz) sound recordings are analysed by passing them through a filter that mimics the hearing ability of the animal in question. The output of the filter is therefore a sound level that represents the perceived level of underwater sound by the animal. It should be noted that this filtering will only be used in the analysis of the noise. No filtering will be used on the sound used in the controlled playback experiment on the live subjects.

The importance of this analysis used within this report is that is has allowed the design of the experiment to be analysed prior to it being conducted. Without a formal, objective method of analysis, the design of the experiment would be arbitrary and it is unlikely that the experiment would conclusively demonstrate an effect. The authors are not aware of any other system of analysis which would enable these objectives to be achieved.

3.5 Criteria Based on Absolute Sound Pressure Level

Various measures based on unweighted measures of noise have been used to protect marine species from its effects. For instance, a limit of 180 dB is often applied to the military use of sonar, above which it is presumed adverse effects may occur. The use of such a limit is pragmatic rather than based on any significant body of evidence.

A criterion for the effects of noise from dredging could in principle be based on such an unweighted criterion. In a recent study by Kastelein *et al.* (2006), avoidance of harbour seals of communication signals was measured. It was found that for all 4 signals tested, the subjects tended to avoid an area in which the SPL was 107 dB re. 1µPa or greater. It should be noted that all of the signals had their peaks in energy around 12 kHz although they differed in harmonics and transients. Dredging noise typically has a peak SPL of between 10 and 100 Hz. It is suggested that due to this significant difference in peak frequency, using 107 dB as a definitive SPL of behavioural avoidance may not be applicable.

This result is confusing in that it implies that a reaction occurs at substantially lower than background noise levels in the sea. This result is difficult to interpret, and it may additionally be noted that the spectral characteristics of dredging noise and communications noise vary greatly.

In general, it is thought that there is no simple criterion based on an unweighted metric which would be adequate to describe the effects of dredging noise on marine mammals. Subsequent discussions with Dr. Kastelein have shown that he also does not feel that 107 dB re. 1µPa, for instance, would be an appropriate metric for use in the design and implementation of this experiment.

3.6 Level at source and its variation with range

In order to provide an objective and quantitative assessment of the degree of any environmental effect it is necessary to estimate the sound level as a function of range. To estimate the sound level as a function of the distance from the source, and hence the range within which there may be an effect of the sound, it is necessary to know the level of sound generated by the source and the rate at which the sound decays as it propagates away from the source. These two parameters are:

- the Source Level (i.e. level of sound) generated by the source, and
- The Transmission Loss, that is, the rate at which sound from the source is attenuated as it propagates.

These two parameters allow the sound level at all points in the water to be specified, and in the current state of knowledge are best measured at sea, although it is in principle possible to estimate the transmission loss using numerical models. Usually this data has to be extrapolated to situations other than those in which the noise was measured; the usual method of modelling the level is from the expression

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

Where N is a geometric loss constant, α is the absorption and R is range. SL is the effective level of sound at a distance of one metre from the source. If the level of sound at which a given effect of the sound is known, an estimate may be made of the range within which there will be an effect.

This approach is reasonably accurate where the source is far from the point at which the sound is estimated. Where the source is in close proximity, it is necessary to use more sophisticated acoustic models. In the case of this report, Prism, an image-source model, has been used to evaluate the acoustic field from representative experimental geometries.

4 A brief review of available literature on acoustic experiments on marine mammals

There is a substantial body of literature addressing the effects of underwater noise on marine animals, especially fish and marine mammals. Unfortunately, it is common that the quality of documentation of the noise is inadequate to allow the data to be analysed, interpreted or used in subsequent investigations.

4.1 Studies investigating underwater noise avoidance by pinnipeds

Operational underwater noise emitted by a 550 kW wind-turbine was recorded from the sea and modified to simulate a 2 MW wind-turbine by Koschinski *et al*. (2003). The sound was presented via an audio CD through a car CD-player and a J-13 underwater transducer. The maximum sound energy was between 30 and 800 Hz with peak source levels of 128 dB (re. 1 µPa @1m) at 80 and 160 Hz. Measurements showed that this simulated 2 MW wind-turbine noise on calm days (<1 Beaufort) to free-ranging harbour porpoises (*Phocoena phocoena*) and harbour seals (*Phoca vitulina*) in Fortune Channel, Vancouver Island, Canada. Data were collected using an electronic theodolite situated on a cliff top 14 m above sea level, which recorded swimming tracks of porpoises and surfacings of seals. Kastak *et al*. (2005) also used behavioural techniques to determine TTS in *Z. californianus*, *P. vitulina* and *M. angustirostris*; exposure induced threshold shifts of over 12 dB, with full recovery of hearing sensitivity after 24 hours. Kastak et al. (1999) obtained pure-tone hearing thresholds (in water) for one harbour seal (*P. vitulina*), two California sea lions (*Z. californianus*), and one northern elephant seal (*M. angustirostris*) before and immediately following exposure to octave-band noise. Additional thresholds were obtained following a 24-h recovery period. Test frequencies ranged from 100 Hz to 2000 Hz and octave-band exposure levels were approximately 60-75 dB referenced to the auditory threshold at the centre frequency. Each subject was trained to dive into a noise field and remain stationed underwater during a noise-exposure period that lasted a total of 20 to 22 minutes. Following exposure, three of the subjects showed threshold shifts averaging 4.8 dB (*P. vitulina*), 4.9 dB (*Z. californianus*), and 4.6 dB (*M. angustirostris*). Recovery to baseline threshold levels was observed within 24 hours of noise exposure.

A behavioural response paradigm was used to measure underwater hearing thresholds in two California sea lions (*Zalophus californianus*) by Finneran et al. (2003), before and after exposure to underwater impulses from an arc-gap transducer. Pre-exposure and post-exposure hearing thresholds were compared to determine if the subjects experienced temporary shifts in their masked hearing thresholds (MTTS) at 1 and 10 kHz. No MTTS was observed in either subject at 178 and 183 dB (re. 1 µPa), though behavioural reactions were observed in both subjects. These reactions primarily consisted of temporary avoidance of the site where exposure had previously occurred.

Similarly, Kastak et al. (2005) used psychoacoustic techniques to evaluate the residual effects of underwater noise on the hearing sensitivity of a California sea lion (*Z. californianus*), a harbour seal (*Phoca vitulina*), and a northern elephant seal (*Mirounga angustirostris*). The subjects were exposed to octave-band noise centred at 2.5 kHz at two sound pressure levels of 80 and 95 dB referenced to the auditory threshold at 2.5 kHz. Noise exposure durations were 22, 25, and 50 minutes. Mean threshold shifts ranged from 2.9 to 12.2 dB at 2.5 kHz and 3.53 kHz. Threshold shift magnitudes increased with increasing noise exposure levels for two of the three subjects, and full recovery of auditory sensitivity occurred within 24 hours of the experiment.

Romano *et al*. (2004) looked at the Norepinephrine levels in blood samples from *D. leucas* and *T. truncates*. Though both methods will provide either useful behavioural data or indicate physiological trauma/stress, neither will show evidence of raised hearing thresholds following exposure. Nachtigall *et al.* (2004) measured the temporary threshold shift recovery time in *T. truncatus* using the Auditory Brainstem Response (ABR) technique. This protocol has the distinct advantage of being able to be applied rapidly on wild free living animals, generating directly comparable data between measurements taken in the field, and those made under controlled conditions.

4.2 Audiograms and hearing processes of harbour seals

In general, pinnipeds hear sounds ranging from approximately 100 Hz to somewhere approaching 30 kHz in air, and up to as high as 100 kHz in water; with best sound detection threshold in air of somewhere around 15 dB re. 20 µPa from 1.1 kHz to 10 kHz, to around 65 dB re. 1 µPa at 10 kHz underwater. According to Mulsow & Reichmuth (2009), a number of studies with otariid pinnipeds (sea lions and fur seals) have demonstrated that hearing sensitivity measurements using electrophysiological Auditory Steady-State Responses (ASSRs) can provide an efficient means of estimating an animals behavioural audiogram when compared to psychophysical methods. ASSR data is obtained using a similar electrophysiological technique as in ABR, though it uses a detection algorithm to define hearing thresholds.

Kastak, D. & Schusterman, R.J. (2002) used a behavioural test for detecting changes in auditory sensitivity with depth in a free-diving California sea lion (*Zalophus californianus*). Prior to this, Kastak & Schusterman (1998) defined low-frequency amphibious hearing in *Zalophus californianus* and the harbour seal (*Phoca vitulina*). In addition, Kastak & Schusterman (1995) also investigated aerial and underwater hearing thresholds for 100 Hz pure tones in *Z. californianus* and *Phoca vitulina*. (Schusterman (1974) Auditory sensitivity of *Z. californianus* to airborne sound. Schusterman *et al*. (1972) Underwater audiogram of the *Z. californianus* by the conditioned vocalization technique.) The results of these experiments show that *Z. californianus* can detect underwater sounds of 10 KHz at a sound pressure level of around 80 dB (re. 1 µPa) at depths from 10 m to 50 m.

Ridgway & Joyce (1975) used a cortical evoked response method to define auditory thresholds in the grey seal (*Halichoerus grypus*). Electrodes and a transmitter were fixed to the subject's head, which was able to swim as normal afterwards. Thresholds were detected from 200 Hz to over 100 kHz and best thresholds were obtained at 10 kHz from sound pressure levels of 60 to 75 dB re. 1 µPa.

Wolski *et al*. (2003) measured hearing thresholds in Harbour seal (*Phoca vitulina*) in an experiment comparing a behavioural paradigm with the auditory brainstem response technique. The aforementioned Kastak & Schusterman (1995; 1998) also defined hearing thresholds for *P. vitulina* using behavioural responses to define hearing thresholds. Terhune (1988) obtained thresholds from *P. vitulina* to repeated underwater high-frequency, short-duration pulses using a behavioural paradigm. Møhl (1968) identified auditory sensitivity of *P. vitulina* using a behavioural paradigm in air and water, to sounds ranging from 1 kHz to 30 kHz and best detection threshold of 10 dB re 20 uPa at 10 kHz in air, and from 100 Hz to 200 kHz and a best detection threshold of 55 dB re 1 uPa at 10 kHz in water. Terhune & Ronald (1972) defined underwater hearing sensitivity of the harp seal (*Pagophilus groenlandicus*) using a behavioural paradigm and recorded responses from 800 Hz to 100 kHz and a best detection threshold of 65 dB re. 1 µPa at between 10 and 12 kHz. Thomas *et al*. (1990) identified the underwater audiogram of the Hawaiin monk seal (*Monachus schauinslandi*) using a behavioural paradigm. However, the authors only record a response from this species from 1.1 kHz up to 40 kHz, though the best detection threshold remains fairly constant at 65 dB re. 1 µPa between 10 and 12 kHz. Kastak & Schusterman (1999) defined the in-air and underwater hearing sensitivities of a northern elephant seal (*Mirounga angustirostris*) using a behavioural paradigm. In air, thresholds were obtained from 100 Hz to 30 kHz and underwater thresholds ranged from 800 Hz to 70 kHz with best detection thresholds of 60 dB re. 1 µPa at around 7 to 10 kHz. Moore & Schusterman (1987) used a behavioural paradigm to conduct an assessment of hearing in northern fur seals (*Callorhinus ursinus*) from 500 Hz to 30 kHz (in air) with best thresholds between 8 to 10 dB (re. 20 uPa) at between 1.1 kHz to 20 kHz. In water, hearing thresholds were measured from 1 kHz to 40 kHz at a best detection threshold of 55 to 60 dB re. 1 µPa from 4 kHz to 30 kHz. Terhune & Ronald (1975) investigated underwater hearing sensitivity in the ringed seal (*Pusa hispida*), also using a behavioural approach. The audiogram was recorded from sounds ranging from 1 kHz to 30 kHz and a best threshold of 68 dB re. 1 µPa at 10 kHz. Kastelein *et al*. (2002) measured the underwater audiogram of a Pacific walrus (*Odobenus rosmarus divergens*) using a behavioural approach. The recorded audiogram ranged from 100 Hz to around 30 kHz, with a best detection threshold of 65 dB re. 1 µPa at 10 kHz. A more recent publication of Kastelein (2009) has an audiogram with thresholds lower than previous measurements over a range between 100 Hz and 10 kHz gives a best detection of 55 to 57 dB re. 1 µPa between 1 and 8 kHz.

4.3 Behavioural reactions of pinnipeds to man-made noise

Whilst controlled behavioural experiments are essential for setting baseline data, the protocols are often difficult to apply to wild free living animals that may have been exposed to intense sources of noise. The ability to conduct an audiological assessment of a wild (naive) animal requires that more instant protocols are available that do not require intensive training/conditioning to acquire statistically sound data. Operational underwater noise emitted by a 550 kW wind-turbine was recorded from the sea and modified to simulate a 2 MW wind-turbine by Koschinski *et al*. (2003). In total 157 seals were observed during play-back experiments compared to 141 surfacing seals during controls; both *P. vitulina* and *P. phocoena* were reported to have shown a distinct reaction to wind-turbine noise.

Jacobs & Terhune (2002), Norberg & Bain (1994), Norberg (2000) and Yurk (2000) observed *Phoca vitulina* reactions to acoustic harassment devices (AHDs) deployed around aquaculture facilities and generating noise levels of around 170 dB re: 1 µPa at 1 metre. The authors measured the sound pressure level around the AHDs and observed the behaviour of *P. vitulina* in the surrounding area. In each case, the behaviour of *P. vitulina* was not significantly modified by the noise generated by the AHDs.

Allen et al. (1984); Suryan & Harvey, (1998), Born *et al*. (1999), Moulton *et al*. (2002) investigated the effects of anthropogenic activity (e.g., aircraft, motor vessels, and military rocket launches) on the haul-out and avoidance behaviours of pinnipeds in response to noise. The results of these observations indicate that though some disturbance had occurred (which could have been visual in nature), on the whole animals were unaffected by such activities. Gentry *et al*. (1990) determined that northern fur seals tolerated underground explosions and other quarrying operations in close proximity to haul out and feeding grounds. Holst *et al*. (2005) (from Southall *et al*., 2007) observed behavioural responses in three species of pinnipeds to 47 missile launches over a four year period. The authors observed animal presence and distribution before launches and behaviour during and following launches. No incidences of long-term pup separation or injury were documented. The authors conclude that temporary behavioural responses do not appear to have substantial adverse effects on pinniped populations.

4.4 Underwater sound impact

An acute sense of hearing is of central importance to many marine animals; it is used to retain cohesion in social groups, for echolocation (hunting and navigation) and in the detection of approaching predators etc (Myrberg, 1981). The loss of the ability to hear (be it permanent or temporary) will obviously have some potential effects on the ecology of marine animals, with the magnitude being dependant on the attributes of the species specific biological system for detecting sound and vibration. Once above a specific intensity, the characteristics of a sound e.g. the intensity and frequency along with the duration of exposure will have an effect on both the auditory system and behaviour of animals within range of the disturbance (which considering the acoustically conductive qualities of water can be over a considerable distance). These effects are classed as either Temporary Threshold Shifts (TTS) or Permanent Threshold Shifts (PTS). Symptoms of TTS include the temporary loss of hearing ability, pain, vertigo and tinnitus, though the auditory system eventually recovers and hearing thresholds return to pre-exposure values (no permanent injury to the ear). Above this maxim, hearing thresholds will become elevated, though only if the frequency is within the normal audiological range for the effected species. As the intensity and duration of noise exposure intensifies, a point will be reached where the threshold shift will become permanent. This can be as a result of repeated temporary shifts, or from a single exposure to a sufficiently intense noise. In mammals symptoms of PTS include the destruction of receptor hair cells in the cochlear and vestibular organs by oxidative stress, ossicular fracture and/or dislocation, round and oval window rupture with cerebrospinal fluid leakage into the middle ear.

Many auditory assessments rely on behavioural responses or physiological recording techniques to acquire statistically sound data. Some experiments (especially on fish) have also used histopathological methods to determine the level of trauma to the inner ear receptors causing Permanent Threshold Shifts (PTS). Concise physiological and histological information on the hearing systems is critical to the assessment of the potential effect of anthropogenic noise pollution in the marine environment, being especially relevant where an animal is thought to have died as a consequence of intense noise exposure. Gross trauma to the auditory system can result in lesions developing along the VIII nerve pathway, or ruptures in the blood vessels surrounding the inner ear. A number of techniques have been developed to study this sort of physiological damage to the inner ear, though these investigations do not necessarily verify the impairment (either permanent or temporary) of hearing and balance. In addition, these types of injuries may have been sustained by the animal as it struggles in fishing nets, or thrashes about on the shoreline and thus be unrelated to loud noise exposure. If caused by intense noise, signs of trauma (haematoma and nerve lesions) would probably manifest at the highest end of the impact scale, whereas more subtle damage to the ears may only show in the hair cell body and ultrastructure and thus be missed when using conventional examination methodologies.

Kastak *et al*. (1999) found that noise of moderate intensity and duration is sufficient to induce TTS under water in pinniped species. Control sessions in which the subjects completed a simulated noise exposure test, produced shifts that were significantly smaller than those observed following actual noise exposure. Koschinski *et al*. (2003) showed that both harbour porpoises and harbour seals are able to detect the low-frequency sound generated by offshore wind-turbines. The behavioural experiments by Finneran et al. (2003) showed that *Z. californianus* would avoid an area where exposure had previously occurred, demonstrating the experiment had resulted in the establishment of a particular behaviour through negative reinforcement.

However, caution must be employed during such experiments, as cumulative TTS may eventually lead to a permanent threshold shift (PTS).

Species	Stimulus Source	Stimulus level/ frequency/ duration	Result	Audiological Protocol	Author
California sea lion (*Zalophus californianus*) n=2	Arc-gap transducer	Max. 183 dB re. 1 µPa Single impulse @ 1 & 10 kHz	TTS in masked thresholds	Behavioural response paradigm	Finneran et al. (2003).
California sea lion (*Zalophus californianus*) n=1		Max. 95 dB SL @ 2500 Hz	Max TTS 12.2 dB. Recovery within 24 h	Behavioural response paradigm	Kastak et al. (2005).
California sea lion (*Zalophus californianus*) n=2		Max. 75 dB SL @ 100 Hz to 2000 Hz 20-22 min	TTS averaging 4.9 dB	Behavioural response paradigm	Kastak et al. (1999).
harbour seal (*Phoca vitulina*) n=1		Max. 95 dB SL @ 2500 Hz	Max TTS 12.2 dB. Recovery within 24 h	Behavioural response paradigm	Kastak et al. (2005).
harbour seal (*Phoca vitulina*) n=1		Max. 75 dB SL @ 100 Hz to 2000 Hz 20-22 min	TTS averaging 4.8 dB	Behavioural response paradigm	Kastak et al. (1999).
harbour seal (*Phoca vitulina*) n=157	Simulated 2 MW wind-turbine	128 dB (re. 1 µPa) @ 30 and 800 Hz	Avoidance response	Behavioural response paradigm	Koschinski et al. (2003).
northern elephant seal (*Mirounga angustirostris*) n=1		Max. 95 dB SL @ 2500 Hz	Max TTS 12.2 dB. Recovery within 24 h	Behavioural response paradigm	Kastak et al. (2005).
northern elephant seal (*Mirounga angustirostris*) n=1		Max. 75 dB SL @ 100 Hz to 2000 Hz 20-22 min	TTS averaging 4.6 dB	Behavioural response paradigm	Kastak et al. (1999).

Table 4.1 - Summary of published information on the effects of controlled noise exposure on hearing thresholds in pinnipeds and arranged by species

5 Physical injury and lethality in marine mammals

5.1 Introduction.

This section of the report reviews current literature and examples of physical injuries in marine mammals, and uses these to suggest criteria for injury and death of marine mammals as a result of exposure to noise. In general, there is little information on the effects of high energy underwater sound on marine mammals of good quality. In particular, there are very few instances where the physical parameters of sound have been measured simultaneously with the impact upon the marine animal. This form of data is only likely to be provided from controlled, open water trials. In many cases, however, data arises as a result of accidental exposure which it may only be possible to interpret later in a limited way.

Studies have been conducted using submerged terrestrial animals and human divers: these are also reviewed here to provide quantitative data for the levels of the physical parameters likely to cause death or injury.

In many cases, the quantities quoted in the reports referenced herein are in non-SI units, such as psi, bar etc. Where this occurs, the convention has been adopted in this report of quoting the reference verbatim, including the use of the units as quoted by the authors of the report, followed by the appropriate SI conversion.

5.2 Levels of peak pressure that may cause lethal and physical injury.

5.2.1 Marine mammal data.

There are very few examples of observations of marine mammal mortality concurrently with the measurement of the physical parameters of the incident acoustic wave. Hanson (1954) recorded mortalities in fur seals at ranges of up to 23 m from an 11 kg submerged dynamite charge. Blast scaling laws indicate that the exposures were likely to have been at an incident peak pressure of up to approximately 530 psi (3.8 MPa or 252 dB re. 1µPa peak pressure). Wright (1971) reported that sea otters (*Enhydra lutris*) were injured by incident peak pressures of 100 psi (0.69 MPa or 236 dB re. 1µPa) and killed outright by 300 psi (2.07 MPa or 246 dB re. 1µPa).

5.2.2 Animal studies.

Cameron, Short and Wakely (1943) describe the effects of underwater explosions on submerged monkeys, dogs, goats and pigs, exposed to blast waves from a 320 lb (145 kg) TNT charge fired at a depth of 48 feet (15 m) in 90 feet (27 m) of water. The horizontal range from the charge to the submerged animals varied from 0 to 900 feet (274 m). At incident peak pressure levels from 13.7 MPa to 4.5 MPa, corresponding to impulse levels from 4480 Pa.s to 827 Pa.s, 11 out of 13 animals were killed instantaneously. At incident peak pressure levels of 4.0 and 3.6 MPa, and impulse levels of approximately 690 and 550 Pa.s, the animals were severely injured and would not have recovered. At incident peak pressure sound levels from 2.4 to 0.5 MPa, and at impulse levels from 276 to 14 Pa.s, lung damage was observed, and it was determined that the injury was such that the animal would have been expected to recover.

Wright (1951) reported on the pathological findings in a goat exposed just below the surface to a 2.5 lb TNT charge at a range of 10 feet (3 m). The exposure was estimated at a peak pressure level of 12.2 MPa (262 dB re. 1µPa) and an impulse of 620 Pa.s. The goat died 25 minutes after the exposure with extensive haemorrhage to both lungs and damage to the liver. Studies with submerged rats indicated that a peak pressure of 10.3 MPa (260 dB re. 1µPa) at an impulse of 165 Pa.s was lethal in 80% of cases causing extensive haemorrhage of the lungs together with severe bruising of the caecum (pouch at the beginning of the large intestine) and small intestine. Rawlins (1974) reviews these injuries and suggests that for a submerged rat, 50% lethality (LD_{50}) might occur at an incident peak pressure of 800 psi (5.5 MPa or 255 dB re. 1µPa) and 95% lethality (LD_{95}) at an incident level of 1200 psi (83 MPa or 278 dB re. 1µPa).

Bennett (1955) provides a review of underwater blast impact on submerged rabbits and the use of materials to protect from the effects of the pressure wave. The rabbits were exposed to the pressure wave from three 1 g detonators, equivalent to 0.0066 lbs of TNT, with the charge and rabbits at a depth of 3 feet (0.91 metres). At a peak pressure exposure of 2330 psi (16 000 kPa, or 264 dB re. 1μPa), with an associated impulse of 0.067 psi.sec (462 Pa.s), all five of the unprotected animals died, suffering severe injury to the lungs, stomach and bowel.

Bebb and Wright (1952, 1953, 1954a, and 1954b) made extensive use of animal models, primarily submerged sheep, to determine the effects of underwater blast. Studies were conducted at ranges from 8 ft (2.4 m) to 45 ft (13.5 m) from a 1.25 lb (0.57 kg) TNT charge. At the greatest range, with a peak pressure of 235 psi (1620 kPa or 234 dB re. 1μPa) and an impulse of 0.035 psi.sec (241 Pa.s) the injuries found at post mortem examination were 'hardly visible', but by contrast, at a range of 15ft (4.6 m), with a peak pressure of 900 psi (6200 kPa or 256 dB re. 1μPa) and an impulse of approximately 0.15 psi.sec (1034 Pa.s), the injuries were 'severe and extensive'. It was estimated that by a range of 8 ft (2.4 m), with a peak pressure of 1900 psi (13100 kPa or 262 dB re. 1μPa) and an impulse of 0.26 psi.sec (1790 Pa.s), instantaneous death would have resulted. As a result of these studies a formula to estimate the lethal range from an underwater charge of known weight was proposed. It was based on the conclusion that a peak pressure of 12,000 kPa and an impulse of 700 Pa.s would be lethal, as would a wave of 4300 kPa peak pressure with an impulse of 4900 Pa.s.

Based on the findings of Bebb and Wright, the impact of underwater blast in terms of its peak pressure impact on submerged animals is presented in Table 5-1.

Peak Pressure (psi)	Peak Pressure (kPa)	Sound Level (dB re 1μPa)	Effect
>2000	>13800	>263	Death Certain
500 - 2000	3450 - 13800	251 - 263	Likely to cause death or severe injury
50 - 500	345 - 3450	231 - 251	Likely to cause injury
<50	<345	<231	Unlikely to cause injury

Table 5-1: Injury potential of an underwater TNT blast based on Peak Pressure (US Navy, 1970)

The studies of Fletcher *et a*l. (1976) with submerged sheep indicate that incident peak sound pressures of over 100 psi (690 kPa or 237 dB re. 1μPa peak pressure) have a lethal effect causing pulmonary contusion, haemorrhage and arterial gas embolism. Arterial gas embolism has been demonstrated in a number of submerged animal models, including humans, and is usually accompanied by lung damage. Yelverton *et al*. (1976) found that arterial gas embolism in submerged terrestrial mammals usually results in immediate death.

O'Keefe and Young (1984), Young (1991), Goertner (1982), Richardson (1995) and Ketten (1995) present models to determine the "safe" stand-off range for marine mammals from underwater high explosive charges. The model of Young (1991) was based on preventing injury related to the response of gas cavities such as the lungs, or gas bubbles in the intestines. Examples are provided that are also reproduced in Richardson (1991 and 1995) whereby the 'slight' injury range from a 4540 kg (10,000 lb) TNT charge is estimated at 2300 m for a porpoise calf, 1700 m for an adult porpoise, 1600 m for a 6 m whale and 700 m for a 17 m whale. Using blast scaling laws these correspond to incident peak pressure and impulse levels of 77 kPa or 218 dB re. 1μPa and 1230 Pa.s for the porpoise calf, 116 kPa or 221 dB re. 1μPa and 1700 Pa.s for the 6 m whale and 296 kPa or 229 dB re. 1μPa and 3550 Pa.s for the 17m whale.

Yelverton *et al*. (1973, 1976) used terrestrial mammals immersed in shallow water to establish models for the potential lethal effects of underwater blast. The studies are referred to by Richardson (1995) in converting the expressions for fish mortality into those that are representative of larger sea mammals. The expressions relate the impulse I (Pa.s) of the underwater blast that would produce a mortality probability and "no-injury" exposure, for an animal weight W (kg), where for:

- 50 % mortality $\ln(I_{50}) = 5.01 + 0.3857\ lnW$ *eqn. 4.1*,
- 1% mortality $\ln(I_1) = 4.55 + 0.3857\ lnW$ *eqn. 4.2.*

For a small marine mammal of mass 80 kg these expressions indicate an incident impulse that will produce a 50% mortality I_{50} = 812 Pa.s and a 1% mortality I_1 = 516 Pa.s. For a larger mammal of mass 500 kg, mortality I_{50} = 1647 Pa.s and a 1% mortality I_1 = 1039 Pa.s.

5.2.3 Human exposures.

Hirsh and Ommaya (1972) report on the death of a 23 year old man accidentally exposed to the explosive shock from a firecracker whilst swimming underwater. The firecracker exploded underwater in contact with the skin and 6 inches (0.15 m) from the base of the skull causing severe head injury and death related to the underwater explosion. The reconstruction of the mechanics of the exposure indicated a peak pressure of 440 to 1800 psi (3034 to 12410 kPa or 250 – 262 dB re. 1μPa) with an impulse quoted as between 1.8 to 3.5 psi.sec (12500 to 24400 Pa.s).

Richmond (1977) describes tests with human volunteer subjects exposed to underwater blast waves both as 'head out' exposures and with subjects exposed at a depth of 1 ft (0.3 m). The peak pressures, impulses and cut-off times were measured adjacent to the swimmer. With subjects fully submerged, the underwater blast impacts were described as tolerable, and did not produce tinnitus at impulse levels of 0.25 to 1.31 psi.msec (1.7 to 9 Pa.s) with respective peak pressures of 12 to 52 psi (83 to 358 kPa or 218 to 231 dB re. 1μPa). This was also the case with 1.0 to 2.0 psi.msec (6.9 to 13.8 Pa.s) impulses with corresponding peak pressures of 48 to 71 psi (331 to 490 kPa or 230 to 234 dB re. 1μPa), using 0.5 lb (0.23 kg) charges at a depth of 10 ft.

Wright *et al* (1950) conducted a series of tests with fully submerged divers exposed to underwater explosive charges. In the first of these Wright subjected himself to the impact from small charges at short range. The impacts that Wright underwent concluded with some fairly pernicious effects and resulted in Wright having to spend several days in hospital. A summary of the impacts from a 5 lb (2.27 Kg) TNT charge at shallow depth (approx 5 m) in given in Table 4-5.

In the subsequent trial that occurred at Spithead, Portsmouth, divers were exposed to underwater blast at a considerably greater range than that which Wright underwent (see summary in Table 5-3). The results indicate that shallow water exposure to a 5 lb (2.27 kg) charge at a range of 411 m produced a "slight squeeze" and a sound like a "dull bang" or "rumble". There are no indications that any of the divers were unduly concerned by exposure to the charge at this range, or any signs of physical injury in the subsequent medical examination. However, the divers in this study underwent numerous exposures to underwater blast and so were somewhat accustomed to the effects. The divers involved in the Spithead study were eventually exposed to a 25 lb (11.3 kg) charge at a distance of 65.6 m. At this point the trial was terminated as a significant number of the divers were developing a "wheeziness" in the chest as a consequence of the repetitive transient underwater noise exposure.

Range		Sensations	Estimated Shock Levels			
feet	metres	Subjective comment	P psi	P MPa	I psi-msec	I Pa.s
110	33.5	Sound of intense bang.	160	1.1	75	516
100	30.5	Intense bang. Mild blow on chest.	175	1.2	85	585
90	27.4	Severe blow on chest.	195	1.3	95	654
80	24.4	Blow on head and torso. Body shaken. Brief paralysis of arms and legs.	220	1.5	105	720
75	22.9	Violent blow. Brief paralysis of limbs. Substernal pain for ½ to 1 hour.	240	1.65	110	760
70	21.3	Violent blow. Temporary paralysis of limbs. Substernal pain lasting several hours. Aural damage. Tongue lacerated. Mask blown off. Mild concussion.	260	1.8	115	790

Table 5-2: Subjective comment from a diver exposed to a 5 lb (2.27 kg) charge of TNT (Wright et al (1950))

Range (metres)	**Diver depth (metres)**	**Impulse (Pa.s)**	**Peak Pressure (kPa)**	**Subjective Comments** (Assessed from comments of up to six divers for each underwater blast)
411	3.05	50	83.6	Small impact, waist squeeze, push. Sound like bang, crack, rumble.
411	15.25	50	83.6	Jolt, vibrated through body, hardly felt a thing. Heard dull bang, like Chinese cracker.
183	3.05	103	209	Slight impact, slight vibration - lower half of body. Quite a loud bang, sharp and sudden bang.
183	15.25	103	209	Shudder all over, felt blast - shove from waist upwards. Louder than I expected, two pretty loud bangs.
122	3.05	134	311	Vibration of whole body, slight sharp squeeze all over, fairly powerful thump in belly. Sharp loud explosion, low rumble, fairly loud bang - two distinct echoes.
122	15.3	134	311	Shook whole body, squeeze all over, blow on front of chest and top of head, pressure in ears. Loud explosion, double very loud rumbling bang, loud muffled bang.

Table 5-3: Summary of results from exposure of divers to a 5 lb (2.27 kg) charge in shallow water (Wright et al (1950))..

Christan and Gaspin (1974) evaluated much of the submerged terrestrial animal data to develop guidance for exposure of human divers and swimmers to underwater transient noise. Tests with submerged animals, primarily sheep, indicated that there was no incidence of physical injury provided that the impulse did not exceed 5.5 psi-milliseconds (38 Pa.s) or a peak pressure of 125 psi (905 kPa or 239 dB re. 1µPa) (Yelverton *et al*, 1973 and 1976). A "safe" level for human swimmers of 2 psi-msec (14 Pa.s) was proposed by Christian and Gaspin together with a maximum peak overpressure of 50 psi (345 kPa or 231 dB re.1µPa). The figure of 50 psi for a non-injury peak pressure was quoted in the US Navy Diving Manual (1970). This level of peak pressure is comparable with the impulsive noise incident upon a diver operating some of the noisier underwater bolt guns (Parvin, 1994). It is an extremely loud noise even to a diver wearing a diving suit and head protection.

5.3 Levels of impulse that may cause lethal and physical injury.

As noted in section 3, the use of impulse is relevant where damage may be caused to air-containing structures. Yelverton *et al.* (1973 and 1976) conducted extensive studies using submerged terrestrial animals (sheep, dogs, monkeys) weighing between 5kg and 40kg. The conclusions of these studies are summarised in Table 5-4. These studies showed that for a given peak pressure the likelihood of fatality or injury is related to the incident impulse. Authors such as Richardson *et al* (1995) have extended these findings to applications involving the exposure of marine mammals to underwater impulsive sounds.

Impulse (bar.msec)	Impulse (Pa.s)	Effect
2.76	276	No mortality. High incidence of moderately severe blast injuries, including eardrum rupture. Animals should recover on their own.
1.38	138	High incidence of slight blast injury, including eardrum rupture. Animals should recover on their own.
0.69	69	Low incidence of trivial blast injuries. No eardrum rupture.
0.34	34	No injuries.

Table 5-4. Summary of effects of different impulses on mammals diving beneath the water surface (Yelverton et al, (1973), Richardson et al, 1995)).

5.4 Auditory injury.

Noise-induced hearing loss is well understood in man and other terrestrial mammals and may, by inference, occur in aquatic mammals. The terms Temporary Threshold Shift (TTS) and Permanent Threshold Shift (PTS) are used to describe the upward shift in hearing threshold that can occur after exposure to loud noise. TTS is believed to result from metabolic exhaustion of the sensory cells and reversible damage at the cellular level following over-stimulation. PTS is caused by more pronounced anatomical changes.

Finneran et *al.* (2005), found TTS in bottlenose dolphin (*Tursiops truncatus*) exposed to short duration (a few milliseconds) underwater noise from a seismic source at 224 dB re. 1µPa. TTS has been demonstrated in bottlenose dolphins exposed to single 1 second pulses of narrow band sound (Ridgway *et al,* 1997). TTS was found to occur at received levels of 194-201 dB re. 1µPa at 3 kHz, 193-196 dB at 20 kHz and 192-194 dB at 75 kHz. Schlundt *et al.* (2000) also reports on TTS in bottlenose dolphins and beluga whales (*Delphinapterus leucas*) exposed to simulated 1 second sonar signals at frequencies from 3 kHz to 75 kHz, at incident sound levels from 192 to 201 dB re. 1µPa. Nachtigall *et al.* (2004) report on inducing a small (< 10 dB) TTS in hearing level in the bottlenose dolphin and the monitoring of hearing recovery following continuous 30 minute duration exposures to incident underwater sound at a level of 160 dB re. 1µPa. The TTS occurred at test frequencies of 8, 11.2 and 16 kHz, but not at 22.5 or 32 kHz.

The data for marine mammals presented above, and that for terrestrial animals indicates that hearing damage is related both to the level and to the duration of the exposure. Data for submerged human subjects has indicated, for example, that a 15 minutes continuous exposure to underwater sound at levels of approximately 167 to 180 dB re. 1µPa causes a measurable TTS in hearing level (Smith *et al.*,1996. See Table 5-5). In comparison, however, with an exposure duration of 32 seconds, there was no significant difference in hearing level in a group of human divers exposed to underwater sound over the same frequency range when exposed at levels of up to 191 dB re. 1µPa (Parvin *et al.*, 2002).

	500 Hz (n=11)		1000 Hz (n=6)		2000 Hz (n=13)		4000 Hz (n=11)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
SPL in water	174.5	16.6	167.1	8.9	176.2	15.8	179.0	17.4
SPL in air	132.7	12.1	119.9	4.1	123.2	5.1	123.1	8.2
SPL diff	41.8	17.6	47.2	7.3	53.0	15.5	55.9	14.2

Table 5-5. Summary of Sound Pressure Levels causing a 10 dB TTS in bareheaded divers after a 15 minute continuous noise exposure (SPL in dB re. 1μPa) (Smith et al,1996).

The underwater hearing threshold for typical fish and marine mammal species and for human divers and swimmers are compared in Figure 5-1. The different curves for each group represent different species or trials and give an indication of the variation in sensitivity for each group. From 500 Hz to 2000 Hz human underwater hearing threshold is at a level of approximately 70 dB re. 1µPa, and therefore appears to be more sensitive over this frequency range than most marine mammal species. Assuming a similar dynamic range, it is therefore unlikely that marine mammals would incur an auditory injury to components of anthropometric noise coinciding with the frequencies, exposure levels and durations for human divers set out in Table 4-5 above. At higher frequencies (above 10 kHz) marine mammals have very much more sensitive hearing, with a very wide hearing bandwidth, and are therefore more susceptible to the very high frequency components of underwater sound. Therefore, when assessing the potential for auditory injury in the form of a TTS, the frequency content of the sound as well as the level and duration is of critical importance. High frequency sonar and sound sources such as echosounders and fish finders may therefore be more likely to cause auditory injury in marine mammals than low frequency systems.

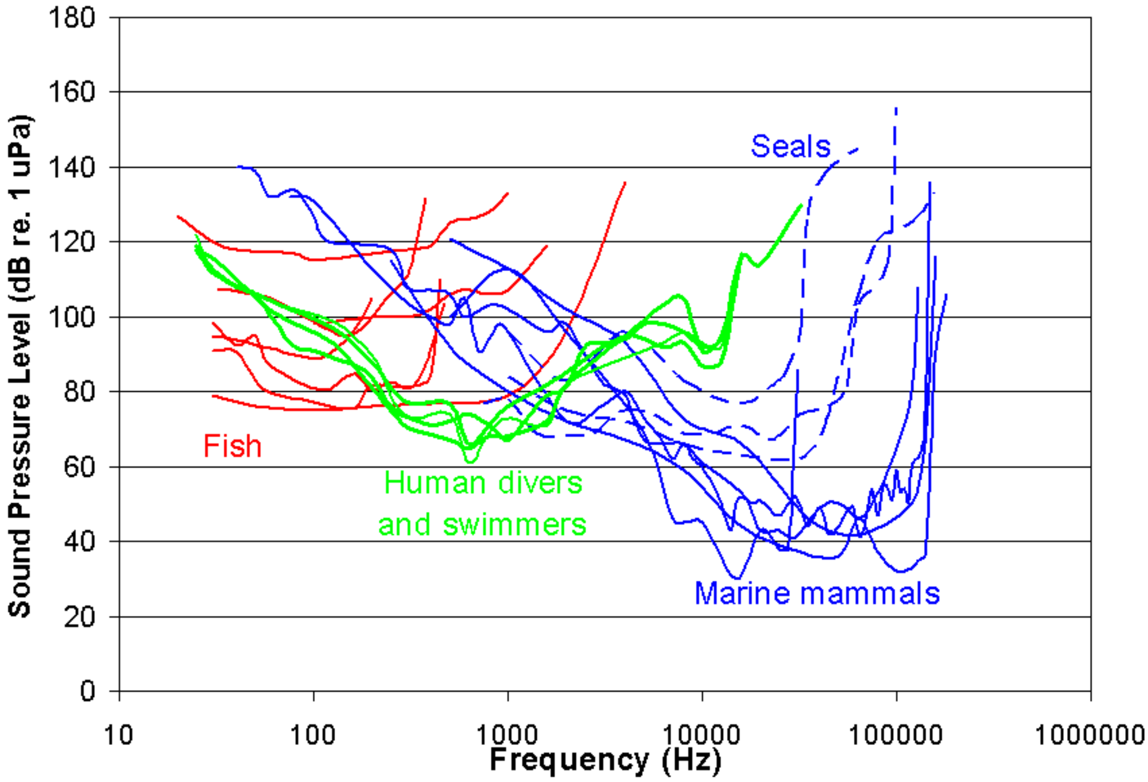

Figure 5-1. Comparison of underwater hearing threshold for species of fish, marine mammal and human divers and swimmers (Parvin et al, 1999).

5.5 Summary and discussion of data.

Currently, the levels of underwater sound that have the potential to be harmful to marine life are not accurately defined. Unless a systematic study of physiological impact from underwater sound sources is conducted, across a wide range of marine species and sound source types (explosive shock, impulse, sonar, shipping, etc), then this position is unlikely to change.

Hill (1978) describes the mechanisms and sites of explosion damage in submerged land mammals and discusses the likely resilience of marine mammals to these affects due to strengthened lungs and air passages that are adapted for deep diving. However, it might equally be argued that less compliant (strengthened) gas cavities might be more susceptible to the forces of a transient pressure wave, and hence greater injury might occur.

The results of human diver and submerged animal exposures indicate agreement with the general philosophy stated by Rawlins (1987), that "the shallower the safer". Theoretical calculations indicate that the inverted reflection from the water surface will tend to reduce underwater impulse and hence the risk of injury (Nedwell 1989). This might suggest that marine mammals at depth are at increased risk of physical injury. However, unlike human divers and submerged terrestrial animals, diving marine mammals are not provided with a gas supply at ambient pressure. Consequently, as the marine mammal dives, gas contained within the body compresses, and is reduced in volume, the volume varying in inverse proportion with absolute pressure. It is possible that at great enough depth, the gas containing structures may be sufficiently small and the gas contained within them at a density whereby the risk of direct physical injury is reduced from that near surface (i.e. there is less risk of injury from overexpansion when exposed to reduced external pressure). There is, however, no observational data to support this.

On a physical basis, there is unlikely to be much difference in the interaction of a blast wave with a marine mammal body compared with its interaction with a submerged terrestrial animal or human diver, the acoustic impedance of the tissues and anatomical structures being broadly similar. Any small variations in stiffness forces caused by differing stiffness of body structures will be greatly exceeded by the large forces experienced during exposure to the high pressures of a blast wave. The motion of body tissues is therefore unlikely to be significantly different between marine and terrestrial mammals.

At present, therefore, it must be assumed that the effects of blast on different species are likely to be similar at least to a first order. The large scale studies that have been undertaken on fish, terrestrial mammals and human divers offer the best information that is currently available, and can provide guidance as to safe levels of impulsive noise, although the guidance should be moderated with the limited available data for marine mammal exposure. In the case of dredging noise, the level is substantially below those which have been established to cause injury, and hence even in the absence of a formal criterion there can be considerable confidence that injury is unlikely.

5.6 Criteria for the impact of transient waves.

In broad terms, the data on impact of underwater transient pressure waves can be summarised as follows:

- At incident peak underwater sound levels of ≥10 MPa (≥260 dB re. 1µPa), or at 700 Pa.s and above – always lethal.
- At incident peak underwater sound levels of ≥1 MPa (≥240 dB re. 1µPa) – increasing likelihood of death or severe injury leading to death in a short time.
- At incident peak underwater sound levels of ≥0.1 MPa (≥220 dB re. 1µPa) – Direct physical injury to gas-containing structures and auditory organs may occur, particularly from repeat exposures.

For a small marine mammal of mass 80 kg

- incident impulse 812 Pa.s - 50% mortality
- incident impulse = 516 Pa.s - 1% mortality.

And for levels unlikely to cause injury

- peak pressure below 220 dB re.1µPa and impulse below 100 Pa.s – unlikely to cause injury

For continuous sound, direct injury to gas-containing structures or auditory organs, or threshold shifts in hearing level can occur at lower incident sound levels depending upon the duration and frequency content of the sound.

It is well established that some underwater noise activities generate high noise levels. It is therefore important to consider and document the potential impact of the subsea noise from marine activities as part of the overall Environmental Assessment process. High levels of underwater noise generated during some marine activities have the potential to cause both physical and behavioural effects in species of fish and marine mammals. The likely effect of TSHD noise on seals can e summarised as follows:

5.7 Summary of the likely effect of TSHD noise on seals.

5.7.1 Lethal effect

At very close range from the source the peak pressure levels have the potential to cause death, or severe injury leading to death, in marine mammals and fish. This generally occurs where the incident peak pressure sound level exceeds 240 dB re 1µPa @ 1m. The source levels associated with this sort of dredging are typically significantly lower than this value (190 dB re 1µPa @ 1m) and hence there will be no lethal effect from TSHD activity.

5.7.2 Physical injury

At greater range the noise can cause physical injury to internal organs in particular soft tissues surrounding gas containing structures of the body are affected. This generally occurs where the incident peak pressure sound level exceeds 220 dB re. 1µPa. The dredging source levels are hence insufficient to cause physical injury.

5.7.3 Traumatic hearing impairment

At high enough sound levels, and particularly where a sound is continuous or there are repeated high level exposures, the underwater sound has the potential to cause hearing impairment in marine species. In humans, a single underwater exposure to a sound of over 130 dB(A) re.1µPa can cause immediate and lasting damage. There is evidence to suggest that a similar criterion can be applied to marine animals, *i.e,* that levels of sound over 130 dB_{ht}(*Species*) may cause traumatic hearing damage.

The predicted dB_{ht} levels indicate that traumatic hearing impairment will not occur as a result of exposure to dredging noise.

5.7.4 Accumulative hearing impairment

At levels of noise that are not sufficient to create a sudden, traumatic hearing loss, hearing damage may nevertheless accumulate in the long term. It may be suggested that this is associated with noise at the upper limits of the dynamic range of hearing. In humans, damage is accepted to occur at levels of noise above 85 dB(A) when exposed to noise for periods in excess of 8 hours per day. In the case of dredging, this effect is likely to occur only if the seal is within

150m of the dredging for 8 hours per day, and hence it may be concluded that accumulative hearing loss will not occur.

5.7.5 Behavioural response

At greater range the underwater sound wave from a noise source may not directly injure animals, but has the potential to cause behavioural disturbance, and in particular avoidance, where the animal flees away from the source of the noise. . This effect is probably related to the preceding effect, in that avoidance has probably developed as an evolutionary response to protect hearing.

This response is of primary interest to this project as it is unlikely that the seals will remain in an area in which the sound pressure level is increasing to a level at which hearing impairment occurs. It has been suggested (Nedwell and Howell 2004) that levels of 90 dB_{ht}(Species) and above are likely to cause strong avoidance. This criterion has been used as the means of designing the experiment, in order that a sufficient sound level, mimicking dredging, can be created to cause a behavioural effect. Calculations show that strong avoidance is likely to occur within 100 metres with mild avoidance occurring at a range of a few hundred metres.

Thus it may be concluded that a degree of behavioural response is likely to occur for seals in close proximity to dredging. It may be noted that a localised response may be beneficial, in that it may serve to prevent animals straying into the inflow to the dredging suction pump.

5.7.6 Audible range

The audible range, or range over which marine species can hear the dredging activity, will extend to the distance whereby the dredging noise either falls below the ambient perceived sea noise level or the auditory threshold of the animal. In the case of dredging, this is likely to occur at ranges over 7000m for Vessel Q and 8000m for Vessel C.

It should be noted that whereas the former avoidance response may be considered to be instinctive, whereby the animal flees from the sound as a result of "unbearable loudness", an animal may also react to noise when the sound has the character of, say, a predator species. This may be termed cognitive avoidance, where the animal flees because of a perceived risk. Unlike the preceding case, where, the noise must be loud enough to cause an effect, in the case of cognitive avoidance the animal may flee at any distance where the noise is audible, and hence within the audible range.

In the case of dredging noise, which is a relatively featureless noise (i.e. there are no significant transient peaks in the noise level), it is thought unlikely that it will have this effect on animals.

5.7.7 Summary

The following table summarises the likely effects of noise from TSHD noise on seals, estimated from information available in the open literature.

Effect	Likely level of impact
Lethal	None
Physical Injury	None
Traumatic Hearing Impairment	None
Accumulative Hearing Impairment	About 8 Hours within 150m
Behavioural Response	Strong reaction within 100m, mild within 500m
Audible Range	Under 7000m

Table 5.6 – Summary of likely impact levels of TSHD noise on harbour seals

6 The hearing of seals

6.1 Seal audiograms

Audiogram data show the threshold of hearing for a particular species, that is, the levels of noise over a range of frequencies where the animal would no longer be able to hear the sound. Figure 6.1 presents audiograms of the harbour seal (*Phoca Vitulina*) from various sources. The data indicate that harbour seal are most sensitive to sound over a frequency range between approximately 1 kHz up to 40 kHz where the threshold of hearing is about 55-60 dB re. 1 µPa. At frequencies below and above this range hearing sensitivity reduces. Sound below the threshold levels indicated in Figure 6.1 would not be heard by the animals while the higher it is above this threshold the louder the sound is perceived.

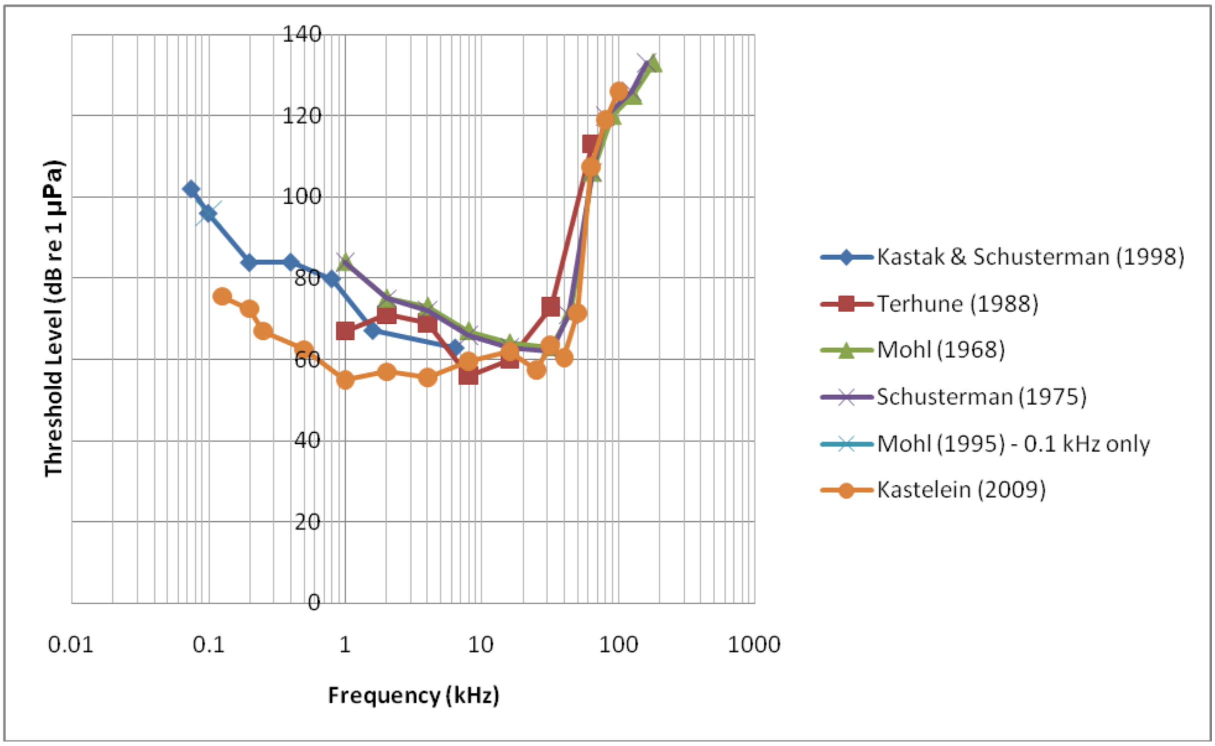

Figure 6.1 – Collected harbour seal audiograms

All of the above audiograms were measured using a behavioural response technique. The subjects are trained to respond to a signal of a specific frequency (e.g. by pressing a lever). The sound level at that particular frequency is said to be inaudible if the subject shown no reaction.

It is interesting to note that there are probably more measurements of hearing for this species than for any other marine mammal, and also that the results from the various authors agree reasonably well compared with those for other species. However, in spite of these comments, it should be noted that at some frequencies the estimates vary by over 20 dB.

In general, it appears that the information available concerning the hearing of the seal is probably adequate at this point for designing the experimental facility and procedures. As a precautionary approach, it might be possible to use the most sensitive parts of each audiogram as a guide as to the hearing threshold of the seal, that is, those of Kastelein, Terhune from 8 kHz to 20kHz and Mohl at the highest frequencies.

Summary:
After a review of available information on the hearing of seals it was found that there is reasonable information regarding the hearing of harbour seals, which are able to perceive underwater noise between approximately 100 Hz and 100 kHz with peak sensitivity between 1 kHz and 40 kHz

7 The characteristics of dredging noise

7.1 Typical levels of dredging noise

This section presents measurements previously made by Subacoustech on two Trailing Suction Hopper Dredgers. The details of the measurements and vessels are as follows.

	Vessel C	Vessel Q
Location of measurements	United Kingdom	Asia
Date of measurements	22nd October 2007 (10am – 6pm)	April 2004
Range over which measurements were taken (km)	0.250 – 16	0.090 – 2.5
Dimensions		
Length overall approx. (m)	97.70	173.15
Breadth (m)	17.35	32.00
Depth (m)	8.10	19.10
Hopper capacity (m^3)	2,473	29,947
Max. dredging depth(m)	36.60 / 45.70 (@ 45 / 50°)	55.00 – 115.00
Diameter suction pipe(s) (mm)	700 with submerged dredge pump	(2 x) 1,200
Dredge pump power (kW)	1,100	3,200

Table 7.1 – Details of recordings and dimensions of two TSHDs

Table 7.2 presents the unweighted data measurements of the two vessels at various ranges.

	Vessel C	Vessel Q
Source Level / Transmission Loss	L_r = 186 - 16 log(r) - 0.0006 r	L_r = 192 – 20 log(r)
dB re. 1 µPa level at 100m	154	152
dB re. 1 µPa level at 1000m	137	132
dB re. 1 µPa level at 10km	116	112
Approximate Range to Background (m)	8000	7000

Table 7.2 –Source Level and Transmission Loss for Noise from TSHD

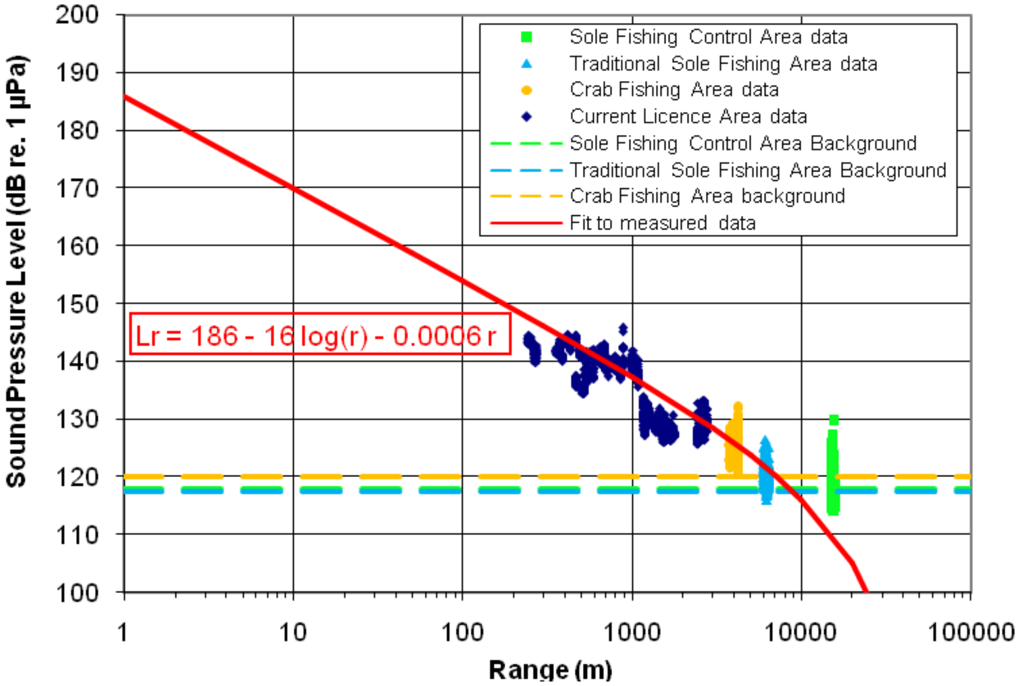

Figure 7.1 – Typical plot of dredging noise measurements against range

Figure 7.1 gives an indication of typical measurements of a TSHD along with the least sum of squares fit line from which the transmission equation is derived. This gives an indication of the spread of results (correlation) at each range. It can be seen that there is a spread of approximately ±5 dB re 1µPa with the exception of the most distant data. The poorer fit to this distant data may have been due to external factors such as vessel orientation.

It may be noted that although vessel Q has a higher source level than vessel C, there was greater transmission loss in the environment around the vessel thus the sound was attenuated more rapidly. It may also be noted that the larger vessel, vessel Q, is rather noisier than vessel C.

Figure 7.2 illustrates the Power Spectral Density of actual noise from vessel C at distances from about 250m to 6.3 km. In addition, the background, taken when no dredger was in the area, is also illustrated. Generally, the background noise determines the lowest level of noise that can be recorded. However, it should be noted that as these recordings were not contemporaneous, the level of the noise from the dredging may on occasion be below the level of the background noise, if this was recorded at a place or during a period when the background noise was lower than that pertaining during the period of measurement of the background. The Source Level (i.e. the estimated Sound Pressure Level at an effective 1 m from the source of the noise) is about 190 dB re. 1µPa @ 1m.

It may be seen that the spectrum is characterised by three regimes. Below about 10 Hz, there is no noise created by the dredging. Between about 10 Hz and 100 Hz, there are tonal components, which are typical of rotating machinery such as pumps, propellers and thrusters. For frequencies above 100 Hz, and up to frequencies of at least 100 kHz, there is a high level of broadband noise or “hissing”, probably caused primarily by sand and other debris rubbing against the side of the suction pipe as it is sucked upwards from the seabed. For convenience, these regimes may be termed “machinery noise” and “flow noise”.

It may be seen that the level of noise diminishes with range, but at 4km or so at some frequencies the flow noise from the dredging is still at 10-15 dB above background.

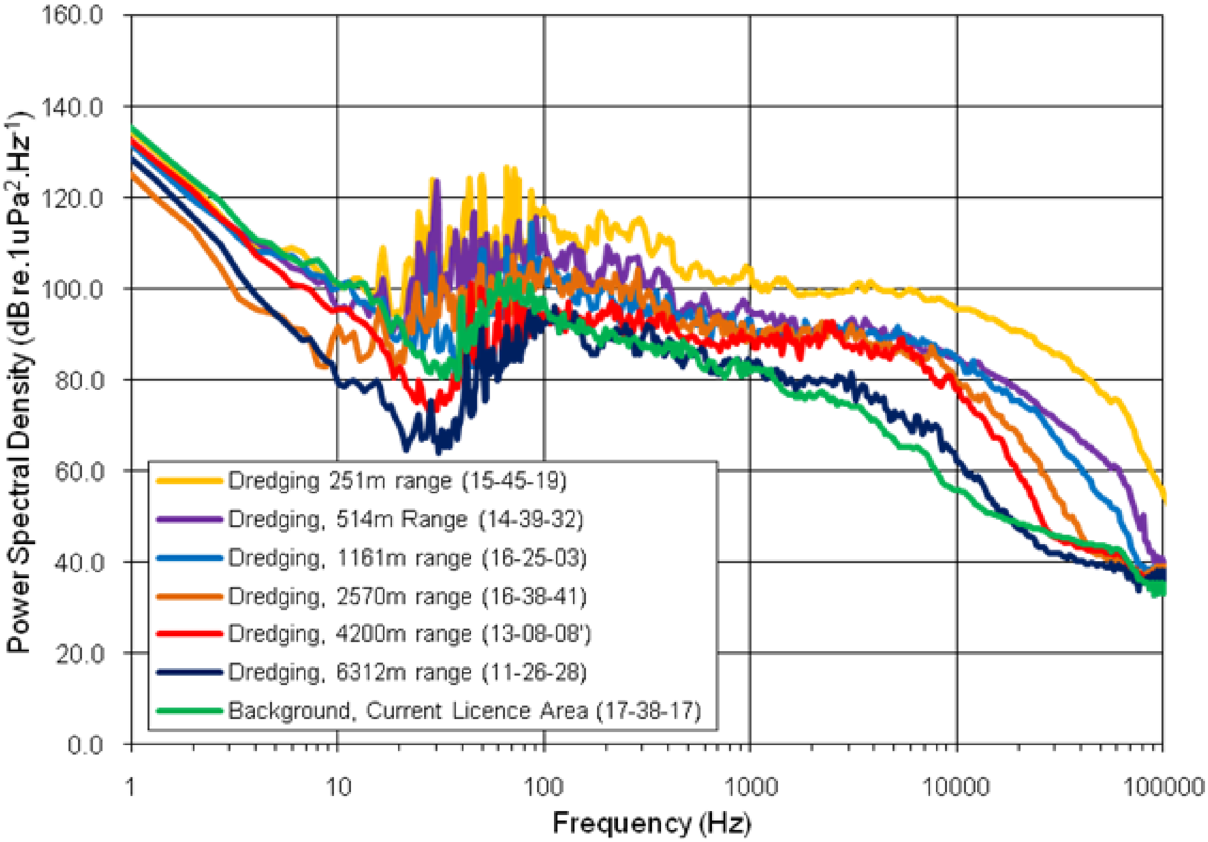

Figure 7.2 – Power Spectral Densities of Dredger C at various ranges

It has been proposed that a model of dredging noise is used as an experimental noise, rather than an actual recording of dredging noise. The dashed lines on Figure 7.3 show an idealisation of the typical noise spectrum of a TSHD that might be used as the basis of an experimental model. The two regions of the noise can be characterised by a straight line for the broadband noise section and smoothed curve for the machinery noise. However, the question arises as to the significance of the machinery noise region, which might be difficult to characterise or synthesize, as compared to the broadband flow noise region, which approximates to pink noise.

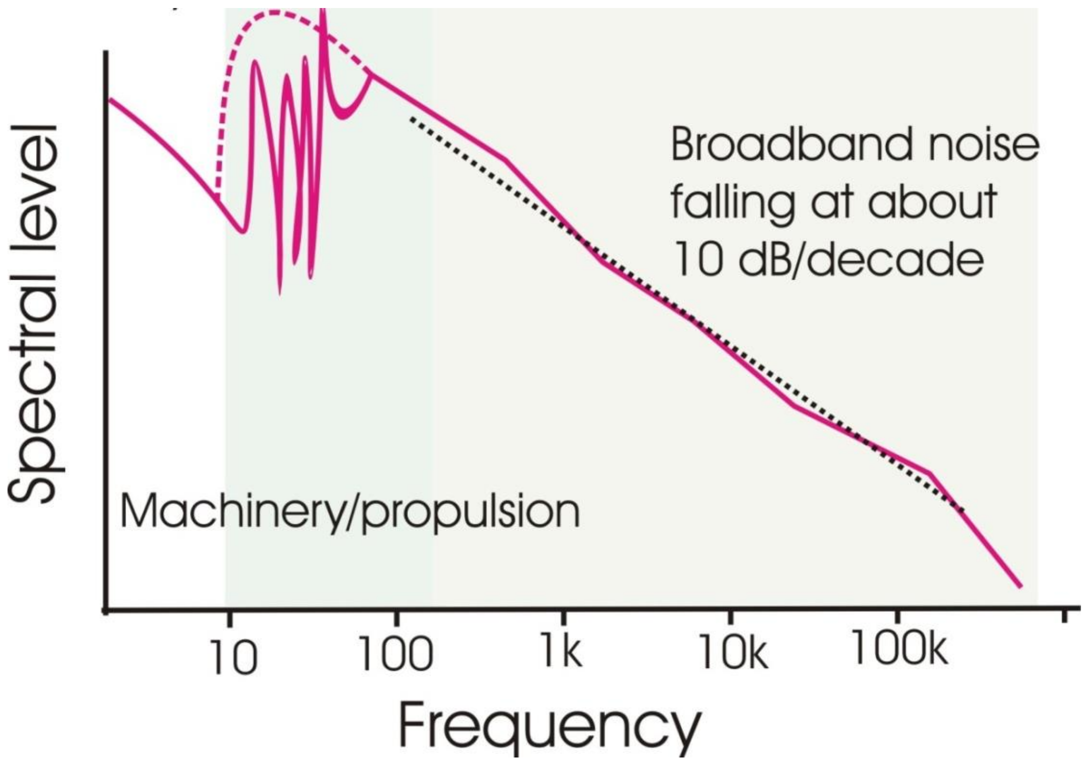

Figure 7.3 – An idealised noise spectrum of TSHD activity

7.2 The perception of dredging noise by seals

It is possible to draw preliminary conclusions regarding the perceivability of the noise from dredging and its effects from the information presented in sections 5 and 6. The perceivability also gives some guidance as to the acceptability of an idealised noise source for an experiment.

Figure 6.4 presents typical TSHD noise spectra measured at a range of 250 m from the dredging operation. Overlaid on the figure are the lowest threshold levels from the audiograms measured by Mohl, and Kastelein and Shusterman. It may be seen that the noise from the dredging exceeds the auditory threshold of the seal, and may therefore be concluded that the noise from dredging at that distance would be audible to a seal. It is interesting to note that the dredging noise has frequency components above the threshold of hearing for the seal from frequencies as low as 50 Hz up to frequencies of 50 kHz, or three decades of frequency. This places a very severe condition on the acoustic equipment for a playback experiment since the sound source must be capable of reproducing sound over this wide range.

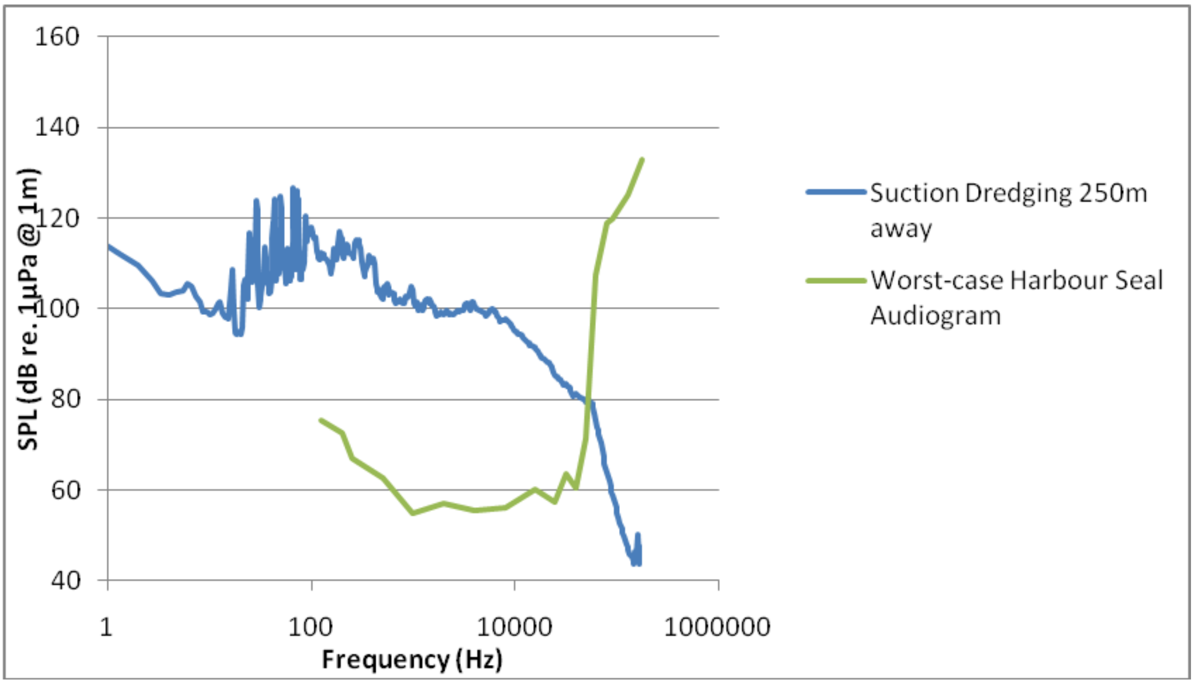

Figure 7.4 – Frequency spectrum of underwater noise from TSHD at 250m, and Harbour Seal Audiogram

A more revealing method of representing the information of Figure 7.4 is shown in Figures 7.5 and 7.6. These figures present the noise from dredging at 250m and 6250m, but in this case weighted by the auditory threshold of a seal. The figures thus present the level of the noise above the hearing threshold, of effectively the noise in “hearing thresholds per Hz” versus frequency. This may be termed a “perceptrum”. This quantity may be considered to be a spectrum of the *perceived* noise level for the seal, and gives an indication of the relative importance of the different frequencies of the noise.

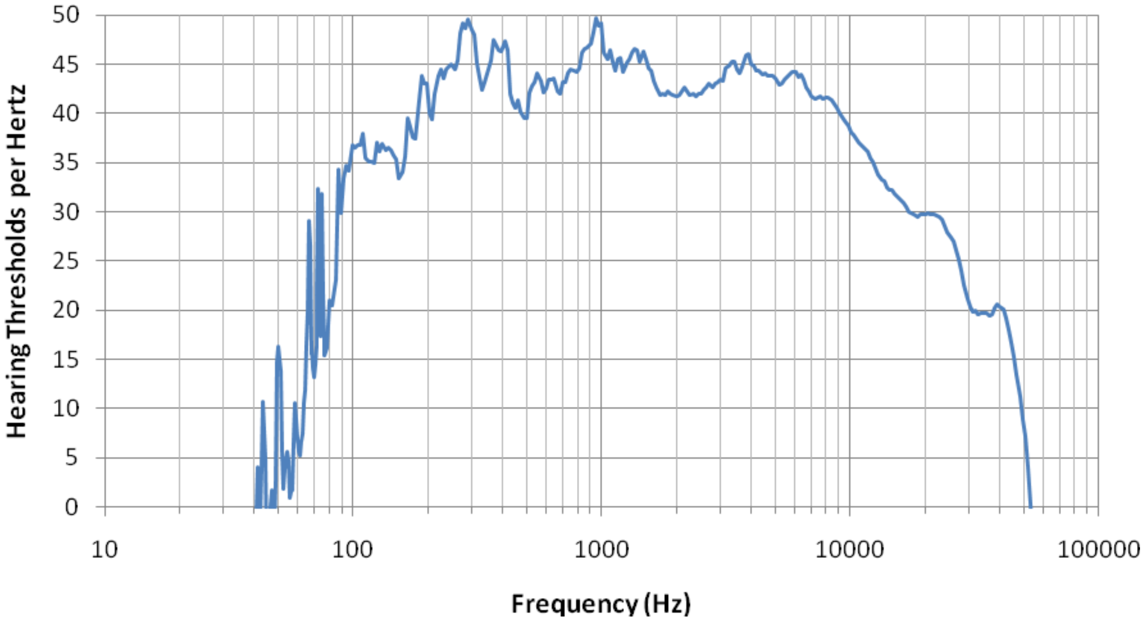

Figure 7.5 – Perceptrum of the TSHD Noise for the Harbour Seal at 250m

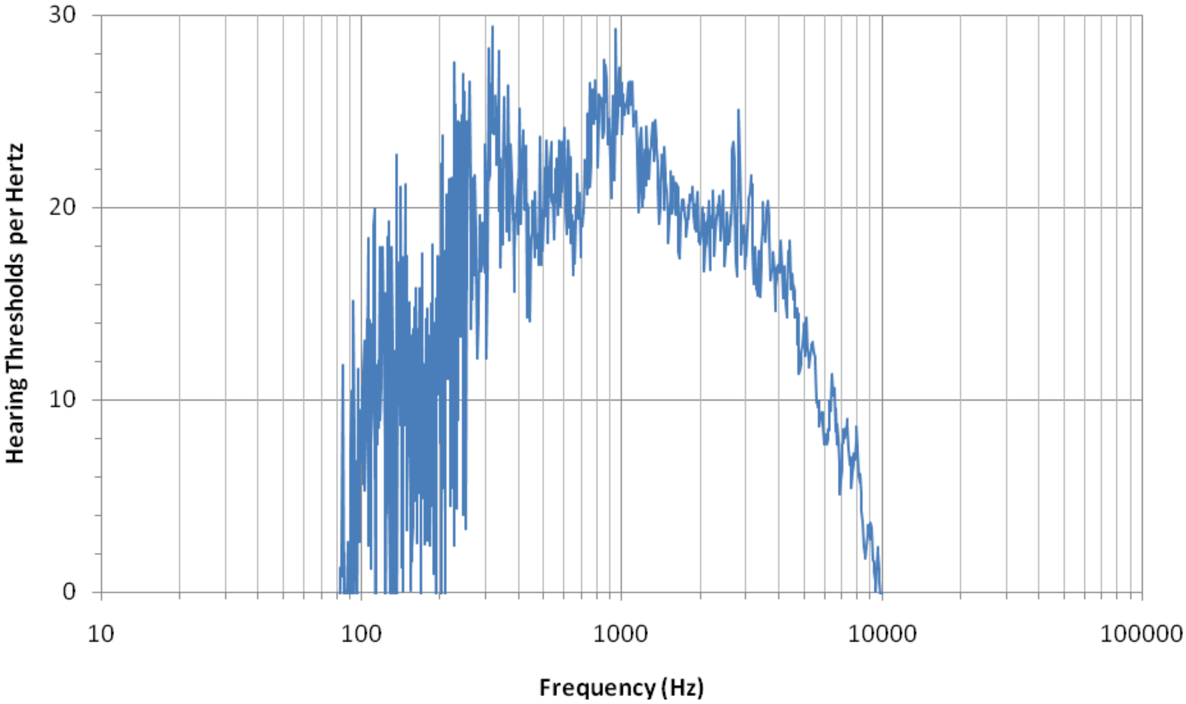

Figure 7.6 – Perceptrum of the TSHD noise for the Harbour Seal at 6250m

To prepare the above figure, it has been necessary to extrapolate the audiogram of the harbour seal at low frequencies to allow the entire range to be covered. The low frequency hearing has been extrapolated to a value of 142 dB at 10 Hz. Also, a single 'worst case' audiogram was constructed from the lowest published threshold values from Kastelein(2009), Terhune (1988) and Mohl (1968) (Table 7.3).

Source	Frequency (kHz)	SPL (dB re 1µPa @ 1m)
Kastelein	0.125	75.5
Kastelein	0.2	72.5
Kastelein	0.25	67
Kastelein	0.5	62.5
Kastelein	1	55
Kastelein	2	57
Kastelein	4	55.5
Terhune	8	56
Terhune	16	60
Kastelein	25	57.5
Kastelein	31.5	63.5
Kastelein	40	60.5
Kastelein	50	71.5
Kastelein	63	107.5
Kastelein	80	119
Kastelein	90	120
Mohl	128	125
Mohl	180	133

Table 7.3 – 'Worst-case' audiogram

It should be noted that any non-positive (i.e. where the graph drops to zero and below) values of the perceptrum indicate an area where the noise level of the dredging has dropped below the harbour seal hearing threshold for those frequencies, and thus it is inaudible. Thus it may be seen that the dredging noise is audible to the seals between about 35 Hz and 40 kHz.

It may be seen that the perceptrum at 250m indicates that the harbour seal is particularly sensitive to the dredging noise at frequencies of about 200 Hz to 10 kHz. It is interesting to note that the machinery noise region of the dredging noise in which there are tonals, from about 40 Hz to 100 Hz, is of significantly lower perceived level than the main peak. It may therefore be concluded that accurate reproduction of the tones of the machinery noise is probably not of great significance. In other words, a simple model for the dredging noise of broadband noise is probably adequate. This machinery noise occurs in the very low frequency area of the graph; the literature of Kastelein suggests that in this frequency band the seals are relatively insensitive to sounds in comparison to frequencies in the 200 to 10,000 Hz band.

At a greater distance, it can be seen that the perceptrum indicates a lower perceived level of sound across all the frequencies. In particular, the higher frequencies of the sound are attenuated by a greater amount; this has had the effect of lowering the upper frequency limit of sensitivity to approximately 10 kHz and also reducing the band of most sensitivity to 200 Hz to 1kHz.

For further comparison, below is a perceptrum indicating the sensitivity of a harbour seal to offshore pile-driving operations (Figure 7.7). The pile used was 4.3m in diameter and the recording was taken at a distance of 100m.

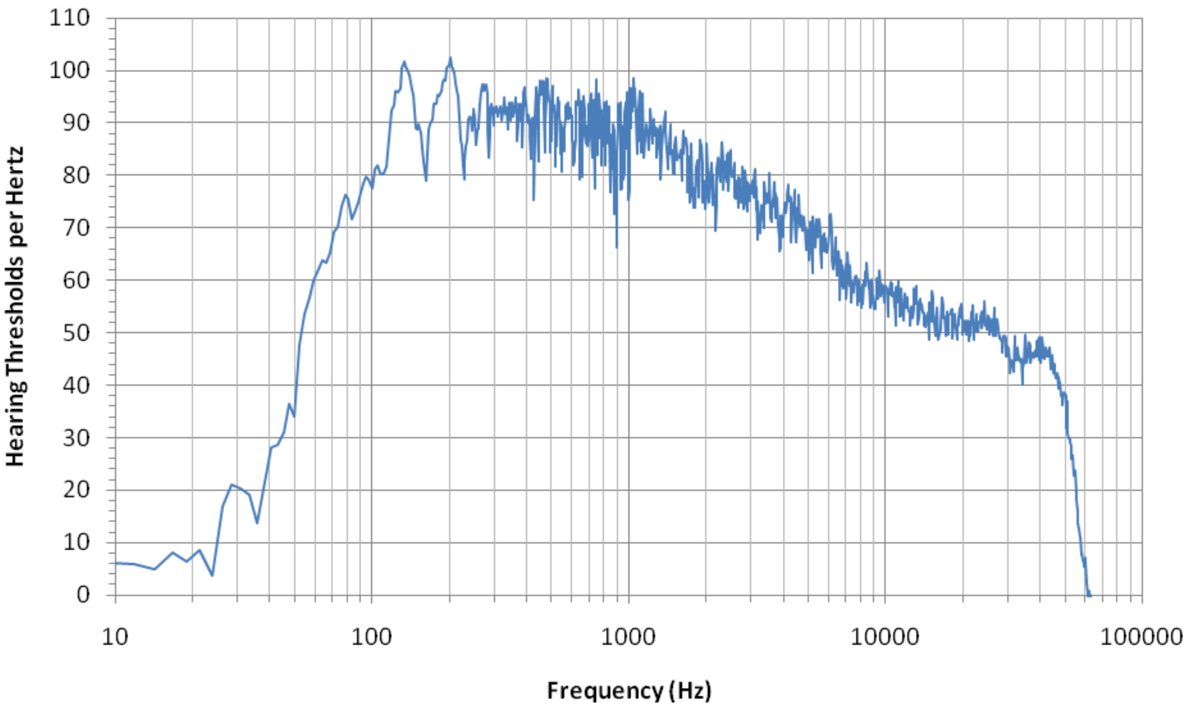

Figure 7.7 – Perceptrum of piling noise at 100m for a harbour seal

It can be seen that the piling is of a significantly higher perceived level than the dredging at a similar range. It is interesting to note that the frequency band over which the seals are most sensitive is similar to the dredging noise at 6250m range. An important question is as to whether seals are likely to react to typical levels of dredging noise. Table 7.4 presents the same information as Table 7.2; however in this case the levels are presented as dB_{ht} levels for seals. A level of 90 dB_{ht} has been used a criterion of strong avoidance reaction, and 75 dB_{ht} for mild avoidance.

It is interesting to note that, in this case, the vessel that was the loudest in terms of unweighted sound level is actually quieter as perceived by seals. This indicates the importance of using a relevant metric when interpreting the biological effects of noise.

The data imply that seals would be unlikely to react strongly to dredging noise at distances greater than 90 m for vessel C and 28 m for vessel Q. The range at which mild avoidance might be estimated to occur is 500 m and 160 m respectively.

	Vessel C	Vessel Q
Source Level / Transmission Loss for Seal	L_r = 129 – 20 log(r)	L_r = 119 – 20 log(r)
Seal Strong Behavioural Avoidance Range (90 dB_{ht}) (m)	90	28
Seal Mild Behavioural Avoidance Range (75 dB_{ht}) (m)	500	160
Seal Low Likelihood of Disturbance (50 dB_{ht}) (m)	9000	3000

Table 7.4 – TSHD Source Level and Transmission Loss in dB_{ht} for harbour seals

These results indicate that, in practice, it is fairly unlikely that a strong avoidance reaction to TSHD noise would be noted for seals. For both of the vessels, a 20 log (r) transmission loss has been used to calculate the ranges of avoidance.

The results have an important bearing on the proposed experiment. They imply that at noise levels typical of exposure at ranges from dredging, the level of noise is unlikely to create a reaction. Hence, in order to ensure a reaction experimentally, it will be necessary to generate a noise characteristic of dredging, but at higher levels than would be typical. Simple reproduction of dredging noise at actual levels of exposure may not guarantee a response.

Summary:
After a review of available information on TSHDs and the hearing of the harbour seal it was found that:

1. Comparison of a typical spectrum of underwater noise from a Trailing Suction Hopper Dredger with audiogram data for the harbour seal have indicated that this species is likely to be able to hear a range of TSHD frequencies between 35 and 35000 Hz, with a peak in perception between 200 Hz and 10 kHz which corresponds to a broadband ‘flow noise’ region of the dredging noise
2. dB_{ht}(*Phoca vitulina*) values of the measured TSHD noise spectrum suggest that areas of strong avoidance (most animals flee the area) are likely only to occur at ranges of less than 100m with mild avoidance (around half of the animals flee the area) occurring at ranges on the order of a few hundred metres.
3. Initial calculations indicate that the noise produced by TSHD is unlikely to cause a reaction in seals over ranges of more than a few hundred metres. Thus it may be necessary experimentally to increase the level of the noise to higher than would be typical of exposure, if a positive avoidance reaction is required.

8 Legislative issues arising from using seals as experimental subjects

8.1 Introduction

The purpose of this section is to initially address legislative and regulatory issues that may have a bearing on a playback experiment involving seals. The information presented here is intended to be introductory, as it is anticipated that the understanding of these aspects of animal experimental work and their practical implementation will be refined by discussions with prospective subcontractors during the early stages of the experimental phase of the project.

The common seal is not officially endangered. However, since these seals commonly stay only in one location throughout their lives, local populations may be threatened without the overall population being classified as such. For example, the Joint Nature Conservation Committee (JNCC) have found that although the majority of seal assessments made in areas of the UK are favourable, there has been found to be a significant decrease in the harbour seal population in The Wash due to an outbreak of a fatal Seal Distemper Virus in 2002.

8.2 Legislation and treaties

Outlined below are the licences and requirements for live animal testing in the UK and the Netherlands. Also presented are European Union criteria for justified live animal testing.

8.2.1 United Kingdom

In accordance with the Animals (Scientific Procedures) Act 1986[1], the following are needed in order to carry out tests in the UK (Sections 4/5):

1. **Personal licence** – Every person directly involved with a regulated procedure must have individual licences which are only given to those people deemed to have an appropriate level of instruction in a relevant scientific discipline.
2. **Project licence** – Each project must have been granted a licence by the Secretary of State after an application describing in full the proposed experiment.

Licences in the UK are processed by Animals (Scientific Procedures) Division (ASPD). This body is responsible for policy on the use of living animals in scientific procedures on behalf of the Home Secretary.

8.2.2 The Netherlands

The licensing laws in the Netherlands are similar to those in the UK.

1. Institutes, health centres and private companies require licences to perform animal experiments and must be applied for through The Dutch Inspectorate for Health Protection and Veterinary Public Health[2].

2. Persons involved with animal testing must meet requirements laid out by this governing body. There are officially recognised training courses that a person must undergo before they are allowed to conduct an experiment.

Also of interest to this project may be the Agreement on the Conservation of Seals in the Wadden Sea[3]. This is an agreement between Germany, Norway and the Netherlands aimed at

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[1] http://www.archive.official-documents.co.uk/document/hoc/321/321-xa.htm
[2] http://www.vet.uu.nl/nca/userfiles/other/leaflet_animal_experimentation_in_the_Netherlands.pdf
[3] http://www.jus.uio.no/english/services/library/treaties/06/6-05/seals-Wadden.xml

preserving the harbour seal population in the Wadden Sea area. It is concerned with protecting seals and their habitat as well as increasing their conservation status.

It may be noted that it appears that whilst legal aspects are similar, the interpretation of regulations regarding the use of wild (*i.e.* non-captive) seals appears to be stricter in the Netherlands than in the UK. This may have a bearing on experiments performed on wild seal populations, where the impact may be considered to be unacceptable.

8.2.3 European Union

At the European level there are two legal requirements for animal testing (see Council Directive 86/609/EEC[4])**:**

1. It must be shown that no alternative to the test exists
2. Each EU state must actively research alternative methods before the tests go ahead.

In the context of this study, it is not thought that an alternative approach to using live common seals as test subjects exists. Further information on the treatment of marine mammals can be found by visiting the Society for Marine Mammalogy website.[5].

In 2011 a new EU regulation is being put in place to further regulate testing on animals for scientific purposes. However, discussions with research centres have revealed that this new regulation is unlikely to affect the running of any experiment performed.

Any research collaborators will be chosen assuming they already have the relevant licences in place, however, it may be possible that licences need to be amended to include testing of seals outside of the normal operating procedures of the research centre.

Summary:
Having reviewed available literature on live animal testing legislation, it is suggested that:

1. Given the behavioural nature of the experiment, there is no alternative but to use common (harbour) seals as the test subjects.

[4] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:31986L0609:EN:HTML
[5] http://www.marinemammalscience.org/index.php?option=com_content&view=article&id=156&Itemid=182

9 The characterisation of experimental sound fields

9.1 Requirements for an experimental sound field

It has been proposed that the effects of suction dredging noise on the harbour seal are investigated using a playback experiment using an underwater sound projector array. Therefore, for a successful investigation, the sound projector array must produce a sound field which closely approximates that generated by a dredger in real-life. This requirement may be thought of as of critical importance. Without an accurate representation of the sound field from a dredger, the data collected from the experiment will be worthless in helping to determine the effects of dredging noise on harbour seals.

It should be remembered that a sound field is not only characterised by its spectrum, but also by its spatial dependence. Both of these properties are of critical importance in assessing the behavioural effects of noise. In essence, the spectrum determines “what the animal hears” and the spatial dependence determines “where it appears to come from”. Both of these are of importance in determining the effect of noise on a species. Primarily, the noise spectrum determines whether an animal will react. The spatial field however provides a cue as to the direction of the source of the sound, and hence determines its ability to react to the sound by fleeing from it.

A sound wave arriving from a source at distance in deep water will generally be characterised by being approximately plane, that is, it will have surfaces of constant phase and amplitude that are plane and perpendicular to the direction of propagation. In shallow water, the wave may be more complex as a result of reflections from surface and seabed. Near to the source, the wavefield may be complex, and there may be significant variations in both the pressure and particle velocity of the field, but as the wave propagates away from the source it will become more constant in form. Generally, the area around a source where the wavefield is complex is described as the “nearfield” and that far from the source the “farfield”. This is of considerable importance in the context of the proposed experiment, in that it implies the experimental source of noise must be at a sufficient distance to ensure the experimental facility is in its farfield.

9.2 Far Field

The geometric far field is defined as the distance from a source where the difference between the lengths of the longest and shortest signal paths is equal to a half-wavelength. From this point, all distances closer to the source are said to lie in the acoustic near field while those further away are in the acoustic far field. It will be critically important during the experiment to be aware of the extent of both the acoustic near and far fields as measurements taken in both fields can be significantly different. The significant difference lies in the fact that the pressure distribution in each sound field will be dissimilar, in terms of its evenness. It will be vital to position the harbour seals in the acoustic far field where the pressure distribution tends to be more uniform as the difference between signal paths does not result in significant interference. Obviously, when path differences approach a half-wavelength pressure nulls begin to appear. When a receiver moves still closer to a source (past the half-wavelength mark), differences in phase will lead to additional pressure maxima and minima - resulting in an undesirable uneven coverage in the near field.

The geometry of a source alone does not dictate the point of the beginning of the far field; its distance is also dictated by the wavelength of the projected sound. The role of wavelength has already been expressed in the definition of the geometric far field, i.e. ‘the far field begins when the path difference is equal to a half-wavelength’. This frequency dependency implies the far field is more difficult to realise for higher frequencies. The effect of frequency complicates matters as the far-field may only be achievable over a certain practicable frequency range. In other words, if the receiver is not far enough away from the array, the far-field will only be achievable for low frequencies. Additionally, with oblique receivers, the far field distance is greater still due to an emphasised path length difference between signals.

It is possible to estimate the point of the beginning of the far field for a reasonably directive array, when the wavelength of the projected sound is much smaller than the source's largest radiating dimension (Kinsler and Frey, 2000).

$$r_{\min} \approx \frac{L^2}{4\lambda}$$

(where L is the length of the largest dimension of the source and λ is the wavelength of the projected sound)

In the current case, for instance, for the highest frequency of TSHD noise that a harbour seal can perceive (around 40 kHz), a 5x5 array of sound projectors has a far field lower limit of 56m and a 2x2 array has a lower limit of 5.3m.

9.3 Level of test signal

It is of importance to initially determine whether it is possible, at any range, to simulate the sound level of a dredger.

Figure 9.1 shows the spectrum of recorded suction dredging noise at 250m from a TSHD, as presented in the preceding sections. Over this data has been plotted the measured output Source Level from an FGS Type 30-600 sound projector. This may be considered to be the effective sound level at a range of 1m from the projector.

Figure 9.1 presents the sound projector's ability to reproduce signals across the TSHD noise frequency spectrum. It should be noted that the response above 30kHz is misrepresentative because of effects of background limiting. With the presence of background limiting, it is possible to make the assertion that the projector is not capable of reproducing sound at high frequencies. However its operational range would be between approximately 30Hz to 10kHz which acceptably covers the range at which harbour seals are most sensitive to dredging noise. It may be commented that music reproducing loudspeaker systems for human use require a split frequency system, in which two or three different transducers ("woofers" for low frequencies and "tweeters" for high frequencies), are combined to achieve an adequate and similar range. While the level of noise that can be generated by the FGS Type 30-600 sound projector is adequate to reproduce TSHD noise over the entire range that can be perceived by the seal, it can be seen that the response is rather "peaky" at the higher frequencies. This is probably due to mechanical resonances of the transducer, and may be associated with phase changes. It is therefore considered possible that a split frequency system will achieve an optimum sound field for the playback experiment. The design of this split frequency system will be finalised during the second and third phase of this project. However, other than this consideration there can be considerable confidence that a suitable level of noise can be created experimentally.

It should be noted that the field from a single transducer at this range would be unacceptable, in that the field from it would not be representative of the field from a noise source at distance. This is addressed at greater length in the following section.

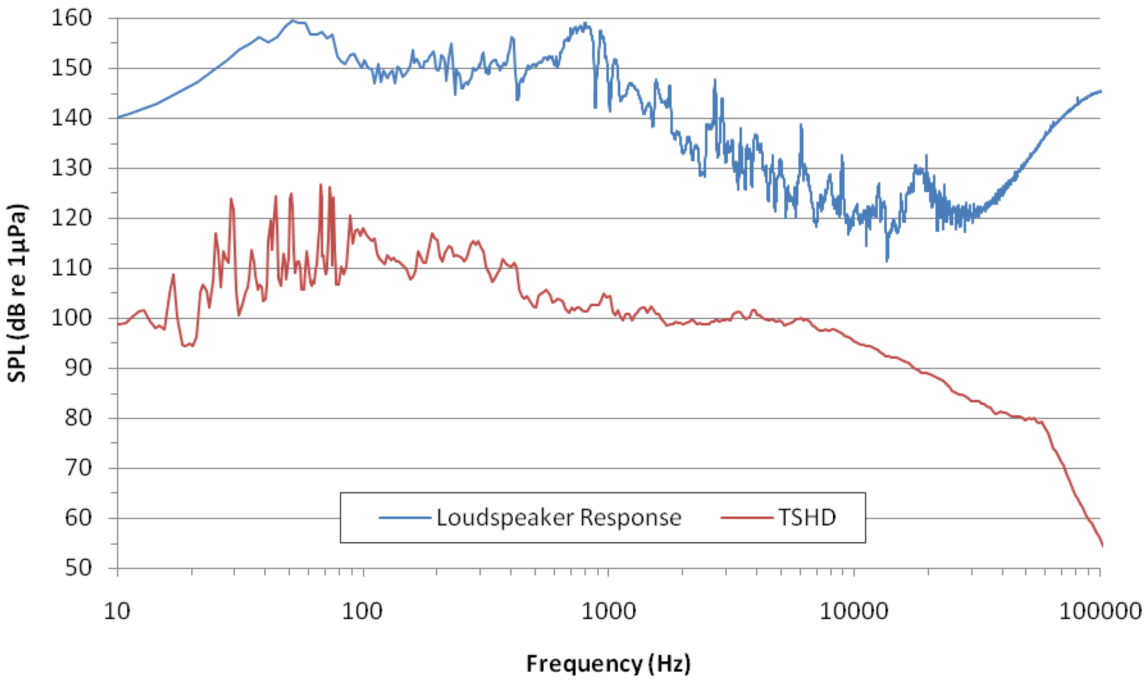

Figure 9.1 - Suction dredging spectrum and low-mid frequency sound projector response

9.4 Reverberant fields in water tanks

When a sound source radiates energy into a non-free-field environment such as a water tank two sound fields are produced (see, *e.g,* Kinsler and Frey, 2000). The two sound fields are referred to as the direct and reverberant fields. As their names suggest, the direct field is composed of sound which arrives directly from the source while the reverberant field is formed of energy which has experienced at least one boundary reflection, say from the walls of an experimental tank.

The distinction is important because whereas the direct field contains information concerning the direction from which the sound is arriving, hence allowing an animal to react to the noise by turning away, the reverberant field consists of sound that arrives from all directions, and hence has no directional cue.

Where a transducer is used to generate a sound field in an experimental water tank, it is common that the direct field dominates in its immediate vicinity; the noise level is highest at the transducer, and diminishes away from it. However, at a short distance from the transducer, often only a metre or two, the field achieves a roughly constant level; this is the region where the reverberant field dominates, it can be said that a field error of more than ±3 dB is a significant one and is audible to a listener. Thus, if conditions typical of exposure to a distant source are to be achieved, a unidirectional direct field will only occur in the immediate vicinity of the transducer. However, this region will also be within the near field of the transducer, and hence not acoustically representative of a distant source.

These considerations lead to an important conclusion. From an acoustical standpoint, and in particular the standpoint of and hence the perception of the noise by a marine mammal, the sound field within a confined water tank is unlikely, in any circumstances, to be from representative of that in true open water conditions. It is relatively easy to undertake behavioural experiments in a water tank. However, the results will be unrepresentative of open-water exposure will be ambiguous and difficult to interpret.

9.5 Characterisation of experimental sound field

It is critically important in designing an experiment to ensure that the conditions in which the animal is exposed during the experiment mimic those in which the animal will be exposed under typical conditions. It is unlikely that, for example, a single projector near to the experimental facility and hence in close proximity to the animal will provide an adequate model of a sound field from a distant source. In order to design an experiment, a criterion must be developed to allow the spatial quality of the sound field to be assessed. When performing a critical experiment such as is proposed in this study, it is essential that the conditions under which the animals are exposed are carefully designed prior to the experiment, and documented to demonstrate that the experiment is representative of typical exposure conditions.

It is relatively simple to address the frequency content of the noise, by measuring it and presenting the results as a spectrum. However, the way in which the spatial behaviour is investigated is worthy of particular attention. Formally, the field may be decomposed as an equivalent set of planewave components, generally known as wavevector analysis. This enables the experimental field to be compared with a true farfield representation. The method is exact but difficult to implement, and so an alternative strategy has been adopted.

The concept of “field error” has been introduced. Conceptually, we might consider an area in which an experiment on seal avoidance of noise might be performed. For an open net cage suspended in open water, perhaps the area might be 20m by 20m. If the source were actually a dredger at distance, it would generate a given sound field in this area. The sound would probably decrease slightly across the caged area. Now consider if the source is a projector array that attempts to mimic the noise. If it is created by a single transducer near to the area, the level will drop significantly across the area and will also probably vary considerably as a result of near-field effects. The *variation* of the noise field from that of a distant source may thus be considered to be a measure of its spatial accuracy in modelling it.

This has been initially evaluated using an acoustic program written by Subacoustech, *PrISM*, which uses the image-source model to estimate the noise level and distribution of sound pressure and sound particle velocity from underwater sound projector arrays in shallow water.

Initially, an assumption has been made of a 20 m x 20 m netted area in open water with a depth of 25m. This may be amended when detailed analysis of an optimised experiment is undertaken.

Source Distance from Test Area (m)	**Number of Sources (N)**	**Average Level dB_{ht} *(Phoca vitulina)***
1	1	104.2
4	1	101.1
40	4	101.9
80	9	101.2
120	16	99.9
150	25	101.5

Table 9.1 –Estimated dB_{ht} (Phoca vitulina) Level for Various Numbers of Transducers

Table 9.1 illustrates the considerations that might apply when choosing the size of the array for the experimental sound field. Only a square array (*i.e. n* transducers by *n* transducers where *n* is an integer) has been considered at this point. If, say, it is decided that a minimum average level of 100 dB_{ht} (*Phoca vitulina*) is required, to ensure a reaction, this may be achieved by 4 projectors at 40m from the cage, 9 projectors at 80 metres, or 25 projectors at 150 m. A single projector cannot achieve an adequate level of sound. However, the field from projectors in close proximity to the experimental caged area will not be representative of sound from a distant source. A uniform field with a clear directional cue is important because, if not achieved, a harbour seal exposed to the noise will not perceive it as a distant source and so will not be able to respond in a consistent fashion, making testing for a reaction extremely difficult and the results ambiguous.

Figure A1.4 (Appendix 1) illustrates this effect. The figure presents the level of sound from a source, calculated using PrISM. However, the results are presented as the level for a source at various different distances, normalised by the level for a source at 250m.The results may therefore be regarded as the deviation in level from that which would result for a noise source such as a dredger actually at 250 m.

It may be seen that for projector arrays closer than 20m, the deviation from the average level is greater than $\pm 3dB_{ht}$, and thus their field might be considered to be unacceptably different from a true field from a distant dredger.

This information can be combined with that above to provide an initial indication of the number of transducers needed to ensure both an adequate level of noise to ensure a reaction, and a field from a sufficient distance to ensure its behaviour is similar to a field from a noise source at range. It may be seen that if a maximum field error greater than $\pm 3dB_{ht}$ is assumed, an array of 9 projectors at 80 m would be sufficient to both generate an adequate level, and a sufficient field representation.

Figure 9.2 presents the error of the sound field from the TSHD noise within the 20m x 20 experimental area for various numbers of transducers in the array over a range of distances. The value calculated for each distance is a Root Mean Square (RMS) average error of the field at 500 points across the test area, providing information on the overall error in the field. It may be seen that for small distances, this RMS error is very high, but that the error falls rapidly as the transducers are moved away. It may be seen that to achieve an average error of 1 dB, a spacing of anything above approximately 40-50m is required for all three array sizes. Thus when considering experimental design, it is important the transducers are placed at a minimum of this distance in order to achieve an appropriate sound field. This places limitations on both the size of the experimental field as well as the size of the surrounding area.

Further examples of calculations of field error and calculation of sound levels in the test area (both RMS and dB_{ht}) are included in Appendix 1.

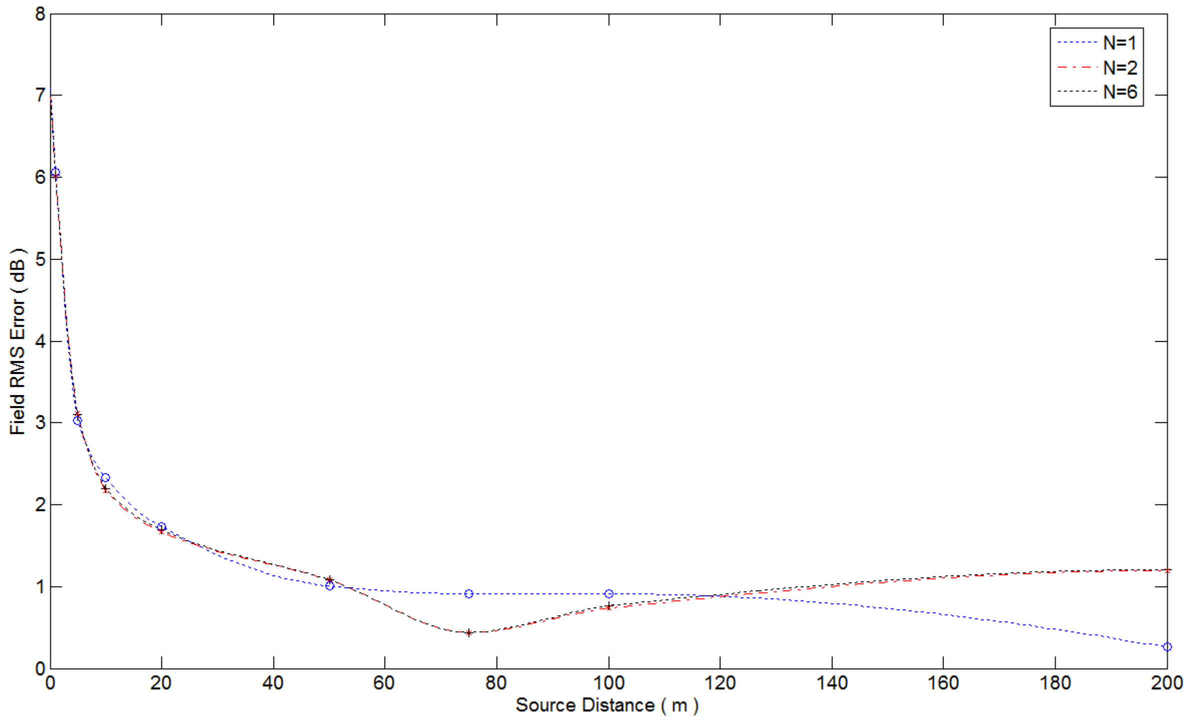

Figure 9.2 - Field RMS error vs. Source Distance and number of sound projectors N

9.6 Particle Velocity Investigation

9.6.1 Introduction

It had been suggested that marine mammals are sensitive to not only sound pressure but also particle velocity (the speed at which a particle oscillates as it transfers wave energy). A complimentary investigation into the state of the resulting particle velocity field has been carried out for a number of different experimental configurations. The investigation allows a direct comparison between particle velocity and pressure fields for the same experimental setups. Much of the work focuses on the similarities between the two types of field, with the remaining work identifying the conditions which lead to a difference in pressure and particle velocity levels.

9.6.2 Results

Table 9.2 allows a comparison of the average pressure and particle velocity levels inside the test area. The results indicate a similarity between the two field types which changes little when the number of sound projectors is varied or the distance between the test area and sound projector array is increased. Average Levels for the two field types differ by approximately 0.3dB_{ht} on average (for the configurations tested) leading to the following conclusion; provided the sound projector array is positioned at least 5m from the test area, the difference between the resulting pressure and particle velocity fields is insignificant. Conversely, when the sound projector array is closer to the experimental area the resulting fields are likely to be significantly different (up to 1.7dB_{ht} at 1m). An increase in level difference is to be expected in the reactive near-field of the source where the particle velocity is much more prominent.

Further evidence of an elevated particle velocity level in the near-field is clear when comparing Figure 9.3 and Figure 9.4. Additionally, results in Appendix A give an idea of the frequency dependence of this phenomenon. They show that, as the wavelength of the source signal decreases, the frequency-dependant far-field distance increases.

Source Distance from Test Area (m)	Number of Sources (N)	Average Pressure Level dB_{ht} *(Phoca vitulina)*	Average Particle Velocity Level dB_{ht} *(Phoca vitulina)*
1	1	104.2	105.9
4	1	101.1	101.5
40	4	101.9	102.1
80	9	101.2	101.2
120	16	99.9	100.3
150	25	101.5	101.6

Table 9.2 - Average Pressure and Particle Velocity Levels in the Test Area

Figures 9.3 and Figure 9.4 present simple views of the pressure and particle velocity distributions across the test area as a function of source distance (for a single source). Y-axis values are given in terms of the deviation from an average level inside the experimental cage. Again, the figures show similar distributions for both pressure and particle velocities, with the largest variation on the side of the experimental cage closest to the source (see x-axis values close to 0m in Figure 9.3 and 9.4).

The above data indicate the importance of the array design and placement in achieving the appropriate sound field. It can clearly be seen that the array must be placed at a distance of at the very minimum 5 m from the test area in order to produce a sound field in which the pressure and particle velocity distributions have a relationship approximately of far-field conditions.

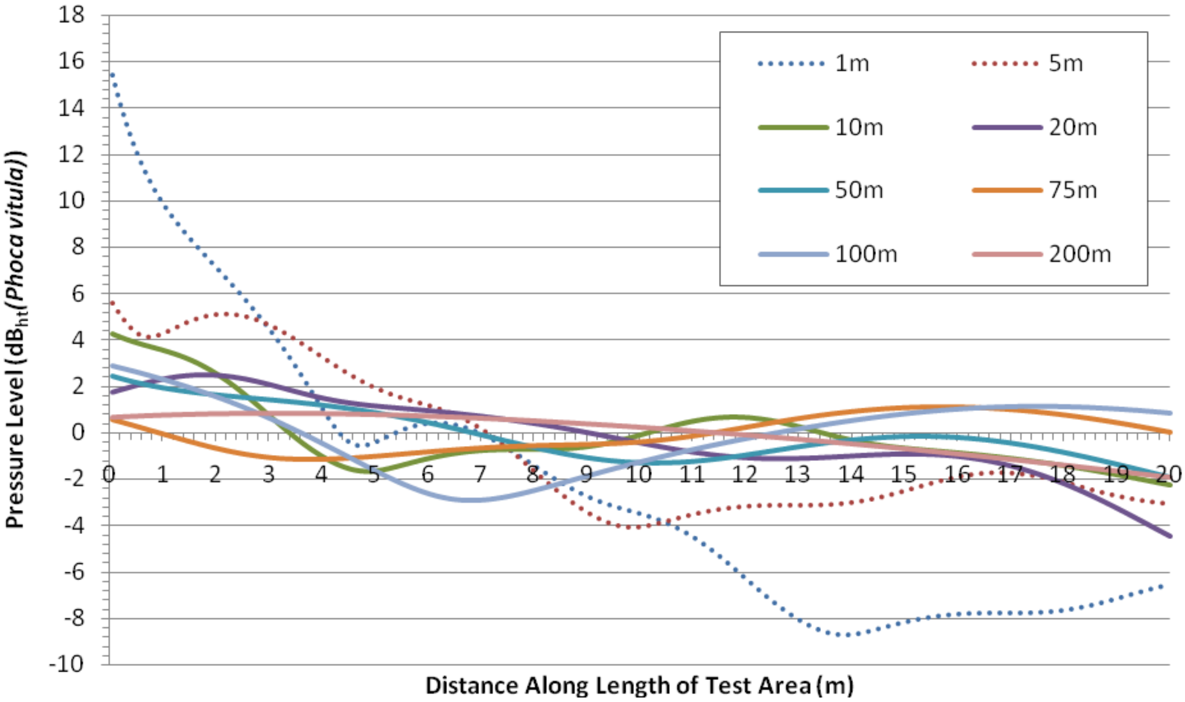

Figure 9.3 - RMS Pressure Levels along a Single Plane of the Experimental Cage

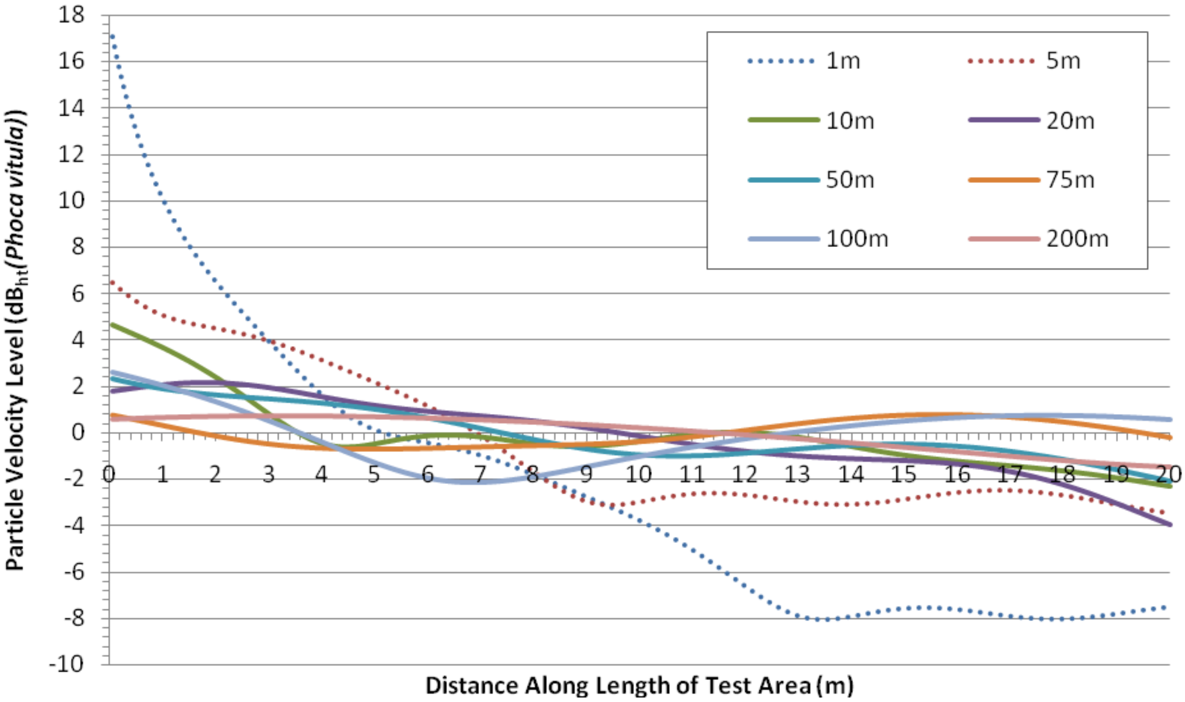

Figure 9.4 - RMS Particle Velocity Levels along a Single Plane of the Experimental Cage

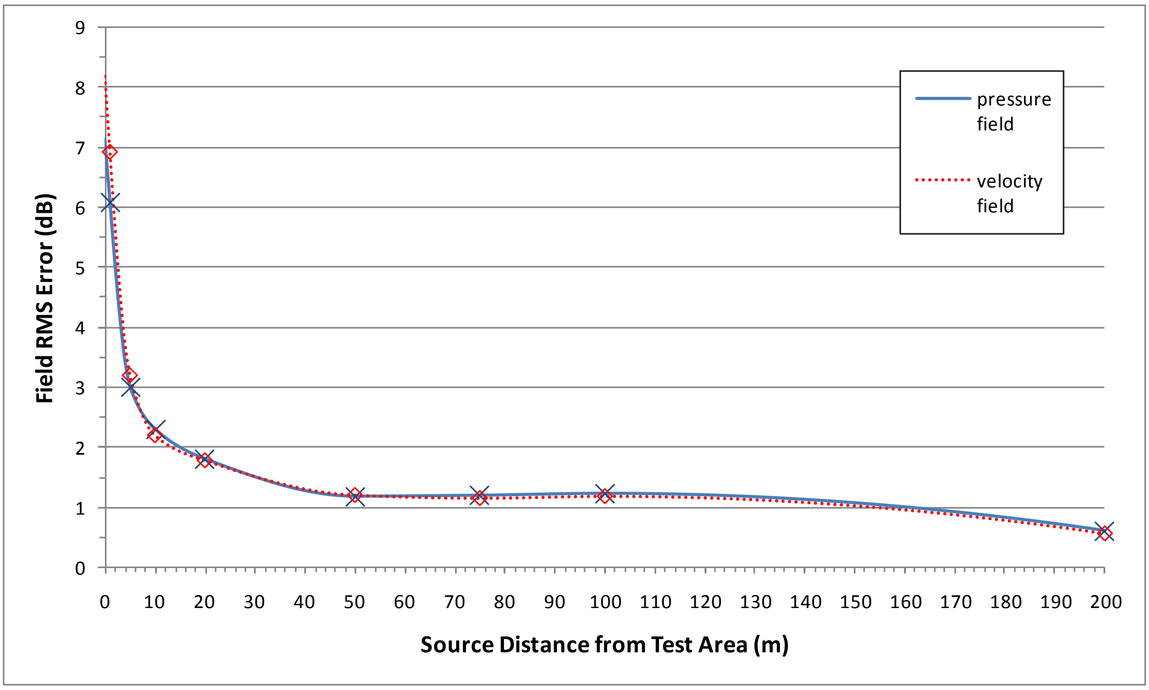

Figure 9.4 - Field RMS Error for a Single Source of Increasing Distance From the Test Area

Figure 9.4 displays RMS values calculated using 500 field points in the test area for a selection of distances and array sizes. An RMS method gives an idea of the magnitude of the deviation from an average level inside the test area at a receiver position anywhere inside it. The figure shows a clear similarity between the shape of the pressure and particle velocity distributions at each source distance. Similar RMS values for both fields provide evidence to suggest that a suitable velocity field can be obtained indirectly with a suitable pressure field.

Figure 9.5 displays PrISM plots for pressure and particle velocity distributions at a far shallower depth of 1m. The figure shows concisely how the two fields can differ much more significantly as the measurement plane moves upwards. Figure 9.5 indicates a level difference of approximately 5dB (ref. 1μPa) between fields when at this depth. Figures 9.6 and 9.7 show a selection of modelling images illustrating the relationship between particle velocity and pressure. The range of number of transducers and distances were chosen to provide and indication of the correlation between the two variables.

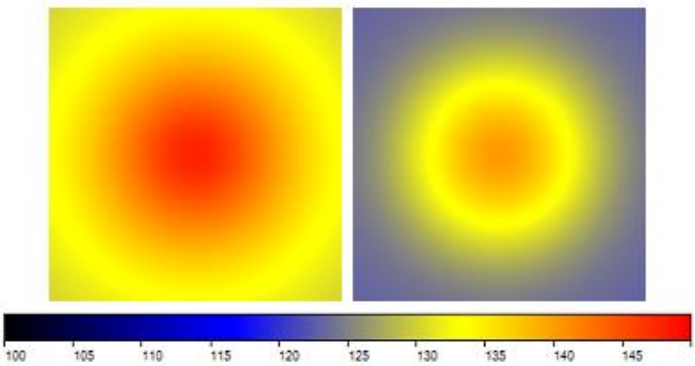

Figure 9.5- Particle Velocity Field (left) and Pressure Field (right) for the same Source Near-surface

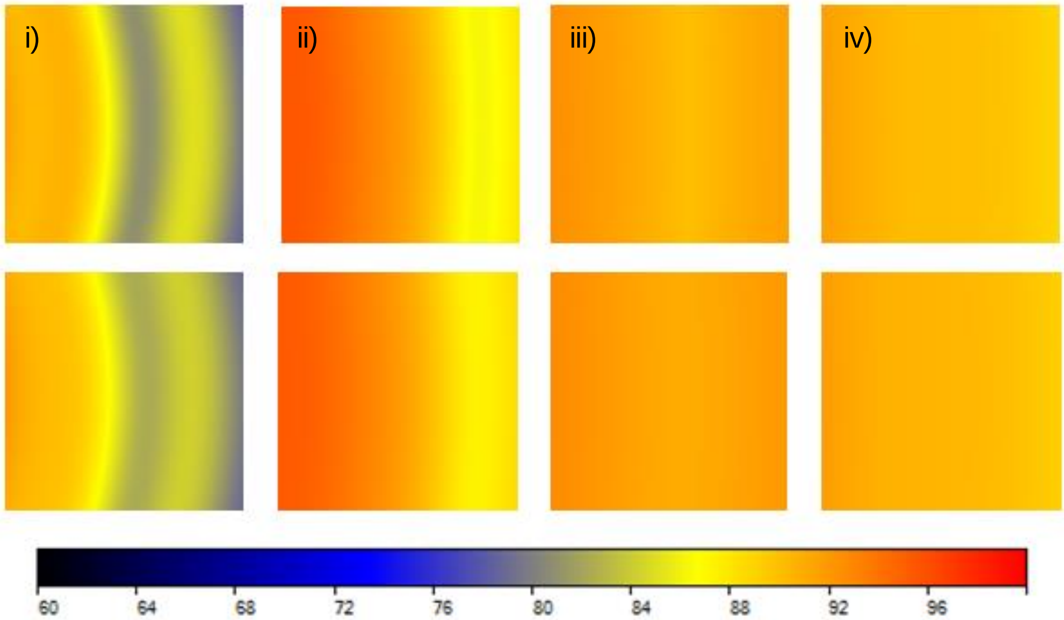

Figure 9.6 – Pressure (above) and Particle Velocity (below) Fields Giving a 90dB$_{ht}$(Phoca vitulina) Broadband Level for; i) 1 source at 40m, ii) 4 sources at 90m, iii) 9 sources at 165m, iv) 16 sources at 210m

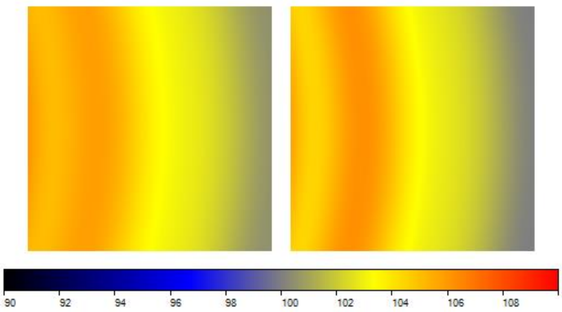

Figure 9.7 – Comparison of the Resulting Particle Velocity (left) and Pressure Fields (right) for 4 Sources at 40m (Each has an Average Level of Approximately 102dB$_{ht}$(Phoca vitulina))

9.7 Altering the Depth of the Calculation Plane

The depth of the calculation plane has been altered to examine the effect on the average particle velocity and pressure distributions. Table 9.3 gives the results of the investigation. The results indicate a layer of lower pressure and particle velocity near the surface of the cage, especially when multiple sources are used. Conversely, below the half-way point (a depth of 5m) the levels begin to increase. When compared to the area below the half-way point, pressure and particle velocity levels can differ by as much as up to 13dB, depending on the source distance. The difference between deep and shallow values seems to be dependent on the number of sources and therefore on the degree of complex interference taking place near the pressure-release boundary.. The difference seems to be also slightly greater for particle velocity rather than pressure.

Depth of Calculated Plane (m)	Source Distance from Test Area (m)	Number of Sources (N)	Average Pressure Level dB_{ht} *(Phoca vitulina)*	Average Particle Velocity Level dB_{ht} *(Phoca vitulina)*
1	4	1	100.6	100.5
1	40	4	92.8	93.1
1	80	9	93.5	93.8
1	120	16	90.7	92.4
1	150	25	96.2	96.8
5	4	1	105.2	105.9
5	40	4	101.1	101.5
5	80	9	101.9	102.1
5	120	16	101.2	101.2
5	150	25	99.9	100.3
9	4	1	100.1	100.3
9	40	4	103.7	103.8
9	80	9	103.5	103.6
9	120	16	103.7	103.7
9	150	25	102.8	102.9

Table 9.3 – Comparison of average pressure and particle velocities at three depths: 1m from the surface, mid-way and 1m from the cage bottom

Summary:
Modelling carried out by Subacoustech has revealed that:

1. An acoustic field characteristic of a TSHD at distance cannot be generated in a confined area such as a water tank.
2. A field that is representative of a TSHD at distance in both pressure and particle velocity, can be generated provided the sound source is a reasonable distance from the test area, for instance, an array at about 40m from a 20x20m enclosure in open water.

10 Experimental methods

Subacoustech have designed a number of experimental procedures for carrying out these tests on harbour seals. The experiments have been designed in such a way that most will be applicable to other marine animals, although there may have to be some changes to the experimental procedure to ensure accurate results for the new species in question. To achieve the same quality of experimentation it will be necessary to have an audiogram of the new species in order to make the dB_{ht} assessments relating to transducer placement. Also, it may be necessary to alter the observational method chosen.

10.1 Observational methods

The experiment relies on the ability to observe behaviour. Various methods with which the seals' behaviour may be observed are:

10.1.1 Locating methods

Visual observation. Cameras are positioned around and above the test area and record the position of the seals for a period with and without noise.

Acoustic camera. Acoustic cameras are a form of high resolution sonar that are capable of producing images in water of zero optical visibility. These have a number of advantages in that the seals do not need to be handled and tagged, which will reduce both experimental time and stress levels, and with an acoustic camera it is possible to passively observe the seals throughout the entire duration of the experiment.

These cameras have been used recently by Stansell et al. (2009) to monitor the predation of Chinook salmon (Oncorhynchus tshawytscha) and steelhead trout (O. mykiss) by California sea lions (Zalophus californianus), Stellersea lions (Eumetopias jubatus), and Pacific harbour seals (*Phoca vitulina richardsi*).

Radio tagging. There are two distinct types of radio frequency transmitters currently available, externally attached transmitters and subcutaneous transmitters. External transmitters are the simplest in use, as they can be attached on the flipper of the seal or commonly they are adhered with epoxy to the neck or head of the animal. Similar considerations apply to acoustic tags. These tags provide information on position, speed and depth.

10.1.2 Physiological methods

Heart rate. It was found by Wright *et al.* (2007) that it is reasonable to extrapolate terrestrial mammals' physiological reaction to stressful situations to those of marine mammals. This 'fight or flight' reaction will include an increase in heart rate. In addition, Boyd *et al.* (1999) describes the use of Archival Data Loggers (small tags that record data on a subject to be collected subsequently) to measure heart rate and swimming information in antarctic fur seals (*Arctocephalus gazella)*.

Blood chemistry. St Aubin *et al.* (1979) have shown that under stressful transport and handling conditions the level of the enzyme creatine kinase significantly increases in harp seals. It is suggested that the increase in level of this enzyme in the plasma of the blood is sufficient to be a reliable indicator of stress in seals.

Acoustic Location. Van Parijs *et al.* (2000) used a triangular array of hydrophones in a bay to monitor vocalisations of seals during mating season. The difference in arrival time of the signal to each hydrophone allowed the location of the seal to be gauged.

It has been suggested that the physiological stress indicators such as blood chemistry and heart rate would not be suitable as observation methods for two reasons:

1. The seals are already likely to be stressed by being in experimental conditions in some of the methods.
2. The reaction to the noise may not induce a stress-related reaction but instead will be a purely behavioural one.

The method of observation will depend heavily on the method of experimentation. For example, in the free ranging methods visual observation may be impossible and so tagging or acoustic locating must be used.

10.2 Possible experiments

All tests are considered likely to last 6 months unless otherwise stated. Discussions with the biological collaborators suggested that newly captive seals will need a certain amount of time to acclimatise to the test enclosure. This varies greatly between individuals but can be up to one month. The 6 month time scale includes this acclimatisation period, however there is some inherent uncertainty when using live animals that may result in a longer test period being necessary.

In view of the fact that the information regarding noise from dredgers is not completely understood or characterised, it is suggested that it would be helpful if a number of careful and thorough measurements of the noise from dredgers during suction, sailing and sand deposition should be made. Subacoustech is capable of taking these recordings quickly and accurately to the specifications needed for the experiment. These studies should enable the noise sources associated with dredging to be specified and rank-ordered in terms of their importance and a final decision as to the nature of the sound used for the experiment to be made.

10.2.1 Pool exposure

As discussed in the preceding section, a pool test is not thought to be optimal, but is discussed here for the sake of completeness. The hypothesis is that seals will indicate avoidance of TSHD noise within a pool by swimming away from the source of it. Pool tests have been used in the past for acoustic experiments such as the measurement of audiograms. However, for avoidance studies it offers a highly constrained experiment.

In the closed pool test a transducer is placed towards one corner of the test area (Figure 10.1). The animals are then observed over a period of time with the sound on and off and average distance to the transducer is then measured. It is expected that if the sound is causing a behavioural avoidance reaction then the average distance to the transducer will increase when the sound is being played.

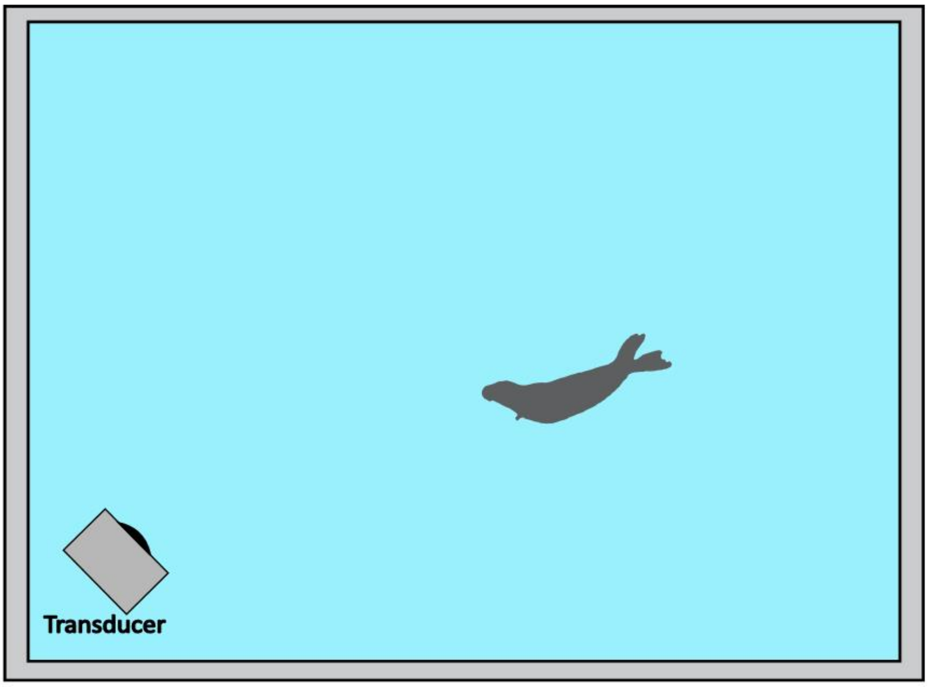

Figure 10.1 –Closed pool test diagram

This experiment has a great deal of controllability and it is relatively simple to achieve a large number of replicates at a low cost. However, it has been shown in the modelling that the sound field will not be representative of the noise produced by a TSHD at distance. Thus it is felt that any results obtained may not be comparable to the behaviour of harbour seals in the wild.

It would be relatively simple to apply this method to other marine animals and using other sounds.

10.2.2 Net Cage with double transducer array

The net cage experiment is interesting as it potentially offers both satisfying basic acoustic criteria as well as offering a reasonable likelihood of yielding useful and credible results.

There is potential difficulty of interpreting the experiment; even if an avoidance reaction was elicited, what is the significance to the animals? It is felt that the experiment may be considered to show a baseline, ideally the level of noise at which an animal swims away. Even at this level, there may well be no impact to the animal, other than moving it on to another area.

The hypothesis for the experiment is that seals will avoid TSHD noise within a net cage by swimming away from it. This method involves having two arrays of transducers either side of a net cage (Figure 11.2). The net will be constructed in a way that provides a safe environment for long term captivity of the seal. This will include netting appropriate for avoiding the escape of seals as well as haul out areas in which the seals can rest.

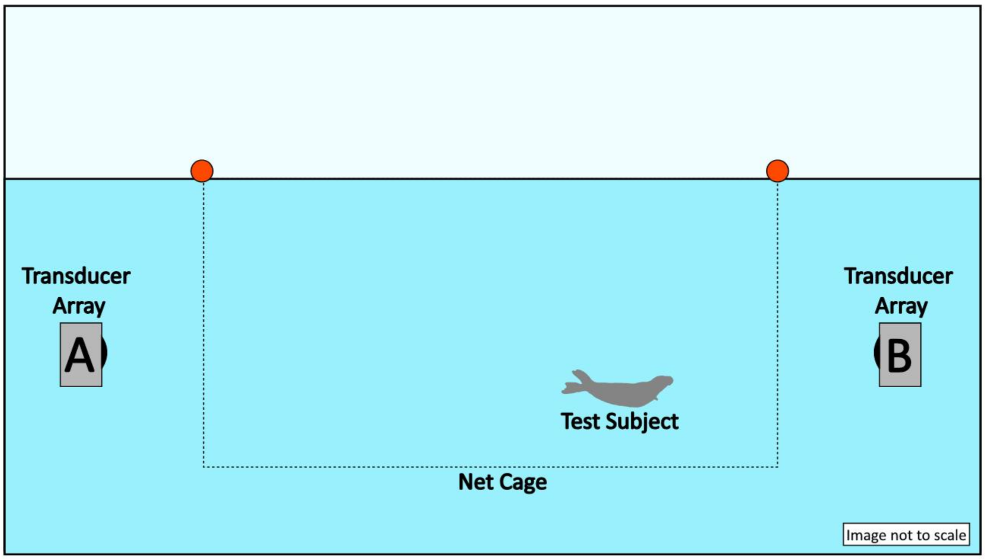

Figure 10.2 – Diagram of net cage and transducer arrangement

The TSHD noise is played through one array of speakers; observation is made of the seals with noise and no noise present. The noise is then switched to the other side and the process is repeated. The intention is to only have sound being projected through one set of transducers at one time. The purpose of the double set of transducers is to remove any preference for one side or the other. There are a range of markers which may be used to identify effect. For instance, it is possible to measure the average distance to the transducer array in both cases.

Similarly to the pool test, there is a high level of controllability as well as the ability to provide a high number of replicates, thus yielding high confidence in the results. Additionally, it will be possible to create the appropriate sound field to accurately replicate the noise from a TSHD at a distance. Finally, it may also be possible to structure the experiment so as to assess habituation (that is, the tendency of the seals to ignore the sound after repeated exposure). The chief difficulty lies in maintaining a suitable cage and seals in open water.

It is felt that that the net cage should be constructed in a sheltered body of water such as a harbour or a sea loch. The waters of these areas are seen to be of sufficient depth to ensure the appropriate sound field with reflections at an acceptably low level. One possibility is that temporarily unused fish farm nets could be used for this experiment. Modern nets are of an appropriate size as well as being reinforced to prevent seals getting through the netting. This may provide an appropriate test area at a lower cost. Similar tests have been performed in the DeltaPark Neeltje Jans between 1995 and 2002. This is a relatively isolated body of sea water with shipping restrictions nearby and also space to construct the net cage.

It may be commented that the engineering challenges are considerable. Constructing a net cage is potentially a major engineering undertaking as the net must be strong enough to keep the seals in for potentially months at a time as well as being able to withstand any adverse weather and sea conditions. There may be a long waiting time as the subjects become acclimatised to the net cage (which may take up to a month depending on the individual seal). It has also been suggested that the behaviour of the captive seals will not replicate that of wild seals under exposure to the TSHD noise.

This option would be applicable for other marine animals (it will be limited, however, by the space in the cage and the size of the net gaps) and other sounds.

10.2.3 Calibrated feeding station

In this method a known feeding station/ area is used to attract the seals to a location. This can either be man-made, or use can be made of existing areas where seals are known to feed such as fish farms and fish ladders. A sound projector would generate noise along the entry path to the feeding station, as illustrated in figure 10.3 and the deflection from the usual path taken would be measured. The hypothesis is that the deflection of wild seals en-route to food by a TSHD noise source could be observed and recorded using an acoustic camera with a range finding capability is used (see Section 10.1) to gauge the deflection The approach is thus similar to the successful experiments that have been undertaken on migrating whales. Tagging might also be used to monitor the route of the seals, although this would of course require them to be temporarily captured.

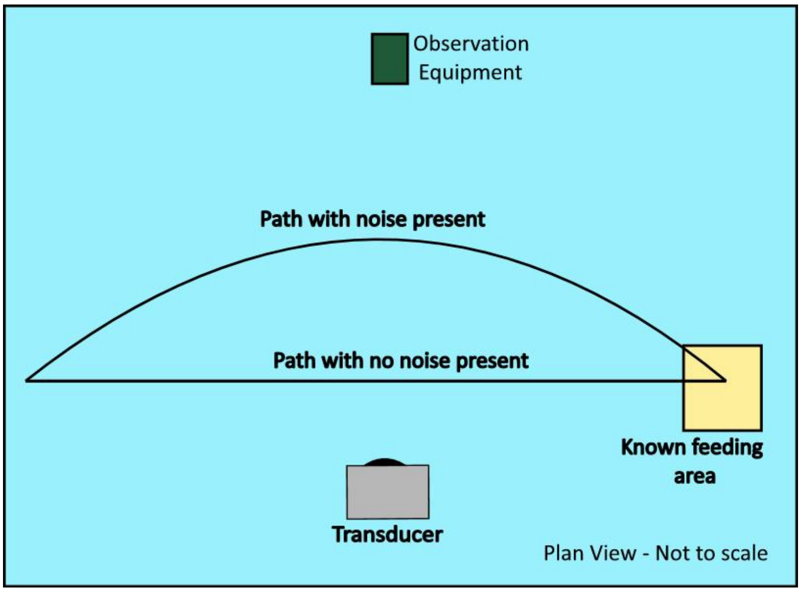

Figure 10.3 – Diagram of feeding station and transducer array placement

The experiment is potentially interesting as it investigates the behaviour of seals motivated to be in an area for a purpose, in this case feeding. Also, it is a relatively simple experimental set up as free ranging wild seals are used as the experimental population. As a consequence, only the transducer array and observational method need be put in place.

It is suggested that a fish farm would be a suitable attractor, however that these seals will be atypical of wild seals. They will be potentially accustomed to stressful and dangerous environment around these feeding stations as Acoustic Harassment Devices and human deterrents including shotguns may be used on them. Also, there are very few areas in which there will be a clear path taken by incoming seals to a known feeding area. However, an experiment could be run for months and yield a high number of replicates.

The experiment would demonstrate avoidance reaction, similar to that of the preceding experiments, and in a representative environment. However, a possible variation of this test would be to have the transducer array placed near the feeding area itself. This would tend to demonstrate whether there is suppression of feeding behaviour by the noise, and hence not just whether there is a secondary effect of the noise (avoidance) but whether a critical effect had occurred, suppression of feeding. However, there is a possibility in this case that the fish in the farming pens will be adversely affected.

The experiment is intriguing, yet the philosophy untested, and might be classed as a high-risk but relatively low cost item.

10.2.4 Male Mating Call Location

An experiment is suggested to use seals' vocalisations to locate the seals during testing. The hypothesis is that seals will avoid a breeding area, cease to call or be otherwise reduced in breeding behaviour by the TSHD noise.

During the mating season (late June – early July) male harbour seals go to the sea bed and make loud vocalisations to attract females and compete with other males. An experiment is proposed where a towed transducer array is moved into position near a group of these calling seals. An acclimatisation period where the vessel will be taken to the area with no sound being produced will take place. Once this period is over then a series of tests with noise/ no noise can take place. Location of the seals will be found using a triangulation method with 3 hydrophones spaced around a large area containing the seals which use the recorded difference in arrival time of vocalisations to pin-point the seals.

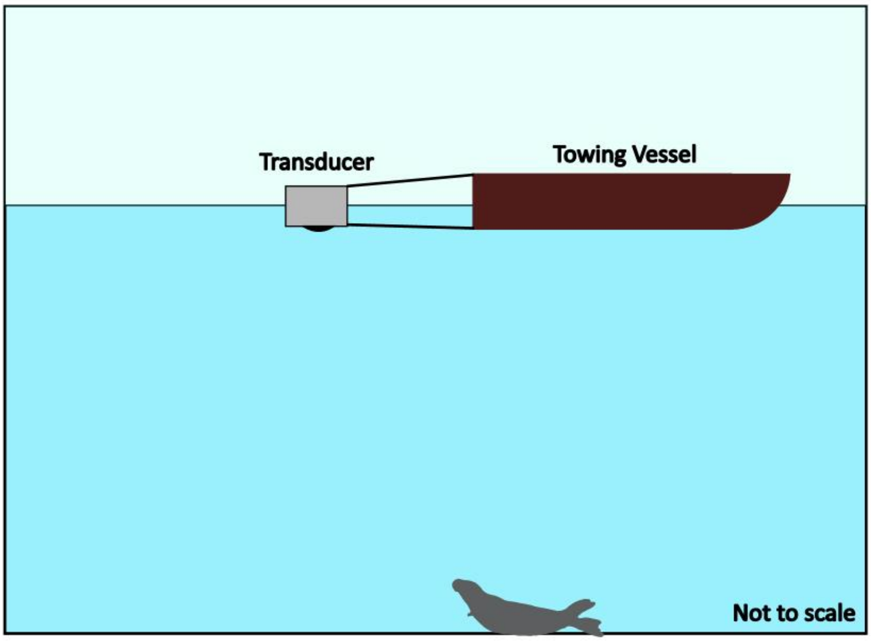

Figure 10.4 – Male mating call experimental diagram

This method has the advantage that the seals are wild and so may provide results that are more likely to be relevant to the seal population affected by TSHDs. Also, during this time the locations of the seals are very predictable, making the experiment relatively easy to implement. However, one common reaction of seals to stressful or startle situations is they stop vocalising altogether. This might be difficult to interpret. Also, there may be some legislative issues as this test may interfere with the mating of the species. It has also been suggested that the presence of a vessel nearby would cause a startle/ stress reaction in the seals without the noise being present as they are particularly sensitive around this time. Thus when the sound is played there may be a false reaction from the subjects, making analysis of results difficult. However, it has been argued that this could be factored out of the results. It may be that with an acclimatisation period the seals will not react to the presence of the vessel.

This experiment is species specific and would not be appropriate for other animals that do not display this behaviour.

10.2.5 Tagged Seals and Towed Array

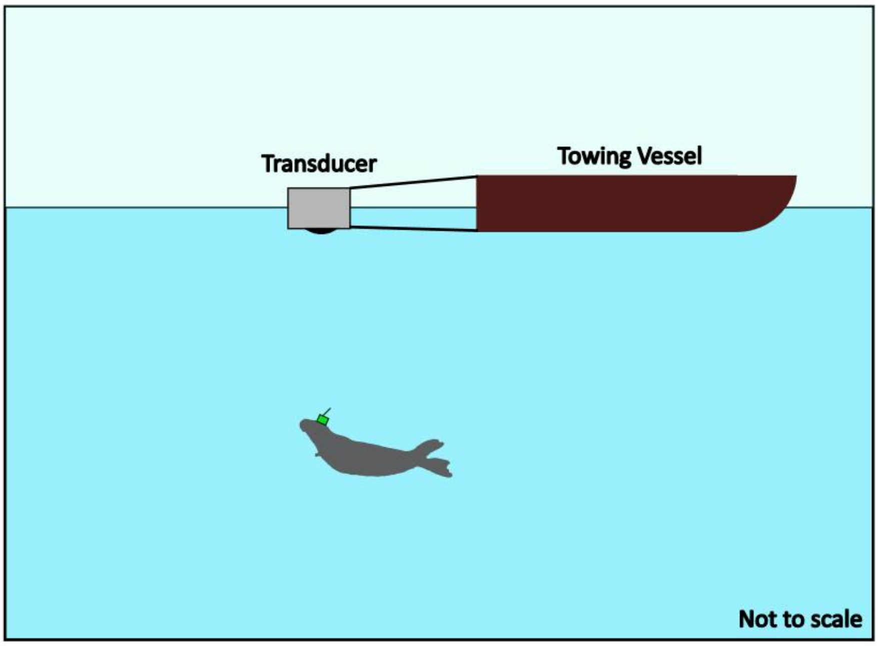

Figure 10.5 – Tagged seal with towed array diagram

An experiment is proposed where around 10 seals are captured and tags are attached to them. These subjects are then released into the wild and their behaviour observed over a period of time. After this period, a vessel towing a transducer array moves into position near one or more of the tagged seals. The sound is then played and the behaviour of the seals is observed using the tags.

It may be that wild, free-ranging seals would give a more representative assessment of the reaction of seals to dredging noise. Also, tagging the seals means that there is no reliance on the subjects vocalising to gauge position. However, similar issues are present in this method of testing as with the Male Mating Vocalisation method, in that the presence of the vessel may contribute to the avoidance reaction of the seals.

However, a greater problem lies in the fact that the TSHD array might have to be within two or three hundred metres of a seal to elicit a response. This is clearly difficult to achieve, and the capacity of the chase boat to cause an unwanted effect is obvious.

This method should work on any territorial species that can be tagged.

10.3 Summary

Below is a table summarising the 6 different experiments proposed. The authors have initially assessed these, by means of details pertaining to the relevance of the test, the costs, and the probable experimental outcomes *etc.*

Inevitably, it is realised that some of these ratings may be regarded as subjective, but it is felt that this assessment provides useful guidance towards the selection of an experiment.

Method	Difficulty of Experiment Implementation	Acoustically Representative	Biological Representativeness	Relative Cost	Likelihood of Success	Quality of Information	Established Methodology	Relevance to Dredging
Pool	Low	No	Low	Low	High	Low	Yes	Low
Net cage – open water	High	Yes	Medium – High	Medium - High	Medium	Medium-High	Yes	Medium-high
Feeding Station	Medium	Yes	High	Medium	Low - medium	Medium	No	Medium-high
Male Calling	Medium	Yes	Medium – High	Medium	Low - medium	High	Yes	Low
Tagged Seals and Towed Array	High	Yes	Medium-High	Medium	Low – Medium	High	Yes	Medium-high
Man-made Trench	Medium	Probably	Medium	High	Medium	Medium	No	Medium

Table 10.1 – Table summarising the various experimental methods along with their merits

Method	Pool	Net Cage - Open Water	Feeding Station	Male Calling	Tagged Seals and Towed Array	Man-made trench
Applicability to future tests	High	High	Medium	Low	Medium	High

Table 10.2 – Table summarising the various experimental methods' applicability to further tests on other animals and using different sounds

11 Summary and conclusions

1 A study has been carried out into the feasibility of undertaking controlled noise exposure tests of captive marine mammals. It is intended that the study will inform further discussions and commissioning of the experimental phase of the project

2 The key metrics associated with the measurement and assessment of underwater noise and the impact it may have on marine species in terms of lethality, physical injury and behavioural avoidance and have been reviewed. Based on this information and in respect of the available information on the characteristics of underwater noise from Trailer Suction Hopper Dredging vessels and the known sensitivity of seal species to underwater noise it was found that noise produced by a TSHD is audible to a harbour seal over a range of approximately 35 Hz to 40 kHz. There is a peak in sensitivity between 200 Hz to 10 kHz.

3 The legislative procedures associated with working with live captive marine animals in both the UK and the Netherlands have been reviewed. The procedures in both countries are broadly similar, with personal and facility licences required for both testing in Holland and the UK.

4 The difficulties in designing an experiment to recreate a realistic sound field of dredging noise using loudspeaker arrays have been addressed. The principal obstacles are ensuring the seal is within the “far field” of the noise source as would be the case in the presence of a TSHD at a distance of hundreds of metres. It is felt this problem can be overcome by having a large array of transducers set back by at least 40m from the test area.

5 Several experimental procedures have been identified as viable options to achieve results. These are: a pool based procedure involving a transducer deployed in a quiet pool, a net cage in a controlled area in open water with arrays of transducers in place either side of the net, a calibrated feeding station where the seals are deflected from a normal feeding route by a test noise from an array of sound projectors, acoustic location of calling males with a towed array of sound projectors, and tagged seals chased with a towed array of sound projectors..

6 The procedures for each option have been summarised and each option has been ranked based on markers such as cost effectiveness and likelihood of achieving satisfactory results.

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Appendix 1 – Further PrISM modelling figures

This appendix presents further figures produced by Subacoustech's PrISM acoustic model.

Figures A1.1, A1.2 and A1.3 present field error values at various distances from the source at 50 Hz, 1 kHz, and 10 kHz in three dimensions. Each plot shows the deviation from an average pressure level calculated over the experimental plane. Consequently, peaks in the surfaces indicate points of high pressure at specific points in the test area which are undesirable. Together the figures illustrate the complexity of the sound field with increasing frequency as well as, individually, exhibiting the relationship between source distance and pressure distribution. Each plot is a visual representation of the pressure at each point in the test area. The source is located a distance to the right of the each plot. It is preferable to avoid deviations in field error values of 3dB or more for an evenly distributed sound field. In all of the diagrams below the sound projector is located half way across the width of the area (Test Area Width = 10m) at the distance stated in the title of each diagram.

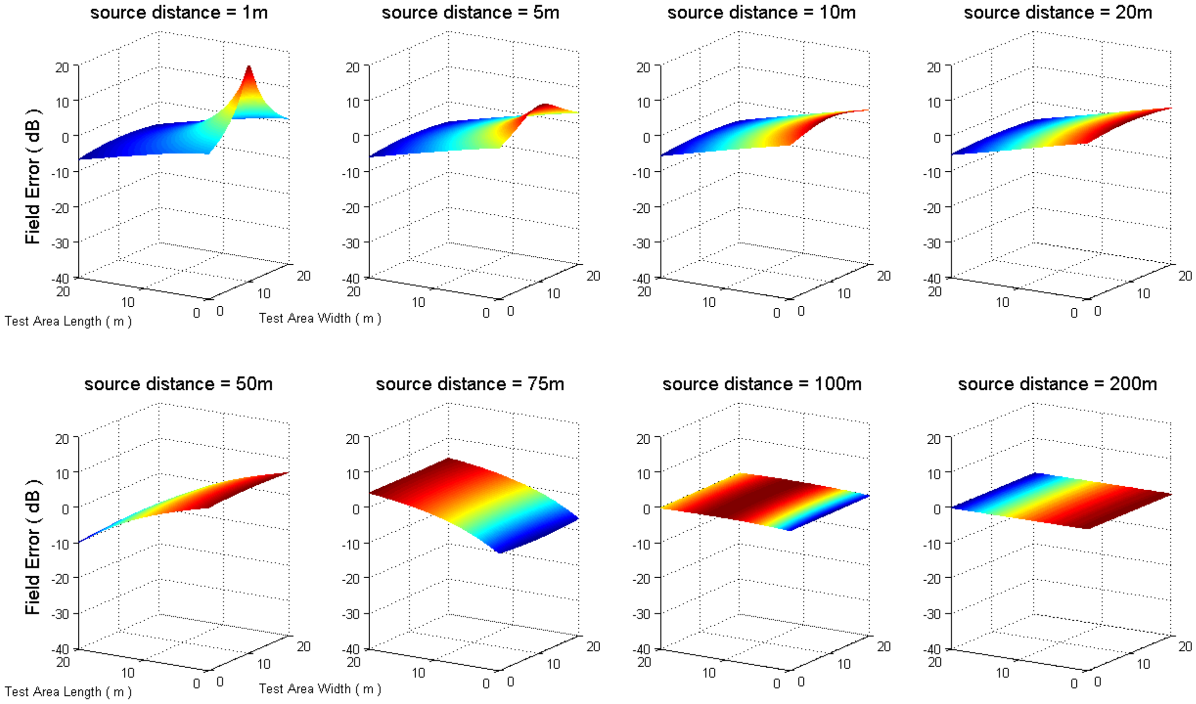

Figure A1.1 – Graphs of increasing source distance for a single source at 50Hz

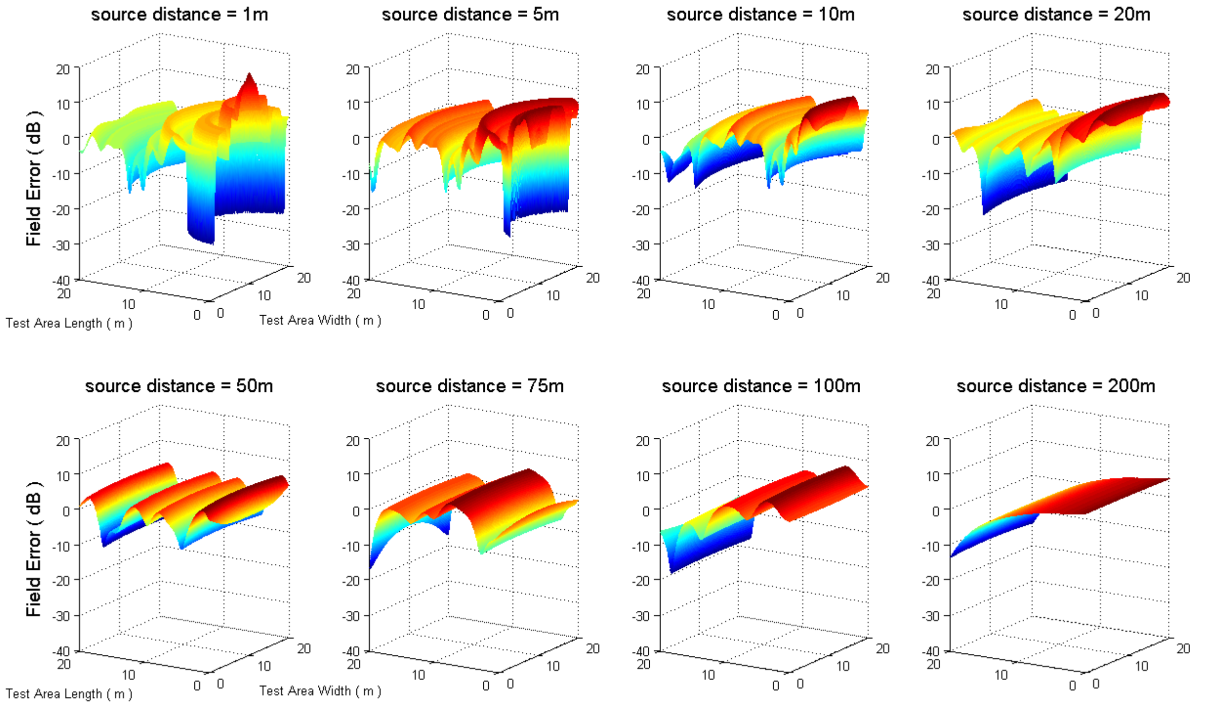

Figure A1.2 - Graphs of increasing source distance for a single source at 1 kHz

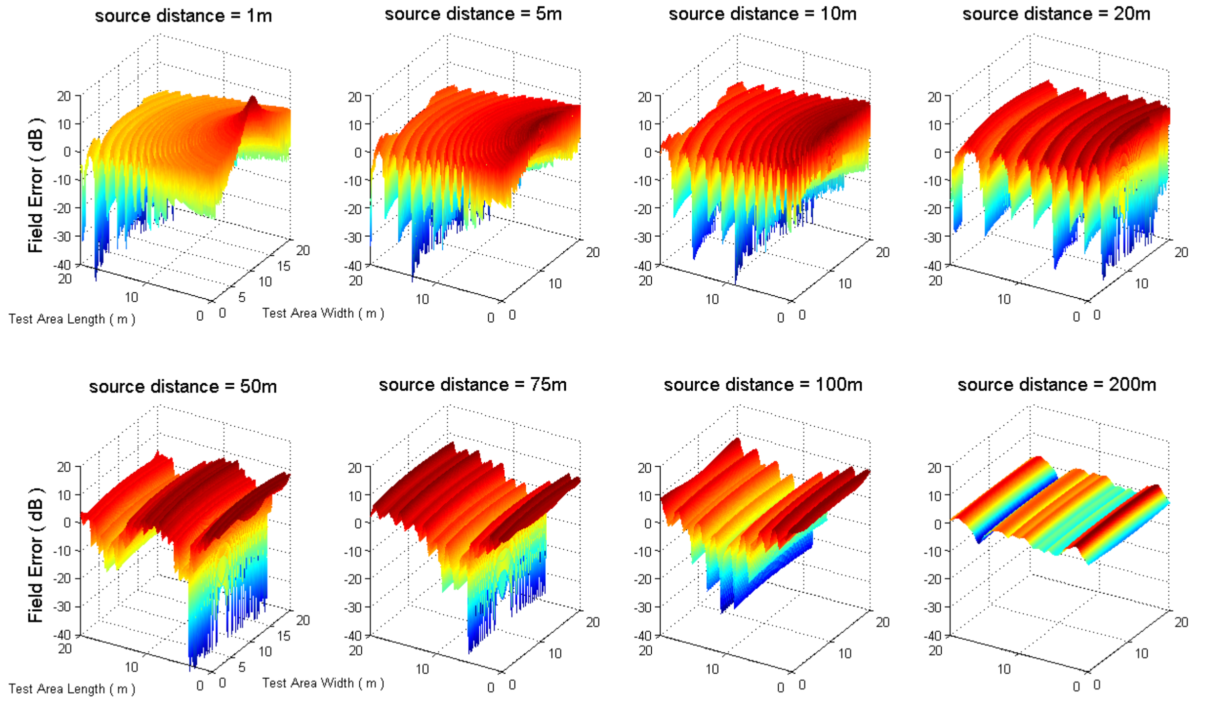

Figure A1.3- Graphs of increasing source distance for a single source at 10 kHz

Figure A1.4 presents a selection of error levels at varying source distances and array sizes.

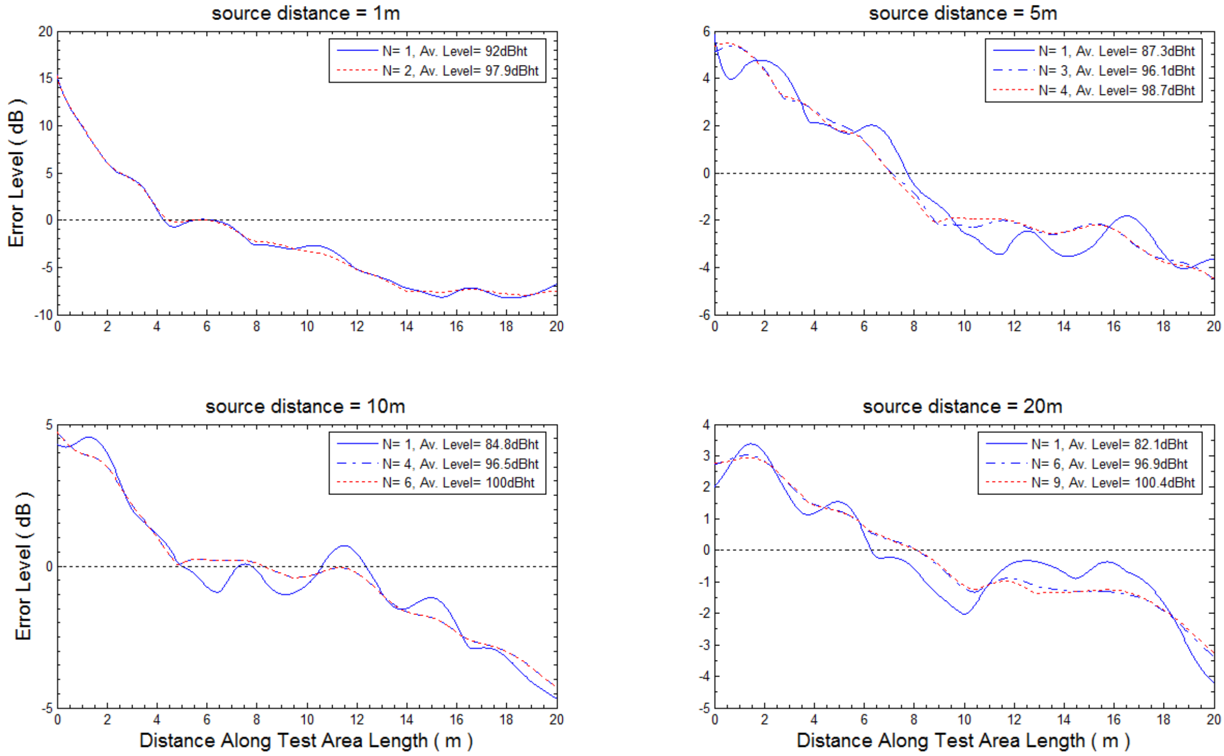

Figure A1.4 - Graphs of Increasing Distance and Increasing Array Size

Figure A1.5 presents the RMS sound level across the test area for a speaker array at varying distances from the test area.

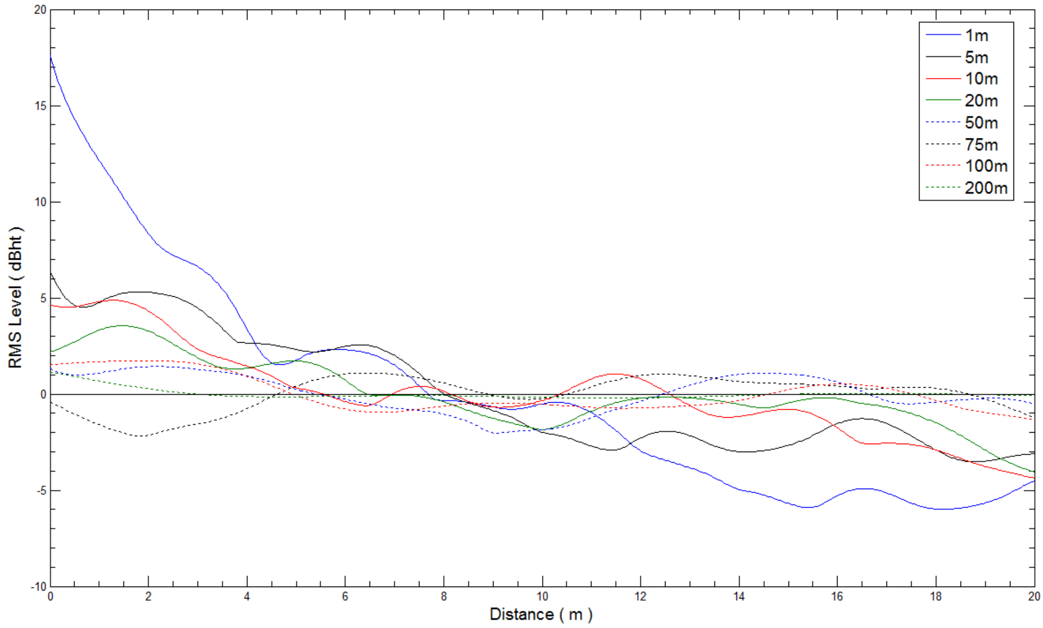

Figure A1.5 - Pressure Distribution in the Test Area

Figures A1.6 and A1.7 present an overhead view of the sound level in terms of dB_{ht} in the 20m x 20m test area, thus they show areas of expected avoidance by the seals.

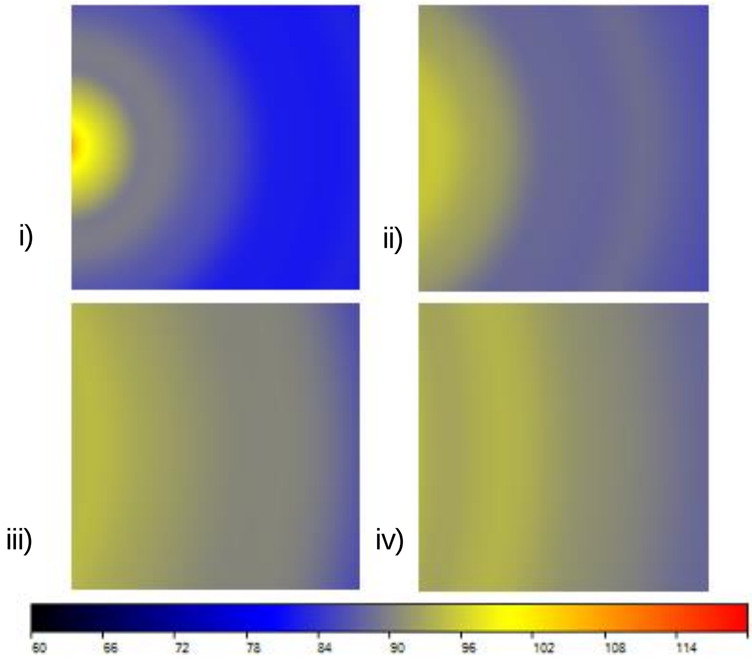

Figure A1.6 - Plots of pressure distribution in the test area at 90dB_{ht} (Phoca vitulina) for various sound projector arrays – i) 1 source at 80cm; ii) 2 sources at 6m; iii) 4 sources at 20m; iv) 9 sources at 40m.

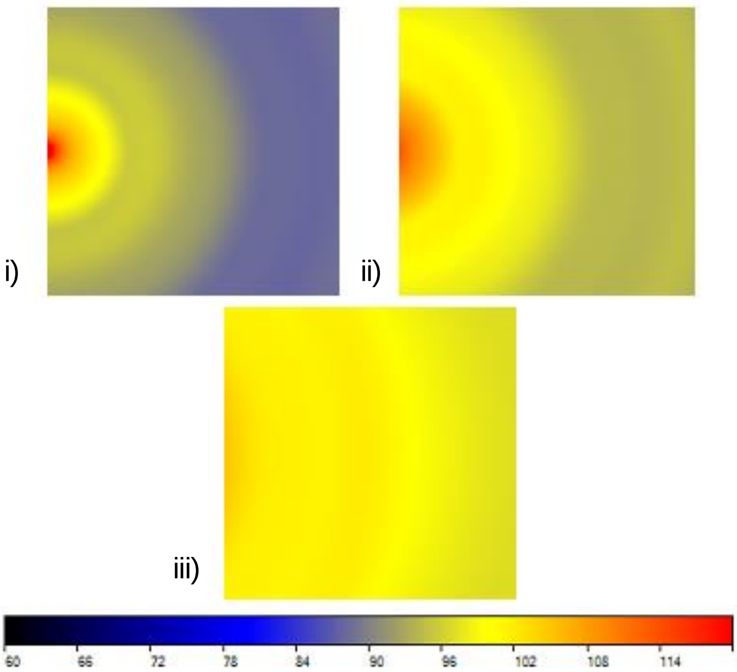

Figure A1.7 - Plots of pressure distribution in the test area at 100dB_{ht} (Phoca vitulina) for various sound projector arrays – i) 2 sources at ~0m; ii) 4 sources at 1.5m; iii) 9 sources at 12m.