

6 THE EFFECTS OF SEISMIC SURVEYS ON MARINE MAMMALS

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6.1 Abstract

The intense sounds produced during seismic surveys may potentially have physical, physiological and behavioural effects on marine mammals. In addition, there may be long-term consequences due to chronic exposure, and sound could affect marine mammals indirectly by changing the accessibility of their prey species. The most likely physical/physiological effects are thought to be shifts in hearing thresholds and auditory damage. No studies have attempted to measure this directly but there are indications that, for sensitive species at least, this may occur at short to moderate ranges.

Behavioural responses, including fright, avoidance and changes in behaviour and vocal behaviour, have been observed in baleen whales, odontocetes and pinnipeds; in some cases at range of tens or hundreds of kilometres.

The biological significance of these known or predicted effects has not been measured. However, biologically plausible scenarios can be constructed which indicate that in

cases, where feeding, migration and social behaviour are affected, populations could also be reduced. Marine mammals may face particular problems when many seismic surveys occur in a region at the same time as happens in areas of high interest, such as the Atlantic Frontier.

This review highlights the large gaps that exist in our understanding of all aspects of this potential problem. Even the nature of the seismic signature itself at different ranges and depths is poorly understood, and there may often be insufficient data to allow the correct propagation models to be applied in particular conditions. Use of inappropriate propagation models can lead to many orders of magnitude differences in predictions of the number of animals whose behaviour could be affected by seismic pulses.

While such large degrees of uncertainty continue, a precautionary approach to management and regulation should be pursued.

6.2 Introduction

Seismic surveys, such as those conducted during exploration for oil and gas, involve the production of some of the most intense man-made noises and often cover extensive areas for extended periods of time. The juxtaposition of these intense sound sources and acoustically sensitive marine mammals understandably gives rise to concerns about the effects that seismic surveys could have on these animals, and it is this subject that is explored in this section.

Potentially, intense sounds can have a number of effects on marine mammals. In this review, we divide these into

physical and physiological effects that directly cause some form of temporary or long-term damage to the animals and behavioural effects in which the natural behaviour of the animal is disturbed. Different consequences can result from long-term and short-term exposure to noise. In addition, there may also be indirect effects, mediated by the responses of prey species to seismic for example. The possible effects of intense underwater noise on marine mammals are summarised below.

Physical effects:

- Damage to body tissues
- Gross damage to ears
- Permanent threshold shift (reduction in auditory sensitivity from which there is no recovery)
- Temporary threshold shift (reduction in auditory sensitivity with eventual recovery)

Perceptual effects:

- Masking of biologically significant noises by man-made noise (including an animal's communication signals, echolocation, and sounds associated with finding prey or avoiding predators or human threats such as shipping)

Behavioural effects:

- Disruption of normal behaviour (e.g. avoidance of a particular area, altered dive and respiratory patterns)

Chronic effects:

- Stress leading to reduced viability and disease

Indirect effects:

- Reduced prey availability resulting in reduced feeding rates

6.3 Investigating the effects of man made noise on marine mammals

Three approaches can be used to assess the effects of noise on marine mammals:

- Direct observations of marine mammals exposed to sounds in the field
- Extrapolation from work on marine mammals held in captivity or from better-studied animals, including man

- Physical-psycho-physiological modelling of hearing mechanisms and processing

Approaches involving extrapolation from other species have some scope for predicting the occurrence of trauma and threshold shift but are of limited value in predicting disturbance reactions, which are likely to vary greatly, depending on species and context.

6.3.1 Direct observations

Marine mammals are perhaps the hardest of animals to study in the field. Virtually every relevant aspect of their biology, including their sensory capabilities, their normal undisturbed behaviour and its adaptive significance, and their distribution and abundance, are only poorly understood. Conducting marine mammal research at sea is always difficult and expensive. It is instructive to review some of the available techniques to gain an understanding of why direct information on the effects of seismic sounds on marine mammals is so sparse and an appreciation of how hard-won are those pieces of information that we do have.

6.3.1.1 Visual observations from ships

This might seem the most direct approach and has often been used to study cetacean behaviour but very rarely that of pinnipeds. Even large whales are difficult animals to observe at sea. They can only be seen for the brief periods that they are at the surface and then only a very simple subset of behaviours can be observed. These simple behaviours may not be good indicators of disturbance, and assessing the significance of any changes detected is fraught

with difficulty. An additional concern is the extent to which the observation platform itself might be affecting the animal's behaviour. For example, dolphins are most often seen at sea when they come to boats to bow-ride.

6.3.1.2 Visual observations from circling aircraft

Aircraft provide a higher vantage-point for observation and, provided they stay above certain heights and outside a critical zone above the subjects, the noise of their engines should not be detected by submerged animals (Richardson *et al.* 1995). They might thus be less likely than a boat to affect the subject's behaviour. However, they can provide only brief observation periods, are extremely expensive and become increasingly impractical as the range between a study site and an airport increases.

6.3.1.3 Coastal vantage-points

Observations from coastal vantage-points have two very significant advantages: they do not rely on an expensive platform and they do not affect the behaviour of the target animals. Surveyor's theodolites can be used to locate and track animals seen at the surface. Inevitably though, observations are restricted to inshore waters with adjacent high vantage-points, and even then, it can be difficult to follow the behaviour of individual animals.

6.3.1.4 Underwater acoustic monitoring

For the more vocal species, acoustic monitoring can provide researchers with a variety of behavioural cues. Generally, acoustic monitoring can be carried out from smaller vessels that are less expensive to operate and less likely to affect the behaviour of the animals being studied, or by the use of remote hydrophones. Some other advantages of acoustics are that: 1) the range for acoustic detection is often greater than visual range; 2) many animals are vocal for a greater proportion of time than they are available to be seen at the surface; 3) monitoring can continue through the night and in poor weather conditions; and 4) there is a substantial potential for automation of data collection and analysis. Acoustic monitoring can often be combined with boat-based visual observations and the two approaches should be seen as complementary. For some species at least, there is the potential for acoustic monitoring using remote hydrophones

(Clark & Fristrup 1997; Clark & Charif 1998). Finally, there is an appealing logic in studying the effects of noise using acoustic methods. Not all marine mammals species are vocal however and the significance of changes in vocal behaviour can be as hard to interpret as those behavioural changes detected visually, though this is likely to improve as the significance of marine mammal vocalisations gradually becomes better understood.

6.3.1.5 Telemetry

Although some current methods for attaching telemetry packages to marine mammals raise ethical concerns (particularly in the case of cetaceans), telemetry could potentially provide large quantities of reliable data, including information on underwater behaviour and even on some physiological responses such as heart rate (e.g. Thompson *et al.* 1998). Collecting detailed data from acoustic or VHF tags usually requires the use of a tracking vessel. Satellite tags allow animals to be tracked over extended periods but the amount of data that can be telemetered back in this way is currently limited. One of the most significant hurdles to marine mammal telemetry is tag attachment. Pinnipeds can be captured on or close to land and good results have been obtained by gluing transmitters to their fur (Fedak *et al.* 1983). Such tags are shed when the animal moults. Acceptable long-term attachment to cetaceans remains a largely unresolved problem and a better approach may be to aim for a larger number of short-term attachments using suction cups. Another important issue is ensuring that the telemetered animals are exposed to the appropriate signals. Once the subject has been tagged, researchers have no control over its movements, and it may well never enter an area of seismic surveying activity. Controlled exposure experiments in which the experimenter has control of when and where a sound source is activated can help to address this. Ideally we would like to know exactly what signals the subjects receive, e.g. received sound levels. Tags, which incorporate a hydrophone and sound recording device, have recently been developed (Fletcher *et al.* 1996), and should provide data on sound exposure, though recording bandwidth, record time and package size remain limiting considerations. The expense of tags, and particularly problems inherent in attaching them, has meant that marine mammal telemetry studies are also characterised by very small sample sizes.

6.3.2 Experimental control

Marine mammal scientists rarely have full control over when and where a seismic source is active during their field trials. However, usually research will be more powerful, particularly in its ability to demonstrate cause and effect, if researchers can direct the operation of the sound source and are able to conduct controlled exposure experiments. This may only be possible with small-scale sources and in a limited set of conditions. Investigations of responses to

full-scale seismic arrays and surveys will have to be conducted around ongoing surveys. Observations can be made before, during and after commercial seismic surveys. Observations may also be made while seismic surveys are underway but this offers only a limited scope for investigating short-term responses. For example, behavioural responses can be investigated at different ranges from guns and comparisons can be made between

behaviour observed during periods of gun-firing and periods when guns are silent. Non-firing periods occur as a matter of course in surveys, during turns between lines for example.

Marine mammals are a large and diverse group, and findings from one species generally do not apply to all others, nor would they be expected to. A final consideration, which is often overlooked, is the temporal

and spatial scales over which effects may occur. The potential for extremely long-range propagation of intense sounds in the ocean, and the long life span and slow reproductive rate of some marine mammals, suggests a potential for effects to occur at temporal and spatial scales far beyond those normally addressed by marine mammal field research projects.

6.4 Effects of seismic noise

6.4.1 Physical damage

The damage that shock waves from explosives could cause to marine mammals has been explored by using both submerged terrestrial animals (Goertner 1982; Richmond *et al.* 1973; Yelverton *et al.* 1973), and dolphin carcasses (Myrick *et al.* 1990). The ability of a pressure wave to cause physical damage depends critically on its rise time, and this is lower for a seismic pulse than for an explosion. Although there is no direct evidence that seismic pulses cause acute physical damage to marine mammals, we are unaware of any study that has specifically investigated potential physical damage from seismic sources.

Human divers exposed to pulses of very intense low frequency sound have experienced non-auditory physiological effects, which include resonance of the lungs and other cavities and symptoms of dizziness, nausea and visual disruption. Likely sources of such pulses include a new generation of Low Frequency Active Sonar Systems, and this is a subject of ongoing research (Cudahy & Sims

1998, cited by Davis *et al.* 1998). The potential for seismic pulses to cause similar effects has not yet been investigated.

Indirect physical damage can also be caused by sound-induced growth of bubbles of free gas in the super-saturated body tissues of diving mammals. Although marine mammals are breath-hold divers and are thus less susceptible to the bends than human divers breathing compressed air, it is believed that during long sequences of dives their body tissues could become super-saturated with gas (Ridgway & Howard 1982). Crum & Mayo (1996) calculated that exposure of humans or marine mammals to 500 Hz sounds at SPLs of 210 dB re. 1 μ Pa could cause bubble growth to occur and they suggest that this could theoretically induce the 'bends' in marine mammals. They considered that this effect was unlikely at SPLs below 190 dB re. 1 μ Pa.

6.4.2 Auditory damage

Ears, that have been adapted through evolution to be exquisitely sensitive to sound, are also the organs that are most vulnerable to being damaged by it. The detonation of explosive charges underwater can result in gross tissue damage in ears. For example, Bohne *et al.* (1985) and Bohne *et al.* (1986) examined the ears of a sample of 10 Weddell seals (*Leptonychotes weddellii*) collected in McMurdo Sound after a series of dynamite explosions, and discovered tissue damage in half of them. Similarly, Ketten *et al.* (1993) found damage, that resembled blast injury in humans, in the ears of two humpback whales (*Megaptera novaeangliae*) which had become entrapped in fishing gear off Newfoundland after explosions had taken place in the area.

There is no direct evidence of tissue damage to the ears of marine mammals resulting from seismic sound sources, though again, we are not aware of any studies that have specifically investigated this.

6.4.2.1 Noise-induced hearing loss: temporary and permanent threshold shifts

Exposure to noise of sufficiently high intensity causes a reduction in hearing sensitivity (an upward shift in the threshold). This can be a temporary threshold shift (TTS), with recovery after minutes or hours, or a permanent threshold shift (PTS) with no recovery. PTS may result from chronic exposure to sound, and sounds that can cause TTS usually cause PTS if the subjects are exposed to them repeatedly and for long enough. However, very intense sounds can cause irreversible cellular damage and instantaneous PTS.

TTS appears to be associated with metabolic exhaustion of sensory cells, and certain anatomical changes and damage at a cellular level. Anatomical changes result when the stereocilia of the sensory hair cells in the cochlea lose stiffness, as a result of disruption of the cross-linking of proteins in the cilia themselves and become disarranged.

Excessive metabolic and electromechanical response activity also leads to swelling in the hair cells, in neural connections and in the vascular system of the cochlea. PTS may be accompanied by more dramatic anatomical changes in the cochlea including the disappearance of outer hair cell bodies and, in very severe cases, a loss of differentiation within the cochlea and degeneration of the auditory nerve. Stimulation by loud narrow-band noise induces threshold shifts in the auditory band of half an octave above the frequency of the noise itself, and anatomical changes in the cochlea are also found in the region most responsive to frequencies half an octave above the stimulating noise. Lower frequency noises induce threshold shifts over a wider bandwidth than higher frequency noises.

There are no direct observations of threshold shifts caused by a known level of exposure of marine mammals to pulses from airguns. However, information on noise induced TTS in marine mammals is becoming available from a series of experiments being conducted in US facilities that involve the measurement of hearing sensitivity in captive marine mammals before and after exposure to intense sounds. Kastak *et al.* (1999) have investigated development of TTS after exposure to octave band noise in elephant seals (*Mirounga* sp.), harbour seals (*Phoca vitulina*) and Californian sea lions (*Zalophus californianus*), and exposure to intense tonal pulses (somewhat similar to sonar) has been studied in bottlenose dolphins (*Tursiops truncatus*) and beluga whales (*Delphinapterus leucas*) by Schlundt *et al.* (2000). Finneran *et al.* (2000a) have also attempted to induce TTS with playback of signals resembling distant explosions, while Finneran *et al.* 2000b described exposure experiments with captive odontocetes using a seismic water gun, though no results from these have yet been published. (A water gun was used because its

signature has similarities with those from UW explosions.) In the future, experiments of this type could be extended to test TTS induction by airgun pulses but information could only be obtained for the few species of smaller odontocetes and pinnipeds that can be experimented on in captivity. The potential for inducing threshold shifts in other species must be inferred from experiments like these (if they are ever carried out), and data from better-studied terrestrial mammals, including man, informed by whatever data on marine mammal hearing sensitivity is available. A schematic representation of this process is shown in Figure 6.1. Each step in the process is given a letter. Data already exist on safe levels of exposure to particular sounds in terrestrial mammals and man (a). An assessment of acceptable exposure levels in man to signals (c) from airgun arrays could be made using these existing data and knowledge of the characteristics of seismic sources as received at marine mammal ears (b). The next step would be to estimate safe levels of exposure for different marine mammals (e) based on knowledge of their hearing sensitivity (d). The final step would involve combining these estimated safe levels with an estimate of likely exposure (f) (based on a knowledge of source levels, propagation conditions, seismic vessel working procedures and animal behaviour) to develop guidelines and practical codes of conduct to minimise the risk of damaging marine mammal hearing during seismic surveys (g). This chain of inference requires inputting, sometimes uncertain, data and making assumptions at each step. As with any such process, the conclusions that arise at the end must be treated with some caution because the errors introduced at each stage may become compounded. Hence, guidelines developed on the basis of these values should be

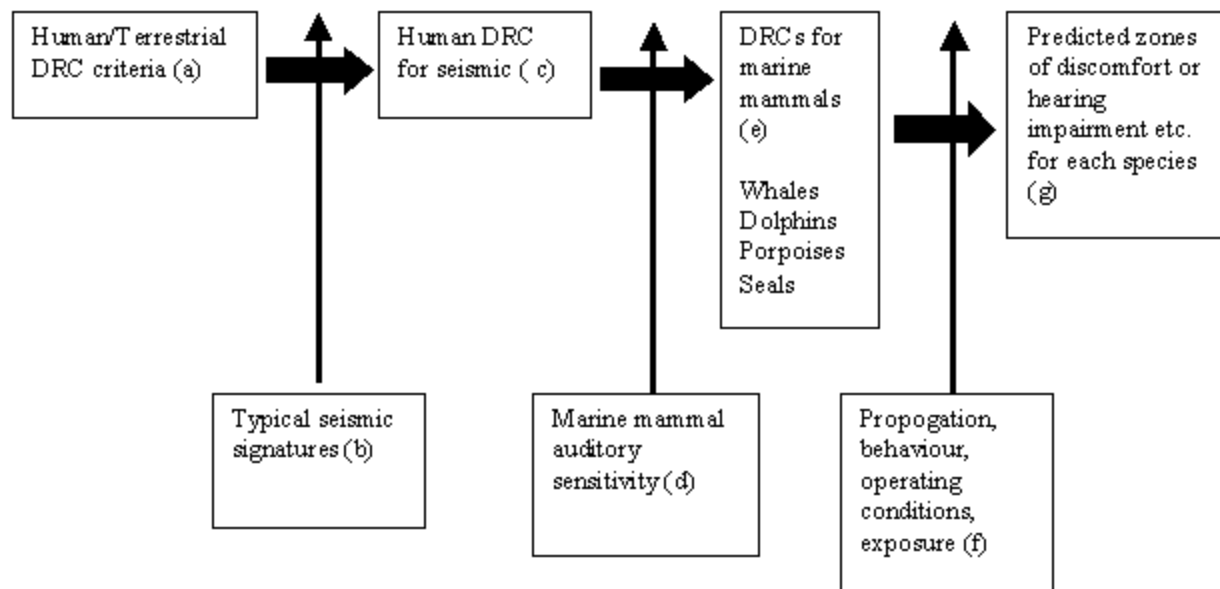


Figure 6.1 Schematic representation of the process for estimating ‘safe’ levels of exposure to seismic pulses for marine mammals

precautionary and rigorously enforced to help ensure that they afford the intended level of protection.

In the following sections we examine some of the steps in this process in greater detail.

6.4.2.1.1 Hearing loss in terrestrial mammals (a)

The investigation of threshold shifts in man, particularly those caused by chronic exposure to industrial noise, has been an area of intense research, and extensive reviews are provided by Kryter (1985, 1994).

Typically, and especially when human experimental subjects are involved, measurements of TTS are made in controlled conditions and these are used to infer the risk of PTS from higher levels of exposure. Often the goal is to calculate Damage Risk Criteria: levels of exposure that cannot be exceeded without risking hearing damage.

Ward (1968) (cited in Richardson *et al.* 1995) investigated human damage risk criteria (DRC) for impulse noise in air, based on empirical observations of TTS, and derived a predictive formula for PTS using peak pressure levels, pulse duration and number of pulses as parameters. For pulses with a certain peak pressure, risk was found to increase with both the number of pulses and their duration. According to Ward's formula, peak pressure threshold for damage diminishes by 2 dB for each doubling of pulse length, up to a pulse length of 200 ms, beyond which there was no further decrease. Thus, for 'safe' exposure to 100 pulses the peak pressure level is 164 dB re. 20 μ Pa when pulses were 25 μ s long and 138dB re. 20 μ Pa for prolonged (>200 ms) pulses. As the number of pulses is reduced, the DRC is adjusted upward, by 5 dB per 10-fold reduction in pulse number. Thus for a single 200 ms pulse, the DRC is 148 dB re. 20 μ Pa. Exposure to a single pulse at this level might be expected to cause damage.

It should be noted here that there is a body of expert opinion that holds that DRC for impulsive noise currently applied to humans, such as the one considered above, may be too lenient and may underestimate the risk of hearing damage from impulsive noises. Procedures for predicting TTS and PTS resulting from exposure to sounds of a certain intensity and duration are based on the equal energy hypothesis. This proposes that threshold shift should be proportional to the product of intensity and time. Thus, equal energy considerations suggest that impulsive noises (such as seismic pulses) have a much-reduced potential to cause threshold shifts because of their short duration. However, Melnick (1991) commented "the relationship of TTS to the properties of intermittent sounds continues to be complex, depending on level, frequency and duty cycle of the noise". Laroche *et al.* (1989) investigated TTS due to impact noise in humans. They found that levels of TTS resulting from prolonged exposure reached an asymptote (indicative of PTS) 16 times faster for impulse noises than for continuous noises. They claim that this may be because during exposure to intense impulsive noise the basilar membrane in the inner ear could attain much greater displacement (thus increasing the potential for sensory cell damage) than it would during exposure to continuous noise. Their measurements suggest that such damage would start

to occur above a peak pressure level of 100-105 dB (150-175 dB re. 1 μ Pa, for marine mammals based on threshold level assumptions made in section 6.4.2.1.5). They point out that the threshold for safe exposure levels in humans would be some 24 dB lower, based on their observations, than those permitted by the widely used CHABA criteria (CHABA 1964).

6.4.2.1.2 Nature of the seismic signals received at marine mammal ears (b)

The acoustic nature of seismic pulses is reviewed in Chapters 2 and 3. Seismic gun arrays are designed to deliver a very well defined and uniform sound pulse in the desired direction – 'downwards'. However, the characteristics of sounds projected in other directions can be very different and the environment also substantially affects pulses. Marine mammals will also be at a variety of different positions relative to a seismic array (including directly below it) when the array is active and the received seismic signal may thus be of complicated and variable nature. In deep water for example, it may include both components with a sharp onset and short duration received directly and longer pulses with slower rise times received by reflection from the seabed. These components may be separated by different time intervals, depending on water depth and the position of the marine mammal receiver within the water column.

It is unclear which measurements of a seismic pulse provide the most reliable indications of its potential impact on the hearing sensitivity of different species of marine mammal, but at short ranges, where hearing damage may occur, the peak broad band pressure and pulse rise time and duration seem to be the most relevant measures. It should be emphasised however, that the effects of underwater seismic signals on hearing sensitivity has not been measured, even in easily studied terrestrial mammals and man, and extrapolation from existing data on the effects caused by generic 'impulsive noise' may be misleading.

6.4.2.1.3 Direct measurements of noise induced TS in marine mammals (c)

a) Odontocetes

Ridgway *et al.* (1997) briefly reported results from the first investigation of threshold shifts in any marine mammal in controlled conditions. These experiments were primarily aimed at assessing the effects of sonar pulses on odontocete ears and consequently short duration, narrow band sounds were utilised. Schlundt *et al.* (2000) have reported on a similar but more comprehensive study involving experiments with five individual bottlenose dolphins and 2 belugas. The hearing threshold of the animals was measured before and after exposure to 1 sec tones at 0.4, 3, 10, 20, and 75 kHz. The levels required to cause a 6 dB reduction in sensitivity for these short exposures at these frequencies were between 192 and 201 dB. At 400 Hz, where sensitivity was lowest, no animals showed evidence of threshold shifts. There was evidence of some inter-

individual variation in sensitivity, one dolphin showed a threshold shift 75 kHz at 182 dB re. 1 μ Pa while another showed no shift at maximum exposure of 193 dB re. 1 μ Pa.

Finneran *et al.* (2000a) measured masked underwater hearing threshold of dolphins after they had been exposed to sounds with waveforms generated to resemble those of distant explosions. Pulses from charges ranging from 5-500 kg Hex 1 at ranges of 1.5 to 55.6 km were simulated, with the highest exposure level generated being equivalent to 500 kg at 1.7 km. No threshold shifts, defined here as being a rise in threshold of 6 dB or greater, were observed after any of these exposures. Disruption of trained behaviour began to occur at exposures equivalent to 500 kg Hex at 9.3 km and 5 kg TNT at 1.5 km for the dolphins and at 500 kg Hex at 1.9 km for beluga.

Finneran *et al.* (2000b) described a series of experiments in which a seismic water gun was used as the sound source. A water gun was used rather than an airgun because its acoustic output is similar to that of underwater explosives. No results have been published from these experiments thus far.

These experiments demonstrate that threshold shifts can be induced in cetaceans. They will be more informative about effects of seismic on cetaceans if they are extended to cover a greater range of sound types and exposure durations.

There have been no direct observations of noise-induced PTS in cetaceans. However, Andre *et al.* (1997) reported patterns of cell damage that are consistent with PTS effects within the cochlea of a mother and calf sperm whale (*Physeter catodon*) that died after being struck by a high-speed ferry in the Canaries. They proposed that this might have been caused by long-term exposure to noise from the relatively high level of shipping in the Canaries.

b) Pinnipeds

Kastak & Schusterman (1996) made opportunistic observations of threshold shifts in a harbour seal that was inadvertently exposed to industrial noise from sandblasting for some 6-7 hrs per day for a period of six days while the animal was mid-way through a program of audiometric testing. Immediately after the cessation of the construction activity, the seal's hearing was tested and an 8 dB increase in threshold at 100 Hz was measured. After a week of recovery the seal's threshold was still raised by 2 dB. Unfortunately, the intensity and effective duration of the subject's exposure to the noise are not known and could not be inferred retrospectively; the animal could escape from the air-born noise by diving underwater for example. However, the authors comment that the magnitude of the TS was similar to that observed in other mammals following brief exposure to intense stimuli. The seal showed a surprisingly high level of false alarm rates in its trained tasks after exposure to the sound and this led Kastak & Schusterman (1996) to speculate that the animal might have been suffering noise-induced tinnitus (ringing of the ears) in addition to threshold shift. The potential for seismic blasts, and other intense sounds, to produce tinnitus in marine mammals has not been widely considered.

Kastak *et al.* (1999) pursued their opportunistic observations with a series of noise exposure experiments with a harbour seal, one elephant seal and two Californian sea lions. Subjects were trained to dive into a noise field and position their heads on a chin-cup close to the bottom of a 2.5 m pool. Exposures lasted for 20-25 mins. Octave band noise with mid frequencies ranging from 100 Hz to 2 kHz, and octave band sound levels of approximately 60-75 dB above the threshold level at the central frequency were used. Hearing was tested before and immediately after each trial, and following 24 hrs of recovery. Pure tone detection threshold increases of 4.8 dB (harbour seal), 4.9 dB (sea lion) and 4.6 dB (elephant seal) were recorded with full recovery in all subjects after 24 hrs. These trials show that threshold changes can be induced in pinnipeds by exposure to sounds of moderate intensity. It should be noted that these pinniped sound exposures differed from those used for cetaceans by Schlundt *et al.* (2000), in that they involved exposure to lower sound levels of greater bandwidth for longer time periods.

6.4.2.1.4 Marine mammal sensitivity to hearing damage (d)

It has been suggested that some features of cetacean ears render them less vulnerable to acoustic damage than those of terrestrial mammals; there is no direct evidence to support this contention however. At first sight, cetacean ears do appear massive and robust compared to those of terrestrial animals. The middle and inner ears of cetaceans are located outside the cranium and are enclosed in two fused, dense, bony capsules. The middle ear is enclosed by the tympanic bulla while the inner ear is within the periotic bulla. These bones are massive by comparison to homologous structures in terrestrial mammals, and this may be an adaptation to withstand pressure changes during diving. In addition, the mass of these large bony structures may also provide inertia necessary to achieve relative movement between the inner ear and the rest of the animal's body, without which of course, the ear could not function. However, noise-induced threshold shifts result from damage to sensory cells of the organ of corti, which sits on top of the basilar membrane within the cochlea, and these structures would seem just as delicate and vulnerable in cetaceans as in terrestrial mammals. In odontocetes, the organ of corti is very well developed and exhibits conspicuous hypercellularity. The stria vascularis, a well vascularised region that runs through the cochlea and maintains the high potassium concentration within the scala media, which is essential for the triggering of the ear's sensory hair cells, is also very well developed. This may make the ear less vulnerable to metabolic exhaustion (though the hypercellularity of the organ of corti would be expected to increase metabolic demands) but it could not protect the stereocilia of the hair cells from the physical damage that often underlies PTS, particularly that caused by relatively short exposure to intense impulsive sounds.

In terrestrial mammals, the ear can be protected from intense noise by the operation of the 'attenuation reflex'. This involves the contraction of small muscles that run

between the walls of the middle ear chamber and the ossicles (the bones of the middle ear that conduct sound from the tympanic membrane to the cochlea). In terrestrial mammals, the ossicles act as a series of levers matching the low impedance of the external medium (air) to the high impedance of fluid filled cochlea; a contraction of these muscles stiffens the ossicular chain and reduces the transmission of sound. In marine mammals, the internal and external media are both liquid and there is no requirement for impedance matching. The ossicles are relatively massive and in odontocetes the ossicular chain is stiffened. Thus, although the muscles that contribute to the auditory reflex are present, it can be argued that their contraction would do little to limit the vibrations of the ossicular chain and disrupt the transmission of acoustic signals to the cochlea. In addition, there is an unavoidable delay between sensing an intense sound and implementing the auditory reflex, in humans this is of the order of 50-100 ms. Consequently, even in terrestrial mammals, the auditory reflex has only a limited potential for protecting the inner ear from intense impulsive sounds such as seismic pulses.

In conclusion, while there are few direct observations of threshold shifts in marine mammals, and none for sounds similar to seismic blasts, experimental observations do indicate that these animals are susceptible to noise-induced threshold shifts. There are also anatomical indications of damage to the organ of corti of marine mammals, similar to that associated with noise induced PTS in man and terrestrial mammals. There is currently no firm evidence to suggest that cetacean ears are less vulnerable to the effects of intense noise than terrestrial mammals or man, or that applying of damage risk criteria developed for humans will necessarily lead to particularly conservative conclusions.

6.4.2.1.5 *Extrapolations from human criteria to assess risks of threshold shifts in marine mammals (e)*

There are no agreements on which measures of a transient sound best describe its ability to cause threshold shifts, but some evidence suggests that peak pressure may be a more appropriate measure than total energy for predicting instantaneous damage. For any sound type, there is an intensity threshold above which damage occurs and below which threshold shifts are the result of metabolic processes. Most human research and noise regulation criteria address

long-term exposure to moderate noise sources. but animals close to an operating airgun array, particularly those below it, may receive very high levels of sound indeed, albeit for a relatively short period. Thus, when considering the potential for seismic guns to cause TTS or PTS in marine mammals, relatively short exposures to intense sounds are of greatest relevance. As already noted, long term exposure to moderate levels may not adequately predict the effects of shorter exposure to more intense sounds.

Richardson *et al.* (1995) considered the application of the human damage risk criteria (derived by Ward 1968) to marine mammals. They allowed for differences in hearing thresholds between man and various marine mammals by expressing critical sound levels in DRCs relative to the likely best hearing thresholds for the species under consideration. They considered that, for the purposes of this exercise, marine mammals could be considered in two groups: sensitive species, with lowest hearing thresholds of around 40 dB re. 1 μ Pa, and less sensitive species, with best hearing thresholds at 70 dB re. 1 μ Pa. Comparisons between different species can be best made as dBs over threshold level. Threshold levels for humans at frequencies of best sensitivity are 0 dB re. 20 μ Pa, so it is necessary to add to that 40 dB or 70 dB (depending on the assumed sensitivity of the species) to any human criteria when applying them to marine mammals. Based on these assumptions, Richardson *et al.* (1995) derived a table of DRCs for exposure to different numbers of 'long' (200 ms or more) or 'short' (25 μ s) pulses, and these data are presented here as Table 6.1. This suggests for example, that sensitive animals might suffer hearing damage from a single 200 ms pulse with a peak level of 188 or 218 dB re. 1 μ Pa, for more or less sensitive marine mammals respectively (148 dB single pulse DRC for humans + 40 or 70 dB).

Below a seismic source, typical pulse durations are short, in the order of 10 ms. Following Ward's procedures for deriving DRCs for humans, 152 dB re. 20 μ Pa is given as a threshold level for 100 1.5 ms pulses. For 10 msec pulses subtract 6 dB = 146 dB (Ward 1968). For a single pulse add 10 dB = 156 dB, then add 40 dB or 70 dB = 196 dB and 226 dB re. 1 μ Pa as DRCs for more sensitive or less sensitive marine mammals respectively. For a 260 dB re. 1 μ Pa- m_{p-p} source, and assuming spherical spreading, these levels would be exceeded out to ranges of 1,585 m and 50 m respectively. It should also be appreciated that an

Table 6.1 Inferred Auditory Damage Risk Criteria for humans and marine mammals exposed to noise pulses underwater. After Richardson et al. (1995).

Number of Pulses	DRC for human in air (dB re. 20 μ Pa)	Speculative DRC (in dB re. μ Pa) for marine mammal listening in water with hearing threshold of 40 and 70 dB re. 1 μ Pa	
		40dB re. 1 μ Pa	70 dB re. 1 μ Pa
100 long (>200 ms)	138	178	208
10 long (>200 ms)	143	183	213
1 long (>200 ms)	148	188	218
1 short (25 μ s)	174	214	244

animal might receive several loud pulses while it was within the maximum intensity beam beneath the array.

For an animal to the side of the array, pulse length is greater than 200 ms and DRCs from Table 6.1 would apply directly. DRCs are 188 dB or 218 dB for more or less sensitive marine mammals. Assuming spherical spreading, these levels would be exceeded out to ranges of 1,260 m and 40 m.

If exposure to 100 pulses is considered, then DRCs from Table 6.1 would be 178 dB or 208 dB and, for spherical spreading, these levels would be exceeded out to ranges of c.4,000 m and 130 m.

A seismic survey vessel making 5.5 knots and emitting one shot every 10 secs will travel 2.8 km in the 1,000 secs required for 100 shots. Exposure of stationary sensitive marine mammals, with a 40 db threshold would then exceed the levels prohibited by these DRCs out to a range of ~3,700 m. (An assumption of spherical spreading at such ranges may overestimate attenuation and if so then effects at even greater ranges would be anticipated.)

Davis *et al.* (1998) considered the implications of Ridgway *et al.*'s (1997) finding of a 192 dB threshold for TTS from a 1 sec pulse (Ridgway *et al.* 1997). They suggested that, because of the shorter duration, seismic pulses would have to have to be 10 dB louder, 202 dB re. 1 μ Pa, to achieve the same sound exposure levels. This 10 dB difference assumes the seismic pulse is only 0.1 sec in

duration. However, in deep water, the primary pulse and echo can last for 0.4 secs, in which case only around 4 dB should be added to Ridgway *et al.*'s (1997) threshold for TTS. More importantly, these calculations make the assumption that the damaging effect of a pulse is directly proportional to its energy. This is clearly not the case with transients for which peak pressure seems to be the most important factor. For example, as outlined above, Ward (1968) found that, in humans, there was not additional damage from impulse noises once pulse length exceeded 200 ms. This then would seem to be the most appropriate integration time to apply, suggesting a possible addition of 3 dB to Ridgway *et al.*'s (1997) value to allow for a 0.1 sec pulse length and giving a threshold for TTS of 195 dB re. 1 μ Pa.

Clearly, extrapolations such as these, between different species, conduction media and noise types, are highly speculative. They could be either significantly over- or under-estimating the risks. Given the current state of knowledge, it is not possible to reach firm conclusions on the potential for seismic pulses to cause threshold shifts or hearing damage in marine mammals. Extrapolations that have been made here and elsewhere do at least serve to indicate that the risk of seismic sources causing hearing damage to marine mammals is far from negligible. This problem should be taken seriously; a more thorough expert investigation is required.

6.4.3 Perceptual effects

6.4.3.1 Auditory masking

Background noise will reduce an animal's ability to detect certain other sounds. We are all familiar with this 'auditory masking' from everyday life but it is a complex phenomenon, and the ability of one sound to mask another is affected by many factors. Richardson *et al.* (1995) reviewed masking in humans and marine mammals. Generally, noise will only mask a signal if it is sufficiently close to it in frequency. Conceptually, to be effective in masking a signal, noise must be within that signal's 'masking band'. At low frequencies, masking bands are broad and have a constant bandwidth. At higher frequencies, bandwidths are narrower and their width scales with frequency. Johnson *et al.* (1989) found that, in beluga whales, bandwidths were fairly constant below 2 kHz, while data for pinnipeds (summarised by Richardson *et al.* 1995) suggest broadband critical ratios below ~200 Hz. Thus, marine mammals might be expected to be most susceptible to masking of low frequency sounds by low frequency noise, such as seismic. A masking bandwidth of 1/3 octave at higher frequencies has often been assumed. However, in their review of this topic, Richardson *et al.* (1995) found masking bandwidths are typically narrower than this and often >1/6 octave, at higher frequencies. Studies of masking have usually considered the masking of a pure tone by other tones or by noise in a frequency band around it. The situation is more complex when, as would be the case for masking most biologically significant sounds by seismic

sources, both the noise and the signal are broad-band and the noise is intermittent rather than continuous. Signals that are structured, stereotyped and repeated may also be less susceptible to masking because they have in-built redundancy. The effects of masking can be reduced when the noise and the signal come from different directions and the receiver is able to directionalise one or both. In effect, the signal to noise ratio is then reduced in the direction from which the signal is coming. Directional hearing has not been investigated in marine mammals at the low frequencies where most seismic source energy is centred however.

Au *et al.* (1985) describe an example of a likely behavioural response to increased noise levels and masking in cetaceans. They reported changes in the vocal output of a captive beluga whale when it was moved to a facility with higher levels of continuous background noise. In the noisier environment, the animal increased the average intensity and frequency of its vocalisations, as though it were compensating for the masking effects of the increased background noise levels. Presumably though, there should have been some cost to the animal concerned in terms of energy expenditure and perceptual efficiency resulting from the requirement to make louder sounds at a new (possibly sub-optimal) frequency.

There is no direct information on the extent to which seismic pulses mask biologically significant sounds for marine mammals. At greater ranges from the source the main potential for masking will be at the lower frequencies where masking bands are wider and susceptibility to

masking may thus be greater. Baleen whales that are believed to be low-frequency specialists might thus be most vulnerable. Most of their vocalisations are below 1 kHz and some, such as blue (*Balaenoptera musculus*) and fin (*B. physalus*) whales make predominantly low frequency calls (Clark 1990). It has been suggested that baleen whales could use low frequency sound to communicate over great distances (Payne & Webb 1971), and monitoring of whale calls using the military SOSUS array (Clark & Fristrup 1997) lends some support to this suggestion. Recently, attempts were made to monitor for baleen whales off the west coast of the British Isles using SOSUS array hydrophones (Clark & Charif 1998). Levels of background noise were so high in the summer months, due to oil-related seismic surveying, that monitoring had to be abandoned for long periods. We can only assume that the ability of baleen whales to monitor their acoustic environment might be similarly compromised by seismic surveys. The intermittent nature of seismic pulses might be expected to reduce their potential for masking. However, the length of a seismic pulse increases with range from the source (see Chapter 2) so that at range it may approach the 1-sec

duration of the 20 Hz pulses produced by fin whales: possibly increasing the potential for masking.

Phocids, especially elephant seals, are another group with good low frequency hearing that would be expected to be more susceptible to low frequency masking.

It is not possible, given the current state of knowledge, to properly assess the potential for biologically significant masking by noise from seismic sources. On the one hand, mammals show a number of adaptations to enable them to minimise the effects of masking. On the other, it is likely that being able to detect a variety of sounds at very low levels is important for their well-being and survival. (Indeed, the fact that such sensitive hearing and sophisticated mechanisms for minimising the masking effects of noise have evolved is one indication of the importance of this for their biological success). If this is the case, then any reduction in a marine mammal's ability to detect biologically significant signals could reduce its viability and the noise from seismic surveys could be having deleterious effects on marine mammals over very substantial ranges.

6.4.4 Disruption of behaviour

Many studies have measured changes in behaviour in response to exposure to seismic noise. Table 6.2 summarises the findings from some of those that provide data on received noise levels and/or ranges from sources for behavioural responses.

6.4.4.1 Baleen whales

6.4.4.1.1 Bowhead whales (*Balaena mysticetus*)

Oil exploration in the Bering, Chuckchi and Beaufort Seas has prompted considerable research to investigate disruption of bowhead behaviour by seismic pulses and other noises associated with industrial activity offshore. The bowhead whale is of particular concern because it is an endangered species and is also the subject of an aboriginal hunt by Alaskan Inuit. Research has included both opportunistic observations made during seismic surveys (e.g. Reeves *et al.* 1984; Richardson *et al.* 1986), and experimental exposure to airguns (Richardson *et al.* 1986; Ljungblad *et al.* 1988; Richardson & Malme 1993). Richardson *et al.* (1991, 1995) provide comprehensive reviews of much of this work.

Bowheads typically exhibited overt avoidance behaviour at ranges as great as 6-8 km, corresponding to received noise levels of 150-180 dB re. 1 μ Pa. Occasional observations of avoidance at greater ranges, e.g. >20 km by Koski & Johnson (1987), have also been made. Changes in behaviour characteristic of disturbance, including reduced surface interval and dive duration, and lower numbers of blows per surfacing, have been recorded at ranges of up to 73 km from seismic vessels (Malme *et al.* 1988) where received levels were between 125 and 133 dB re. 1 μ Pa.

6.4.4.1.2 Grey whales (*Eschrichtius robustus*)

Grey whales migrating south, close to the Californian coast, on their annual migration to breeding lagoons in Mexico provided an opportunity for a series of particularly well-controlled and informative experiments reported by Malme *et al.* (1984). Observation teams on the shore tracked the highly predictable paths of migrating grey whales as they swam past a moored source-vessel during periods when an airgun was firing and periods when it was silent. Animals that responded to the guns slowed and turned away from them. Some moved into areas where the topography shielded them from the noise of the guns. A comparison of the tracks of individual whales and of track densities at different ranges from the moored source platform, during periods when guns were active and during control periods, allowed the ranges and received levels at which different proportions of the migrating animals diverted to avoid the guns to be determined (Figure 6.2). Received levels for avoidance by 10%, 50% and 90% of the animals were 164, 170 and 190 dB re. 1 μ Pa. A smaller-scale experiment with grey whales summering in the Bering Sea yielded similar results with 10% and 50% avoidance at 163 and 173 dB re. 1 μ Pa respectively.

6.4.4.1.3 Humpback whales

Malme *et al.* (1985) conducted playbacks to feeding humpbacks using a 1.64 L airgun and elicited a startle response at levels of 150-169 dB re. 1 μ Pa. Recently, McCauley *et al.* (1998) have reported their observations of migrating humpback whales off western Australia, made during both full-scale seismic surveys and experimental exposures to a single airgun. The 3D seismic survey that

Table 6.2 Summary of observations of behavioural change in marine mammals in response to airguns and seismic surveys

<i>Species</i>	<i>Location</i>	<i>Observation</i>	<i>Source</i>	<i>Received level</i>	<i>Range</i>	<i>Behaviour</i>	<i>Water depth</i>	<i>Model</i>	<i>Reference</i>
Common dolphin	Irish Sea	Operating seismic	2D Seismic 2,120 cu. In.		>1 km	Reduced vocalisation rate within vocal range and/or exclusion within 1 km.	50-100 m		Goold (1996a)
Bottlenose dolphin	Captivity		1 sec 20 kHz pulse	<ul style="list-style-type: none"> 178 (75 kHz) 186 (3 kHz dB) 		Behavioural avoidance responses at 178 dB			Ridgeway <i>et al.</i> (1996)
Sperm whales	Southern Ocean	Opportunistic	Seismic 8x16l 263 dB re. 1 μ Pa	<ul style="list-style-type: none"> 112 dB 	>300 km	Cessation of vocalisation	>500 m		Bowles <i>et al.</i> (1994)
Grey whales	California	Experimental playback	Seismic array	<ul style="list-style-type: none"> 180 dB 170 dB 164 dB 	1.2 km 2.5 km c.3.6 km	90% avoidance 50% avoidance 10 % avoidance by migrating whales	50-100 m		Malme <i>et al.</i> (1983, 1984)
Grey whales	Bering Sea	Experimental playback	Seismic array 1.64l 226 dB	<ul style="list-style-type: none"> 173 dB 		50% avoidance			Malme <i>et al.</i> (1986, 1988)
Bowhead whale	Beaufort Sea	Operating seismic	Seismic array	<ul style="list-style-type: none"> 163 dB 142-157 	8.2 km	10% avoidance by summering whales Behavioural changes. Changes in blow rates and dive patterns.			Various studies in Richardson <i>et al.</i> (1995)
Bowhead whale	Beaufort Sea	Operating seismic		<ul style="list-style-type: none"> 152-178 		Active avoidance. Swimming away from the guns and behaviour disrupted for 1-2 hrs.	30-60 m		"
Bowhead whale	Beaufort Sea	Operating seismic		<ul style="list-style-type: none"> 125-133 dB 	54-73 km	No avoidance behaviour but significantly shorter dives and surfacing periods.			"
Humpback whale	S.E. Alaska	Experimental playback	Seismic gun 1.64L 226 dB	<ul style="list-style-type: none"> 150-169 	<3.2 km	Short-term startle response No clear avoidance at levels up to 172 dB re. 1 μ Pa effective pulse pressure level.			Malme <i>et al.</i> (1985)
Humpback whale	North West Cape, W. Australia	Operating seismic	Seismic array 44L 258 dB re. 1 μ Pa ² -mp-p	<ul style="list-style-type: none"> 170 dB P-P 162 dB P-P 157 dB P-P 	3- 4 km 5 km 8 km	Stand-off (General avoidance) Avoidance manoeuvres Avoidance manoeuvres	100-120 m	25 logR	McCauley <i>et al.</i> (1998)
Humpback whale	Exmouth Gulf, W. Australia	Experimental playback	Seismic gun 0.33L, 227 dB re. 1 μ Pa ² -mp-p	<ul style="list-style-type: none"> 168 dB P-P 	1 km	General avoidance	10-20 m		McCauley <i>et al.</i> (1998)
Blue whale	North Pacific Ocean	Operating seismic	Seismic source 1,600 cu. in. 215 dB (P-P) re. 1 μ Pa 1-m.	<ul style="list-style-type: none"> 159 dB P-P 143 dB P-P 	2 km 10 km	Course alterations begin Closest approach 10 km? Cessation of vocalisations for c.1 hr. Resumption of vocalisations and movement away from source.	2,400 m		Macdonald <i>et al.</i> (1995)
Grey seal	Scotland and Sweden	Experimental playback. 1 hr exposure	Single gun or small array (215-224 dB re. 1 μ Pa-1 m)			Avoidance. Change from feeding to transiting behaviour. Haulout. Apparent recovery c 20 mins after trial.	20-100 m		Thompson <i>et al.</i> (1998)
Common seal	Scotland and Norway	Experimental playback 1 hr exposure	Single gun or small array (215-224 dB re. 1 μ Pa-1 m)			Initial fright reaction. Bradycardia. Strong avoidance behaviour	20-100 m		Thompson <i>et al.</i> (1998)

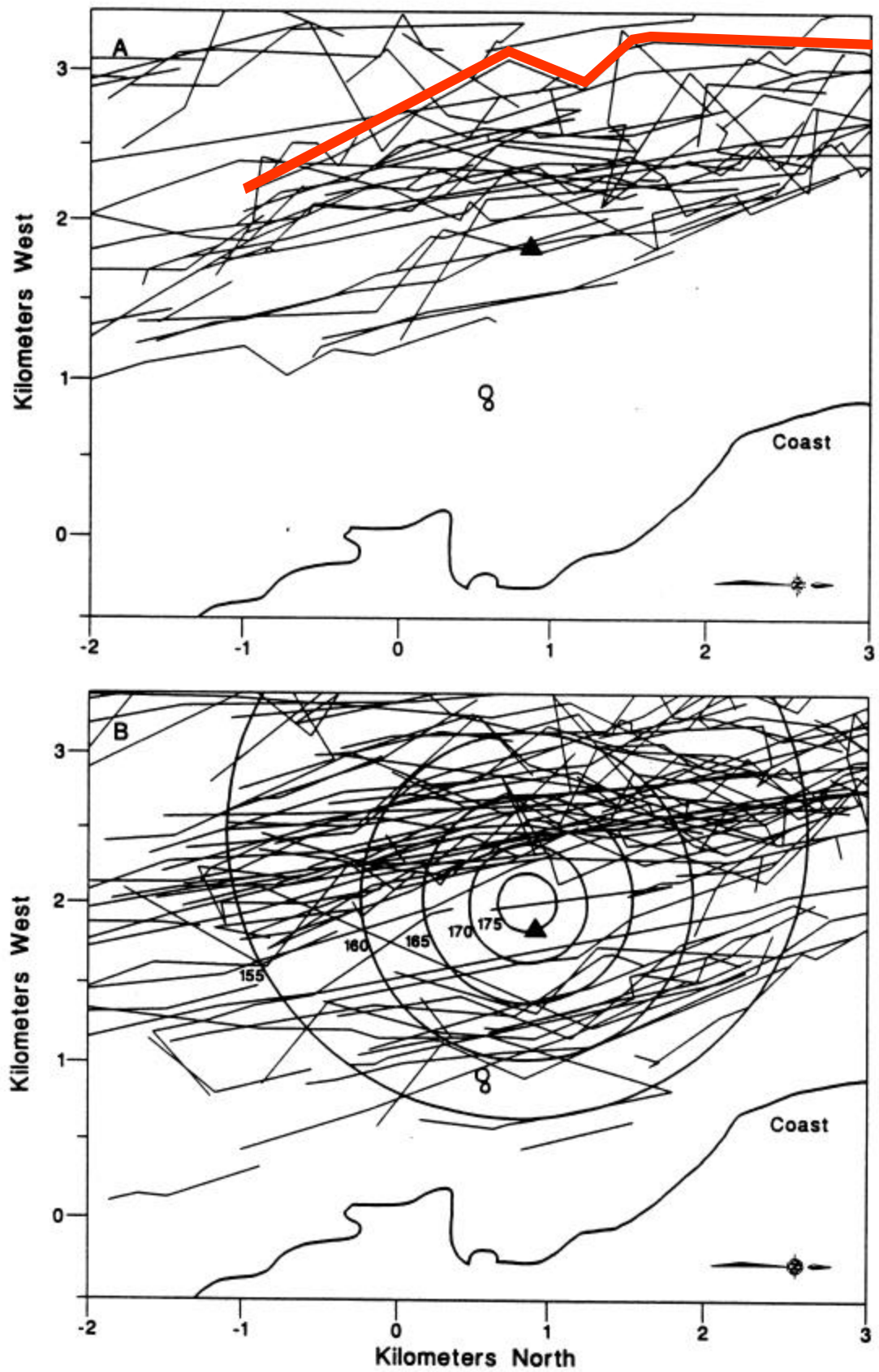


Figure 6.2 Tracks of grey whales migrating along the Californian coast. Upper pannel shows tracks when airgun was silent, lower panel tracks while airgun firing. Range lines indicate approximate received levels of sorce (dB re. 1 μ Pa

prompted this research took place between October and November 1993 and survey tracklines ran across the path of humpback whales migrating south to Southern Ocean feeding ground from breeding grounds to the north (Figure 6.3). Observations were made in conjunction with the main seismic survey from three different platforms: from aircraft

conducting aerial surveys, from the seismic survey vessel itself and from an independent tracking vessel.

Comparison of the onshore-offshore distribution of sightings made during pre-seismic aerial surveys, and the distribution of sightings from the seismic survey vessel did not indicate any gross disruption of the whale's migration route.

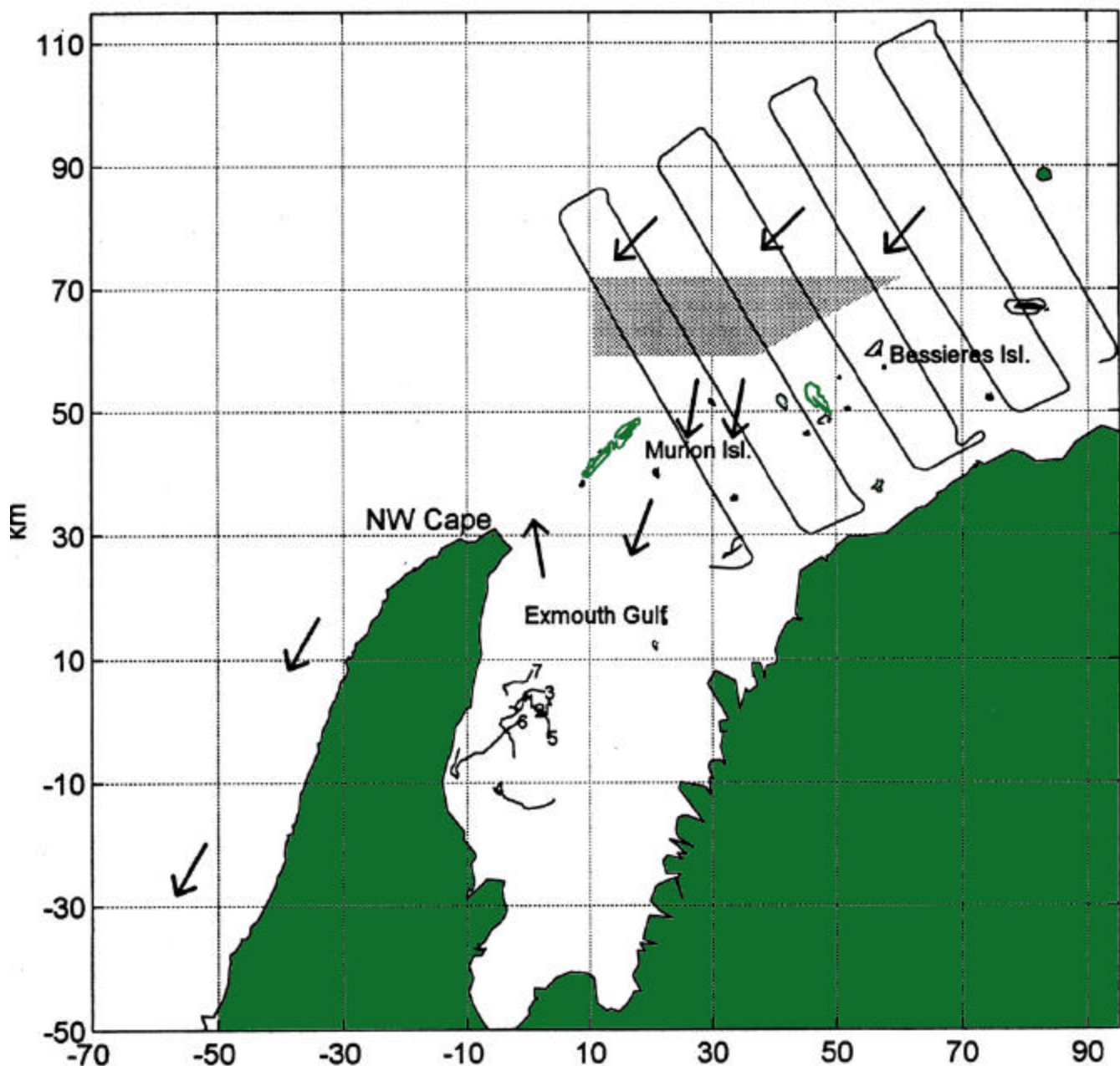


Figure 6.3 Seismic survey tracks and typical routes of humpback whale migrations off Western Australia. Numbered tracks in Exmouth Gulf relate to experiments with small airgun array (from McCauley *et al.* 1998; Courtesy of APPEA)

The tracking boat followed pods of whales as they approached the operating seismic vessel on four occasions. All of these pods responded to the seismic vessel. On one occasion (shown in Figure 6.4), the single whale being tracked showed a dramatic alteration of behaviour, swimming at high speed (10-15 knots) and staying close to the surface so that its tail flukes often broke the surface while swimming. The whale passed 1,500 m ahead of the seismic vessel, slowing when some 3 km beyond it and eventually resuming its previous course when 6 km south of the seismic vessel. Two of the other pods that were followed showed less dramatic course changes at ranges of 5-8 km to pass 3-4 km behind the survey vessel. The fourth pod followed an erratic zigzag course and eventually passed approximately 3 km behind the survey vessel. On two occasions during tracking, animals spent an unusually high proportion of time at the surface. The authors speculated that this could be due to a reduced sound level in surface waters due to the Lloyd's mirror effect explained in section 3.2.5.

Observations made from the seismic vessel were used to compare sighting rates for monitoring periods when guns were on with periods when they were off. These showed that proportionally more animals were seen within 3 km and relatively fewer at ranges of greater than 3 km during periods when guns were off. In fact, sighting rates at ranges greater than 3 km were some 3 times higher during guns on than guns off periods. These observations are consistent with whales avoiding the survey vessel out to ranges of c.3 km and more. Total sightings rates were highest during 'transition periods', the periods when guns were turned on and when they were turned off. It was suggested that this could be a startle effect, or curiosity, causing whales to come to the surface.

Experiments using a small airgun array under the control of experimenters were conducted in an adjoining bay (Figure 6.3). During playback experiments humpback groups were approached by a vessel deploying the active air gun array and its movements were tracked by a dedicated tracking vessel. Figure 6.5 shows the tracks of a whale, tracking vessel and playback vessel during a typical experiment. Whales generally showed speed and course changes to avoid coming closer than 1-2 km from the airgun vessel. However, on several occasions humpbacks were observed to approach and circle the seismic vessel at ranges within 100-400 m (expected exposures 192-177 dB re. $1 \mu \text{Pa}^2 \text{p-p}$, from McCauley *et al.* 1998).

In summary, humpback whales showed avoidance behaviour at a range of 5-8 km from a full-scale array and maintained a stand-off range of 3-4 km. Typical received levels at 5 km were measured as 162 dB re. $1 \mu \text{Pa}^2 \text{p-p}$. During the trials with a smaller airgun, avoidance was evident at 2 km at which received levels were 159 dB re. $1 \mu \text{Pa}^2 \text{p-p}$.

McCauley *et al.* (1998) also commented on the likelihood of different classes of humpback whales exhibiting different levels of sensitivity. They reasoned that mothers and calves were most likely to be disturbed, while males, perhaps primarily motivated to seek mates, might be least likely to alter their behaviour in response to seismic

surveys. The authors also suggested that males might even confuse seismic pulses with the noise made by the flipper slaps and lob-tails of competitors.

Much of the data collected during this study has yet to be presented and no doubt when it is it will reveal more details of the effects of seismic pulses on this species. This productive research project is an exciting example of the useful insights that can be gained when a substantial long-term study is conducted with a reasonably tractable species in an area with favourable field conditions. The integration of several different research techniques, including detailed tracking of individuals and experiential playbacks, has provided a more complete understanding of responses and helped with their interpretation.

6.4.4.1.4 *Blue whales*

McDonald *et al.* (1995) tracked the locations, and inferred the movements, of blue whales by analysing data from an array of seismometers mounted on the seafloor. On one occasion, a blue whale was tracked while an active seismic survey vessel was moving through the area. The seismic array being deployed was a relatively low-powered research array and consisted of four airguns with a total capacity of 1,600 cu. in. and a source level of 215 dB re. $1 \mu \text{Pa}_{\text{p-p}}$ @ 1 m over a 10-60 Hz band. The location of blue whale vocalisations, the whale's assumed track and the track of the seismic vessel are shown in Figure 6.6. Initially, the whale was tracked moving at a speed of about 10 km/hr on a course converging with that of the vessel. At a range of 10 km from the seismic vessel (received level for the seismic pulse in the 10-60 Hz band was calculated to be 143 dB re. $1 \mu \text{Pa}_{\text{p-p}}$) the whale stopped vocalising. After a silent period of around an hour, a whale (presumed to be the same one) began to call again at a range of 10 km. This whale then proceeded to move on a course that diverged from that of the seismic vessel by about 80° and from its original course by c. 120° . If this change in course is evidence of avoidance of the seismic vessel, then it indicates that blue whales are probably rather more sensitive to disturbance by air guns than humpbacks, bowheads or grey whales.

6.4.4.1.5 *Other rorquals*

Stone (1997, 1998) summarised reports from seismic vessels operating around the British Isles, collated by the UK Joint Nature Conservation Committee. Most of these seismic vessels were operating along the 'Atlantic Frontier'. Minke whales (*Balaenoptera acutorostrata*) and fin/sei (identification was not always possible to the species level) were sighted significantly further from the seismic vessels when guns were firing than when they were not, suggesting active avoidance. The swimming speed of fin whales was also reported as being higher during firing.

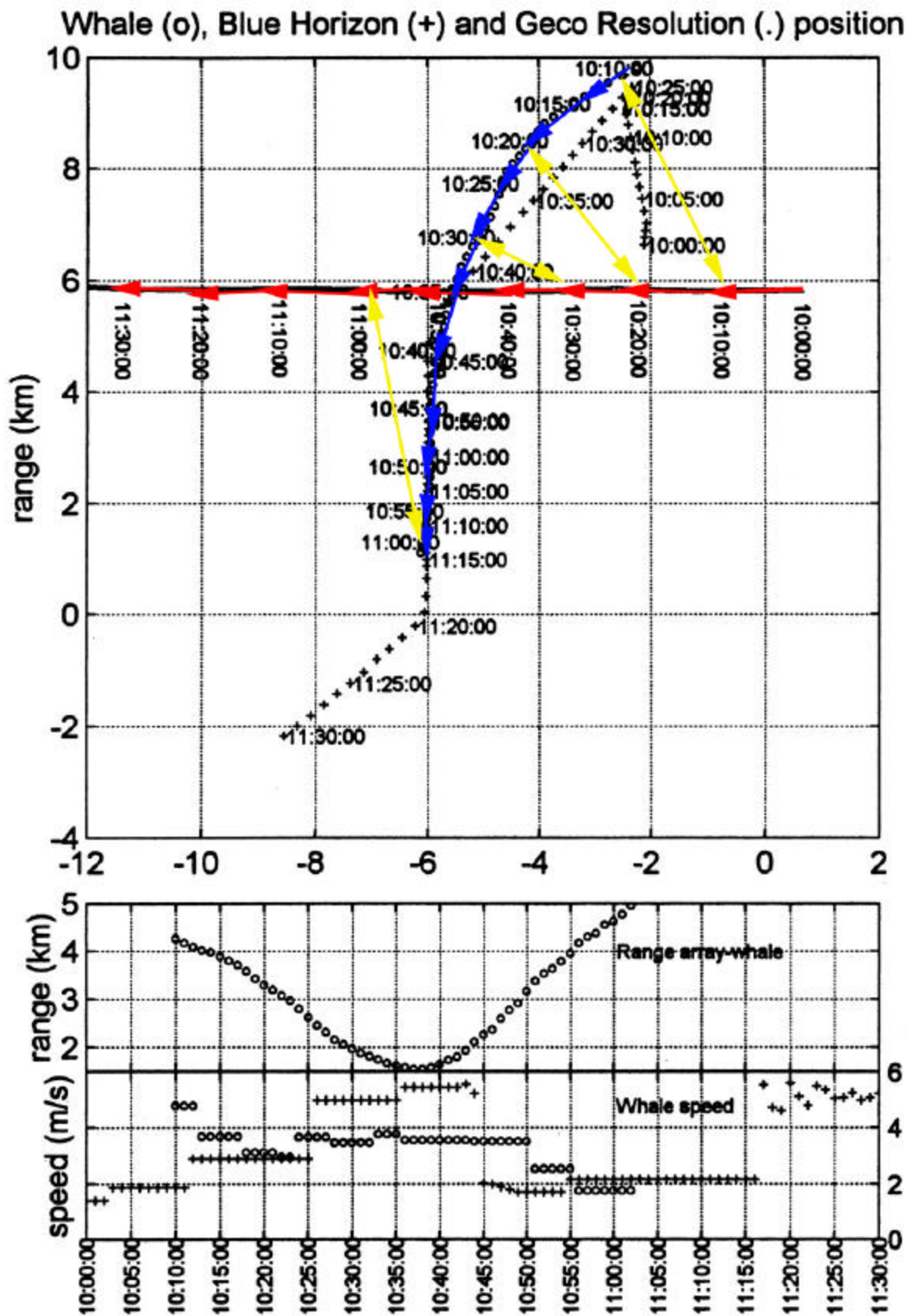


Figure 6.4 Track of an active seismic vessel (Geco Resolution), cetacean tracking vessel (Blue Horizon) and humpback whale as the whale avoids the seismic vessel. (from McCauley *et al.* 1998; Courtesy of APPEA)

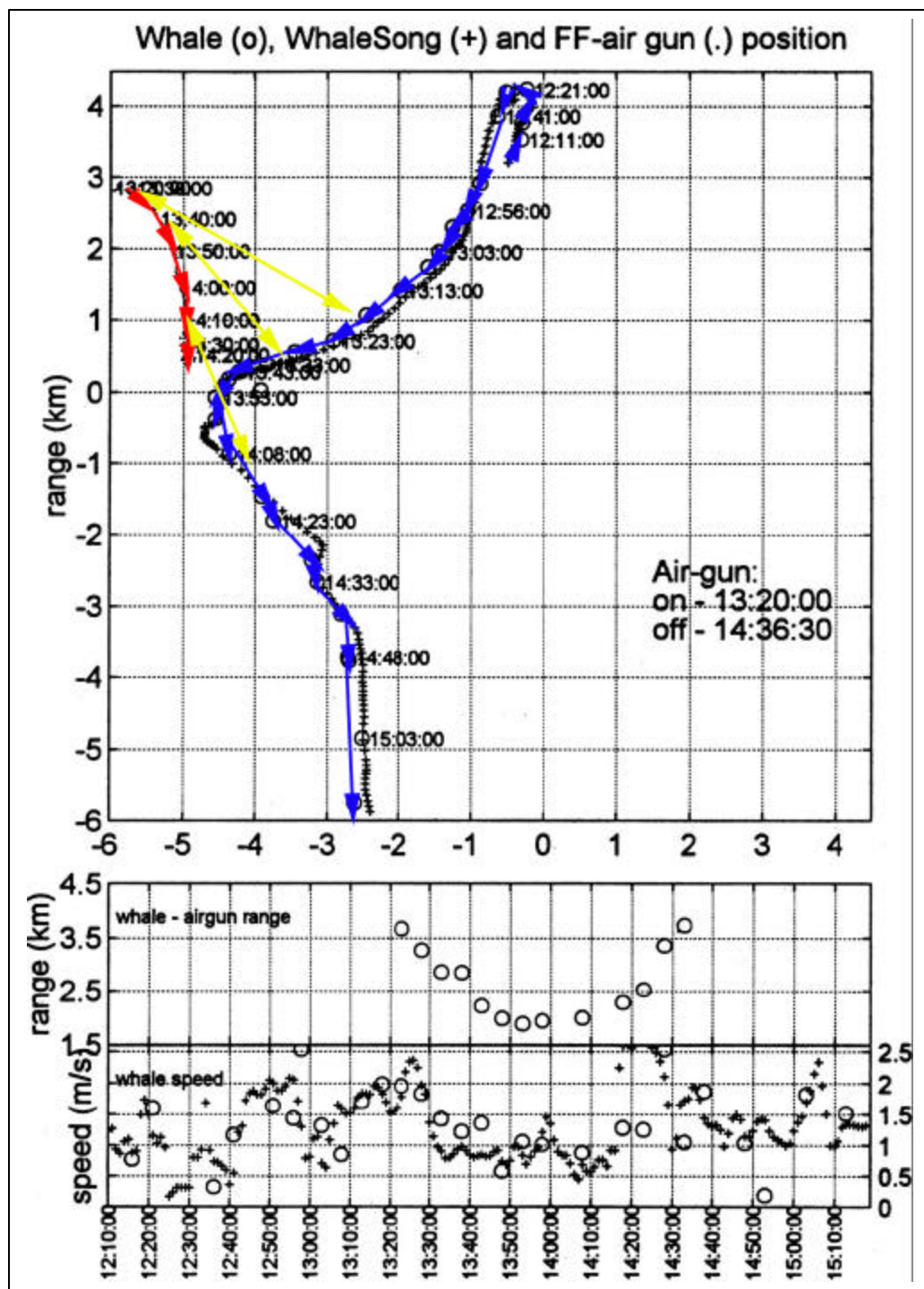


Figure 6.5 Tracks of small airgun source, cetacean tracking vessel and humpback whale during experimental playback in Exmouth Gulf, Western Australia. (from McCauley *et al.* 1998; Courtesy of APPEA)

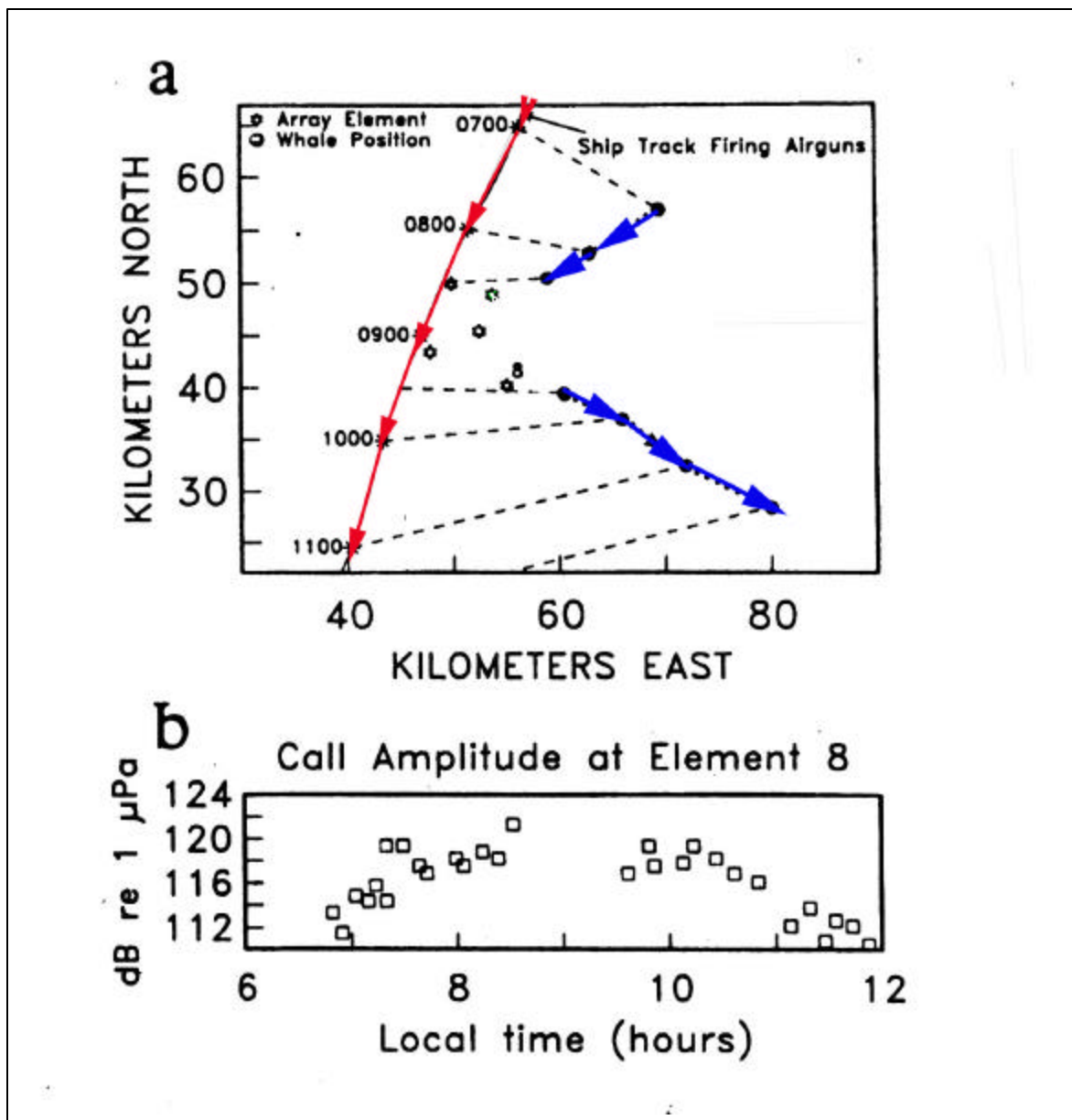


Figure 6.6 Tracks of research vessel deploying active research seismic source and acoustic locations of blue whale. Dotted lines join locations of boat and whale at the same moments in time. Stars "*" indicate the location of hydrophones in the monitoring array. (From MacDonald *et al.* (1995) with the permission of the Journal of the American Acoustical Society.

6.4.4.2 Toothed whales and dolphins

The effects of seismic surveys on odontocetes have generally been less thoroughly investigated than effects on baleen whales.

6.4.4.2.1 Dolphins and porpoises

Two studies were carried out during phases of seismic exploration in the southern Irish Sea in 1993 (Evans *et al.* 1993; Baines 1993). Baines (1993) presented data collected from an aerial survey, boat-based sightings surveys and a

land-based harbour porpoise (*Phocoena phocoena*) observation program. Although some of these observations suggested changes in harbour porpoise and bottlenose dolphin behaviour at the beginning of the seismic survey, observer effort was insufficient to obtain evidence of causal effects, and the results were inconclusive.

Evans *et al.* (1993) made sightings from a guard vessel working with a seismic survey vessel off the Welsh coast and from two other boats working closer inshore. Comparisons were made between cetacean encounter rates before, during and after the seismic survey. There were indications of a significant decline in the numbers of

bottlenose dolphins in the study area, but not in the number of dolphin groups. There were too few harbour porpoise sightings from either the guard vessel, or boats working closer inshore, to test for significant differences in relative abundance during the study period. Evans *et al.* (1993) concluded that “constraints on survey design prohibited an adequate test of the effects of seismic activities upon cetaceans”.

Goold (1996) studied the relative abundance of common dolphin (*Delphinus delphis*) before, during, and after seismic surveys off the coast of Wales. Dolphins were monitored in the survey block using acoustic monitoring equipment deployed from a guard boat. Initial surveys were completed just before the start of the seismic survey. During the seismic survey itself, the guard boat was constrained by its primary duties to remain close to the seismic survey vessel. Thus, during seismic surveys, cetacean occurrence was only measured near the seismic vessel. Percentage acoustic contact with dolphins was lower throughout the seismic survey than before it, and was lowest during periods when the guns were actually firing. In addition, fewer dolphins were observed bow riding during seismic surveys. These results were taken to indicate that within 1 km dolphins found the signals from a seismic source to be distressing. In a later paper, Goold & Fish (1998), reported a single occasion on which a common dolphin remained at an average distance of 1.34 km and a closest distance of 1.1 km for over two hours but this seems to have been a singular and exceptional event.

Gordon *et al.* (1998) reported on experimental playbacks to harbour porpoises in inshore waters around Orkney using a small source (3*40 cu. in. airguns; source level c.228 dB re. 1 μ Pa_{0-p} @ 1 m), and observations of harbour porpoise relative abundance made during commercial seismic surveys. In both cases, porpoise groups were detected acoustically using semi-automated detection equipment (Chappell *et al.* 1996). During experiments in inshore waters, no changes in the rate of acoustic contact as a result of exposure to the small array were detected. Harbour porpoises were not excluded from an area of preferred habitat by short-term exposure to this modest source. The authors caution however, that these results only apply to the very precautionary experimental approach that they employed which involved using a small source and short exposure periods.

Detections of porpoises were also made, using the same detection equipment, from a guard vessel during full-scale seismic surveys to the north of Shetland. The guard vessel kept station about one mile ahead of the seismic vessel. There were no significant differences in acoustic detection rates for porpoises during periods when the guns were on and when they were off (during turns between lines for example). This might be taken as lack of evidence for avoidance by harbour porpoises at ranges of a mile and more, though it is of course possible that avoidance could occur at shorter ranges than this.

Probable avoidance of active seismic sources by odontocetes is suggested by analysis of the reports of observers on seismic vessels off the UK collated by the UK Joint Nature Conservation Committee (Stone 1997; Stone

1998). Both white-beaked (*Lagenorhynchus albirostris*) and Atlantic white-sided dolphins (*L. acutus*) were seen less often, and the range to white-sided dolphins sightings was greater, during periods of seismic array activity (guns-on) than inactivity (guns-off). Conversely, more pilot whales (*Globicephala melas*) were seen during periods of firing than periods of silence (Stone 1998). It could be that these contrasting responses represent the adoption of different avoidance strategies by the two species: the faster moving dolphins escape, while pilot whales may come closer to the surface because they are alarmed or because the sound levels are lower there. Other observations in Stone (1998) suggest that pilot whales seen at the surface were attempting to avoid the seismic source. They were more likely to be recorded as moving quickly and to be heading away from the seismic vessel during periods of gun activity than periods of silence.

6.4.4.2.2 *Sperm whales*

It is generally accepted that the largest of the toothed whales, the sperm whale, is likely to have better hearing sensitivity at low frequencies than other odontocetes, and may thus be more vulnerable to disturbance from seismic surveys. Mate *et al.* (1994) reported that whales moved out of what seemed to be an area of high abundance off the Louisiana coast in the Gulf of Mexico after a seismic survey started in the area. Sperm whale density had been reduced to approximately 1/3 of pre-survey levels after two days and they were completely absent from the area after five days. The authors acknowledged that this was a single opportunistic observation rather than a planned study, but suggest that it should at least serve to prompt further investigation to ensure that surveys do not exclude sperm whales from important habitat. Sperm whales were also reported to temporarily vacate the waters off Kaikoura after a seismic survey (Liz Slooten, pers. comm. Cited in IFAW 1996).

Indications that sperm whales respond to seismic surveys at extreme ranges come from observations made in the Southern Ocean by Bowles *et al.* (1994). They reported that sperm whales did not vocalise during periods when a seismic survey vessel was heard firing at a range of 370 km. These would seem not to have been merely startle or curiosity responses to a novel stimulus, as the seismic source was audible to the researchers over the two weeks in which they listened in the area, and the seismic vessel had been surveying for some time before the start of their study. (The seismic survey vessel was using an array of 8 x 161 Bolt airguns with an estimated source level of 263 dB. At these extreme ranges, the seismic pulses had a duration of c. 3 secs, ranged in frequency from 30-500 Hz and received levels of 120 dB re. 1 μ Pa were measured at a range of 1,070 km.)

In contrast to these reports of extreme sensitivity, other observations suggest that sperm whales are not excluded from habitat by seismic surveys (e.g. Rankin & Evans 1998; Swift 1998). Swift (1998) used acoustic monitoring techniques to determine the relative abundance and distribution of sperm whales in a survey block west of UK,

close to Rockall. Sperm whale abundance was monitored before, during and after the seismic survey. Acoustic detection rates were actually higher during the seismic surveying period than before and after the survey. It is possible that whale density did actually increase in response to the seismic survey, sperm whale in this area, with long experience of seismic surveying, might have learned to feed on debilitated fish for example. More probably, changes in detection rates were the result of a seasonal change in sperm whale distribution.

Swift (1998) also found no significant difference in detection rates between 'guns on' and 'guns off' periods during the seismic survey itself, suggesting a lack of short-term responses as well. However, it should be remembered that, using hydrophones, these researchers were able to detect sperm whales at ranges of c. 5 miles and this may have made changes in behaviour and distributions at lesser ranges more difficult to detect.

Sperm whale vocalisations consist of series of regularly spaced clicks. These are superficially similar to seismic pulses in that they are both powerful transients. It has been suggested that because they make these types of noises themselves, sperm whales may be less susceptible to damage by them. On the other hand, if sperm whales did perceive seismic pulses as resembling their own vocalisations, then masking and disturbance effects might be expected to be more severe in this species.

6.4.4.3 Pinnipeds

There have been surprisingly few studies of the effects of seismic air gun noise on pinnipeds, even though members of this group have good underwater hearing and their feeding grounds will often overlap with seismic survey areas. When Richardson *et al.* (1995) reviewed the subject, they could only find two anecdotal reports, and both suggested that seals did not react strongly to seismic. Recently, detailed observations of the behavioural and physiological responses of harbour and grey seals (*Halichoerus grypus*), have been reported by Thompson *et al.* (1998). These researchers conducted 1 hr controlled exposure experiments with small airguns to individual seals that had been fitted with telemetry devices (source levels of the airguns used were 215-224 dB re. 1 μ Pa p-p). The telemetry packages allowed the movement, dive behaviour and swim speeds of the seals to be monitored and thus provided detailed data on their responses to seismic pulses. Two harbour seals equipped with heart rate tags showed evidence of immediate fright responses when playbacks started. Their heart rates went down dramatically from 35-45 beats/min to 5-10 beats/min. However, these responses were short-lived and following a typical surfacing tachycardia; there were no further dramatic drops in heart rate. In six out of eight trials with harbour seals, the animals exhibited strong avoidance behaviour, swimming rapidly away from the source. Only one seal showed no detectable response to the guns and approached to within 300 m of them. The behaviour of

harbour seals seemed to return to normal soon after the end of each trial.

An avoidance response was seen during all trials with grey seals; they changed from making foraging dives to v-shaped transiting dives and moved away from the source. Some seals hauled out (possibly to avoid the noise); those that remained in the water seemed to have returned to pre-trial behaviour within two hours of the guns falling silent. The authors comment that responses to more powerful commercial arrays might be expected to be more extreme, longer lasting and to occur at greater ranges.

6.4.4.4 Habituation sensitisation and individual variation in responsiveness

One thing that is clear from the above review is that, even within species, the behavioural responses of marine mammals to seismic are quite variable. Perhaps this should not surprise us. A host of factors may affect an animal's response to a particular stimulus including: 1) its previous experience of it; 2) any associations it may have made with that signal; 3) the individual's auditory sensitivity; 4) its biological and social status; and 5) its behavioural state and activity at the time. Thus, by their very nature, behavioural responses are likely to be unpredictable.

Habituation occurs when an animal's response to a stimulus wanes with time. This often results because the stimulus is no longer novel and no aversive events have become associated with it. Animals are most likely to habituate to sounds which are predictable and unvarying. The opposite process is sensitisation, when experience of a signal leads to an increased response. Often, sensitisation will occur when an animal learns to associate a sound with a harmful or unpleasant event. In such cases, animals might be expected to respond to signals when they were only just audible. The calls of predators are one example of signals in this class. In the case of seismic sounds, one might conceive that an animal that had been exposed to levels of sound at a level high enough to cause discomfort might show avoidance responses at a lower level on subsequent exposures, while other animals, which had only been exposed to lower levels, might become habituated. Thus, quite different response behaviours might become established in different individuals.

Within a species, different classes of individuals might be expected to be differentially vulnerable and/or responsive. For example, a mother nursing a young calf might be expected to be more likely to show avoidance behaviour than a male guarding a breeding territory.

Finally, the animal's behavioural state might make it more or less likely to exhibit disturbance behaviour: animals that are resting or engaged in some non-essential activity would be expected to show greater behavioural change than animals highly motivated to perform an important activity, such as feeding or mating.

6.4.4.5 Long term behavioural responses and exclusion

There have been no directed studies to investigate whether or not repeated seismic surveys in an area can lead to long-term disturbance and exclusion from habitat. However, some authors have drawn attention to examples where repeated seismic surveys do not appear to have caused animals to desert areas of preferred habitat. For example: grey whales continue to migrate along the west coast of America (Malme *et al.* 1984); bowheads are still found in the Beaufort Sea each summer (Richardson *et al.* 1987); and bottlenose dolphins are still resident within the Moray Firth (Turnpenny & Nedwell 1994; Evans & Nice 1996), in spite of repeated seismic surveying activity within these areas. We should, however, be cautious in deriving much reassurance from these observations. In the first place, such observations tend to be qualitative: they are not backed up by either quantitative surveys or analysis to show what the population levels might have been in the absence of airgun noise. Further, moving to a new habitat, or changing a migration route, represent very drastic undertakings for members of any population. At first sight, the ocean may seem like a single, homogenous and largely empty habitat

but this isn't the case. Different species will often have very specific habitat requirements in terms of water depth, temperature and oceanographic conditions. Even in offshore waters, groups of animals may have quite limited and well-defined home ranges. The northern bottlenose whale (*Hyperoodon ampullatus*), whose range is restricted to a small area on the edge of the continental shelf, the Gully off Nova Scotia, is one example (Whitehead *et al.* 1997). In addition, the habitat may be effectively full: marine mammals may not be able to move to other blocks of suitable habitat, even if they exist, because other animals are already living there.

The stress of having to remain within a habitat subject to a harmful or aversive signal could have damaging physiological and behavioural effects (see section 6.4.5), and leave animals vulnerable to disease. In the particular context of the Moray Firth, for example, it is interesting to note that a high proportion of animals now exhibit serious skin lesions (Wilson 1995). There is no evidence that stress due to acoustic disturbance has caused these, but unexplained health problems within cetacean populations, like this one, with a long history of exposure to seismic surveys, should serve as a warning against making complacent assumptions.

6.4.5 Chronic effects and stress

In man, sound, even at quite low levels, is a cause of stress and can lead to a number of health problems resulting from the chronic activation of stress-related hormonal complexes. Elevated levels of noise are also known to impair some mental and psychomotor functions in man (Kryter 1994). Of course, noise also disrupts normal sleep and rest patterns in man and other mammals. In humans for example, levels between 30 and 80 dB above threshold are sufficient to waken sleeping individuals (Kryter 1994). The long-term disruptive effects of seismic surveys on the normal resting and sleep patterns of marine mammals have generally not been considered; they will be very difficult to demonstrate and quantify, but we must expect them to occur.

In mammals, stress is often associated with release of the hormones ATCH (adrenocorticotrophic hormone) and cortisol. For example, transportation stress (associated with noise and vibrations) is evidenced by elevated plasma cortisol levels in domestic animals, e.g. pigs (Dalin *et al.* 1993; McGlone *et al.* 1993) and goats (Greenwood & Schutt 1992). Increases in hormone levels are typically also associated with changes in behaviour, e.g. increased

aggression, changes in respiration patterns or social behaviour; they can lead to harmful physiological effects and a reduction in the effectiveness of the immune system.

Thomas *et al.* (1990) attempted to measure stress induced in four captive belugas by playback of recordings of drilling platform noise (source level 153 dB re. 1 μ Pa-m). Levels of catecholamines in blood samples did not increase during the experiment. However, the authors noted that playbacks were relatively short and the captive animals used as subjects may have already adapted to living in a noisy and stressful environment.

Even in humans, the role that sound plays in causing a variety of serious stress-related complaints is often far from obvious and we must assume that it will be very difficult to prove that such effects occur in wild marine mammals in the field. In spite of these problems, the potential for noise-induced stress to have effects on so many aspects of the health of individuals and populations makes it a matter of real concern.

6.4.6 Indirect effects

Noise may indirectly impact cetacean populations through its effects on prey abundance, behaviour and distribution.

6.4.6.1 Fishes

Bony fish are particularly vulnerable to intense sound because of the presence, in most of them, of a large air-

filled swim bladder. Although marine fish typically have less acute hearing than marine mammals their hearing is most sensitive at frequencies between 100 and 500 Hz where most seismic sound is produced. At these frequencies, their hearing is certainly more sensitive than that of the odontocetes studied so far. Effects of air gun pulses on fish range from serious injury at short ranges, to

avoidance behaviour, possibly at the range of many kilometres (Turnpenny & Nedwell 1994). Reduced catch rates have been reported for several species of fish in areas of seismic surveying activity (See review in McCauley 1994). In a series of controlled experiments, Skalski *et al.* (1992) demonstrated a 50% decline in catch per unit for rockfish (*Sebastes* spp.) during exposure to noise from airguns. They attributed this to changes in behaviour that made fish less likely to be caught in fishing gear rather than dispersion of fish aggregations. They did not indicate how long these effects lasted. Bohne *et al.* (1985) found decreases in average fish abundance, measured acoustically, during a 3D survey in the North Sea. Populations were reduced by 36% for demersal species, 54% for pelagic species, and 13% for small pelagic species, compared with pre-shooting abundance. Engas *et al.* (1993) found an average 50% reduction in catch and availability of cod and haddock within a 20 nm radius of an operating seismic vessel, and showed a 70% reduction for both these species within the seismic shooting area (a 3 x 10 nm box). Longline catches of both species were reduced by 44% in the seismic shooting area, though at 18 nm from this area they failed to show any reduction in catch. There was some evidence that different classes of fish responded differently.

They report a relatively greater reduction in large (>60 cm) as opposed to small fish (<60 cm) during shooting, but an increase in the number of small cod caught on longlines. They suggested that these results were consistent with displacement from the survey area for both of these species.

6.4.6.2 Invertebrates

Invertebrates may be less susceptible than fish to seismic pulses. Steffe & Murphy (1992), for example, were unable to show any significant effects on prawn catch rates before, during and after seismic surveys.

These studies indicate a variety of effects from seismic pulses on potential marine mammal prey species. If seismic surveys cause fish (or other animals) that are the prey of marine mammals to become less accessible, either because they move out of an area or become more difficult to catch, then marine mammal distributions and feeding rates are likely to be affected. In the long-term, this could lead to effects at the population level. There have, as yet however, been no attempts to investigate this process in marine mammals.

6.5 Marine mammals in a three dimensional environment: the particular vulnerability of deep divers

In assessing the effects of airgun noise, managers have tended to consider zones of influence based on horizontal distances from the sound source. However, as seismic exploration increasingly moves into deeper offshore waters the magnitude of the third dimension, depth, becomes more significant.

All marine mammals dive, in fact many will spend the majority of their lives underwater, and some can spend significant times at very substantial depths. Sperm whales, for example, regularly make dives in excess of 1,000 m (Watkins *et al.* 1993), and have been recorded down to 2,500 m (Norris & Harvey 1972). Beaked whales are also known to be impressive deep divers, possibly exceeding the abilities of sperm whales. Beaked whales are a cause of particular concern. Their biology is very poorly known but in some areas they appear to have discrete offshore home ranges (Whitehead *et al.* 1997). There is also evidence that they are particularly vulnerable to being disturbed, to an extent leading to stranding and death by military activities (Simmonds & Lopez Juado 1991); and powerful sonar (Frantzis 1998). Some seals are even more accomplished divers than cetaceans. For example, elephant seals have been recorded at depths greater than 1,000 m (Delong & Stewart 1991).

Deep divers are worthy of special consideration for a number of reasons. Diving takes them into regions in which received levels are higher than those measured or predicted close to the surface, including the zones beneath air gun arrays in which most sound is focused. A diving animal is also committed to a strict energy budget, which ensures that the oxygen stores within its body are managed to allow the animal to dive to a certain depth for a particular length of time. These considerations may mean that a diving animal's options for avoiding loud noise sources are constrained and the consequences of their taking avoiding action may be greater than they would at first seem.

A diving mammal leaves the surface with stores of oxygen in its blood and muscles that must sustain it through its entire dive. Physiological strategies for making the best use of these reserves include: 1) shutting down non-essential activities such as digestion; 2) restricting peripheral blood flow; and 3) a dramatic reduction in heart rate (bradycardia). Some parts of the body, such as the brain, must be kept supplied with oxygen continuously. During dives, energetic activities are minimised and movement will tend to take place at close to the most energy efficient swimming speed. It is possible for muscles to respire for short periods without oxygen (anaerobically) but this incurs an 'oxygen debt', which is expensive to

‘repay’ both in terms of energetic and time budgets. From the perspective of an animal wishing to avoid loud noise sources, this is likely to mean that strategies involving energetically costly activities, such as rapid swimming, may be precluded, particularly towards the end of dives when oxygen stores will be minimal. It is also likely that the natural response of an air-breathing diver to an unknown threat, will be to head to the surface where they will at least have access to air, but for deep divers this may take them closer to the noise source.

The considerations of the particular restrictions that deep diving behaviour places on marine mammals illustrate how important an appreciation of the animal’s biology can be to

understanding the significance of potential disruptive activities.

Generally of course, submerged divers are not visible at the surface, and some divers, such as elephant seals and sperm whales, may routinely perform dives of between 30 mins and an hour. For animals like these, the fact that observers have not seen them at the surface before starting a seismic line is no guarantee that they are not within the ‘danger zone’. For some species, notably the sperm whale that is highly vocal, acoustic monitoring can provide helpful information on the presence of submerged cetaceans (Chappell & Gillespie 1997). Unfortunately, this is unlikely to be a reliable method of detecting the presence of beaked whales or seals.

6.6 Zones of influence

A useful concept for regulation and management are zones of influence within which different types of effects would be expected to occur. If a uniform field of propagation and attenuation is assumed, these can be represented as a series of concentric circles around a noise source, whose radii are the ranges at which the level of the sound might be expected to have fallen to a certain threshold level. Four zones considered by Richardson *et al.* (1995) are:

- 1) the zone of audibility (the area within which the sound is both above the animal’s hearing threshold and detectable above background noise)
- 2) the zone of responsiveness (the region within which behavioural reactions in response to the sound occur)
- 3) the zone of masking (the zone within which the sound may mask biologically significant sounds)
- 4) the zone of hearing loss, discomfort or injury (the area within which the sound level is sufficient to cause threshold shifts or hearing damage)

The radius of the circle defining each zone will depend on the characteristics of the sound itself, the susceptibility of the animals being considered and the sound propagation characteristics in the survey area. In devising management guidelines and regulations that are appropriate for a particular survey, managers will often decide to use threshold sound levels for certain effects (measured perhaps by research in a different area) and calculate the ranges at which the sound level from the particular source being used will fall to this threshold in the survey area being considered. In these situations, the nature of propagation conditions in the survey area becomes critical.

Seismic exploration around the UK takes place in a wide variety of locations: in the North Sea water depths can be as little as 20 m, whereas along the Atlantic Margins, depths of over 1,000 m may be encountered. The propagation of sound in the ocean is extremely complicated and depends strongly on the local conditions of depth and bottom type,

and on the temperature (and therefore sound velocity) profile of the ocean. The received sound level is also a function of both source and receiver depth. Ideally, detailed modelling and direct measurements should be made for each area of interest.

In the absence of the environmental data needed for more realistic models, researchers often use a generalised propagation loss model of the form $n \log(r)$: where r is range and the value of n depends on the general characteristics of the environment and range.

Close to a seismic source in deep water, spreading of the sound field is assumed to be spherical (with attenuation being given by $20 \log(r)$) out to a distance approximating to the water depth, beyond which point, the sound may spread cylindrically (with an attenuation of $10 \log(r)$). In shallower water, theory suggests that spreading may be cylindrical as the sound is trapped between the seabed and the surface. Sound energy is, however, lost due to scattering on reflection from a rough surface such as the seabed and there are also bottom losses due to penetration and shear-wave conversion. In addition, low frequencies in shallow water would be expected to attenuate more quickly and may also have lower amplitudes very close to the surface due to destructive interference with their own surface echo (this is the Lloyd mirror effect discussed in Section 3.2.5).

In some deep waters, acoustic energy may become trapped in a sound channel, in which case $10 \log(r)$ attenuation would apply and seismic pulses might propagate many 100s or even 1,000s of km.

As might be expected, different propagation models have been found empirically to apply in different locations. In the North Sea, van de Sman (1993) found that spreading of the sound field from a seismic array in 30–40 m water depth was approximately spherical out to a distance of several kilometres while McCauley *et al.* (1998) found that a $25 \log(r)$ spreading model provided a reasonable fit in a water depth of <120 m up to a range of 20 km. The combination of cylindrical spreading with surface and

bottom losses has led some researchers to use 15 log(r) or 17 log(r) propagation models.

For the purposes of investigating the effects of different propagation models, we will assume that sound spreads

spherically within the ranges at which the possibility of physiological impacts on marine mammals (i.e. hearing damage or temporary threshold shift) are considered

Table 3 Ranges (km) for different received levels with different propagation models				
Received level dB _{p-p} re. μ Pa	Model 1 (km) ¹	Model 2 (km) ²	Model 3 (km) ³	Model 4 (km) ⁴
220	0.03	0.10	0.02	0.03
210	0.10	0.46	0.04	0.10
200	0.32	2.2	0.10	0.32
190	1.0	10.0	0.25	1.00
180	3.2	46.4	0.63	10.
170	10.0	215	1.6	100
160	31.6	1,000	4.0	1,000
150	100.	4,641	10.0	10,000
140	316.	21,544	25.1	100,000

¹Model 1: transmission loss = 20 log(r) (spherical spreading)

²Model 2: transmission loss = 15 log(r)

³Model 3: transmission loss = 25 log(r)

⁴Model 4: transmission loss = 10 log(1000) + 10 log(r) (spherical spreading to 1,000 m, then cylindrical spreading).

possible. Modelling the sound field at greater distances is highly dependent on conditions in the sea area of interest, a detailed discussion of which is beyond the scope of this chapter, and several different values are used for comparison.

Clearly, different propagation models produce different results but what is sometimes not well appreciated is the way in which the critical ranges predicted by these models become proportionally larger as the distance from the source increases. Table 6.3 shows the ranges at which various sound levels would be expected using four different models, assuming a source level of 250 dB_{p-p} re. 1 μ Pa. It can be seen that at the relatively high exposure levels of 200 dB (which might define a zone of hearing loss, discomfort and injury), the models differ in their predicted ranges by a factor of 21. However, for a received level of 140 dB (a candidate for a threshold defining a zone of responsiveness) different models predict ranges that vary by a factor 4,000. When these differences are translated into the sea area ensonified, the differences are squared, leading predictions that vary by factors of 16 million times! Clearly, from a

conservation or welfare perspective, our concerns are primarily with the numbers of marine mammals potentially exposed to a given sound level, so area ensonified is the most appropriate parameter to consider.

These models are all oversimplifications, but for each there are real-life situations in which they would realistically apply. It should also be appreciated that, even within a single survey location, propagation conditions may be quite different in different directions from the source (e.g. travelling up or away from the continental shelf) and at different water depths. Propagation conditions will also be expected to vary through the day and seasonally. The huge differences in sea areas exposed to different sound levels that result from differences in propagation characteristics in different areas, especially for those lower sound levels at which behavioural changes might be expected to be our main concern, makes it difficult to extrapolate from one study to another, and impossible to devise reliable range-based management rules in the absence of empirical data or detailed environmental data for reliable modelling of propagation conditions.

6.7 Biological significance of possible effects of seismic pulses for individuals and populations

There are both ethical and legal reasons for being concerned about the welfare of individual animals. In addition to this are concerns for the health and viability of populations and species, irrespective of individual suffering. Much legislation is couched in conservation terms, while public

opinion often responds strongly to animal welfare issues. Economically important human activities, such as whaling or whale-watching, can be affected if the behaviour of individual animals is altered, in ways that make them less easily approachable for example.

6.7.1 Hearing damage

Hearing is the most important sensory modality for marine mammals underwater and the ability to hear well seems to be vital in many important aspects of their lives such as finding food, navigating, locating mates and avoiding predators. It would seem indisputable then that any reduction in hearing ability very seriously compromises the

viability of individual animals. If a significant proportion of the population was affected in this way, there could be deleterious conservation consequences as well. In addition, exposure to high levels of noise could have animal welfare implications if, for example, it induced panic or caused pain.

6.7.2 Perceptual and behavioural effects

The biological significance of behavioural effects is much more difficult to assess. Masking of biologically significant sounds by background noise can be considered to be equivalent to a temporary loss in hearing acuity. Little is known about the importance to marine mammals of hearing low-level sounds in background noise but the very fact that they have developed such sensitive hearing, and seem to be adept at detecting signals in background noise, suggests that this is an important ability for them.

The significance of disruption of behaviour in part depends on the importance of the behaviour being disrupted. Small-scale course changes to avoid surveys during migrations, such as those measured for grey whales by Malme *et al.* (1986), might, in themselves, seem to have few long-term consequences for individuals or populations. The consequences might be more serious in areas where many surveys are occurring simultaneously, such as the Atlantic Margin. In some cases, alterations in migration paths could move animals into dangerous areas. For example, Simmonds & Mayer (1997) suggested that seismic surveys being conducted to the west of the British Isles might have contributed to recent live multiple sperm whale strandings in the North Sea if they caused southward-moving animals to divert to the east of their normal course and into the North Sea. Once within this shallow restricted sea, a deep-sea animal, unaccustomed to shallow waters, might be effectively trapped and eventually strand.

Disturbance could lead to disruption of feeding and deep diving animals could be particularly vulnerable in this respect. If sperm whales use their vocalisations to echolocate, as most believe they do, then the cessation of vocalisations observed by Bowles *et al.* (1994) in the

Southern Ocean in response to seismic at ranges of hundreds of kilometres, would have stopped those animals feeding. In this case, the effects were evident at such extended ranges that hundreds or thousands of animals might have been affected. Seismic surveys could have dramatic effects on the availability of marine mammal prey, especially fish (section 6.4.6.1). Reduced feeding will ultimately lead to reduction in reproductive rates and increases in mortality. However, most marine mammals are adaptable and opportunistic feeders, and the large whales in particular, have evolved to survive for extended periods without feeding.

Disruption of social organisation could have severe consequences for those animals, such as the toothed whales, for which long-term social groupings seem to be important for survival. Payne (1995) stresses the importance of long-range communication in keeping cetacean groups together and introduces the concept of a 'heard' of whales: animals that keep together because they can hear each other's vocalisations. Baleen whales can potentially hear each other over tens or hundreds of kilometres. Sperm whales can probably also hear other sperm whales at ranges of tens of kilometres (pers. obs.). Acoustic disturbance could cause social groups to break down, while increased levels of background noise could hamper the ability of members of dispersed groups to find each other and keep in contact using vocalisations.

Mothers and their dependent calves are probably the elements of populations that are most vulnerable to disturbance. In some species of odontocetes, calves remain with their mothers for several years. Disruption of this bond could leave calves open to a number of dangers,

including predation, interference from conspecifics and stranding, and, of course, nursing calves separated from their mothers, would be unable to feed.

These potentially damaging or disturbing effects of seismic surveys cannot be considered in isolation. Marine mammals are subject to a host of depredations and insults, some of these are natural, but to an increasing extent, many of them are man made. It is the combination of all of these that may lead to biologically significant effects. Some factors will interact and may act synergistically. For example, chronic effects due to disturbance, stress or chemical contamination may weaken the immune systems of individuals making them more vulnerable to disease. With marine mammals becoming subject to an increasing

number of new threats whose effects are likely to be cumulative, it is important to minimise the impacts of all and any of them wherever possible.

There is at present, little or no direct evidence for biologically significant effects of seismic surveys on marine mammals but it must be appreciated that none of the research projects that have been conducted so far have been capable of adequately testing for effects at this level. The fact that plausible cases can be made for some of the responses that have been observed, or are thought possible, resulting in biologically significant effects, is an indication that this is a potential problem that deserves to be taken seriously.

6.7.3 Measuring biologically significant effects

From the discussion in the previous section it is clear that there are reasons to be concerned that seismic surveys could lead to biologically significant effects on marine mammal populations, but such effects have not been measured. This begs the question of what sort of monitoring schemes should be put in place to quantify these. There are two problems: the first is to show that the size or distribution of a population has actually changed significantly; the second is to show that any such change is caused by the effects of seismic surveys. Measuring a change in the size of cetacean population is particularly difficult requiring an intensive survey effort over an extended period. Given the lack of precision that characterises most cetacean surveys (typical CVs of 0.14-0.4), it is likely that, even with intensive levels of effort, only substantial changes in population sizes would be detected. For example, Clarke *et al.* (1998) used modelling to determine the amount of aerial surveying effort that would be required to detect a certain percentage decline in a porpoise population at the 5% level of significance. The model used, estimates for survey precision based on those achieved during the SCANS survey Hammond *et al.* (1995), the largest survey for small cetaceans conducted in European waters. Required survey effort increased as population density decreased. At population levels typical for the Baltic sea, detecting a 20% decline would require c. 500 hrs of aerial survey effort while detecting a 10% decline would require many thousand hours. The authors concluded that conventional surveying methods are not appropriate for monitoring even quite large changes of in abundance for regions with low abundance. Wilson (1995) used a similar power analysis approach to investigate how well population trends might be detected using photo-identification and mark-recapture techniques, assuming a level of effort and precision typical of that achieved during his own studies of an inshore population of bottlenose dolphins in the Moray Firth. Again, the results are not encouraging. For example, given annual surveys and a population declining by 5% per year, it would take 11 yrs to show a significant change, by which time the population would have decreased by 43%. No offshore cetacean populations in the North Atlantic are currently being monitored at a level that would allow

population changes to be detected in the short term. The development of more efficient survey techniques, such as those based on acoustic detection, may allow effort to be expended affordably at levels that would allow smaller population changes to be detected for some species (Gordon 1996), and the use of the military SOSUS arrays (e.g. Clark & Charif 1998) which have an ability to detect some species over large areas shows particular promise for some Mysticete whales. However, such methods are not yet widely accepted, analysis methodologies are not well developed and the necessary surveying effort is not being expended. For the present at least, we must accept that in no cases are surveys of cetaceans being conducted with sufficient levels of precision to allow population trends to be detected before the populations themselves have been substantially depleted.

The situation is more encouraging for seals, especially those such as grey seals whose reproductive rates can be measured efficiently with aerial surveys, e.g. Hiby *et al.* (1988).

Even if sufficient survey effort is expended and population trends can be detected it will still be necessary to carry out directed research investigating how seismic affects marine mammals and how these effects could give rise to significant population changes. Without this, it will be difficult to make the case that seismic surveying, and not some other factor, should be controlled to allow populations to recover. Such research requires considerable dedicated field effort to collect data and an in-depth understanding of the biology of the animals involved to allow it to be interpreted. In addition of course, it should be remembered that different factors can act on whales synergistically, in which case controlling any or all of them will be helpful.

While it is essential that work to monitor populations and quantify the effects of seismic surveys is undertaken and continued, we should be realistic about the very low probability of being able to detect any biologically significant effects and link these causally to seismic surveys, in time to be able to take remedial action. Armed with this appreciation of the limitations of the information available it is essential to take a precautionary approach to management.

6.8 Are behavioural responses to noise always adaptive?

It is generally assumed that when marine mammals respond to loud noises they will behave in a way that will reduce the effects of that noise. In the simplest case for example, they will move away from the source. In this section we explore whether this assumption is always justified. Clearly, to be able to move away from a sound a marine mammal first needs to be able to determine the direction from which the sound is arriving. Mammals can achieve this in two ways: by using the time of arrival (or phase differences) of a sound at the two ears, or by attending to intensity differences. Generally, time of arrival information is most useful for transient sounds, phase differences for lower frequency sounds and intensity differences for higher frequencies. Intensity differences depend on the existence of reflective objects close to and between the ears to create a differential sound field. In terrestrial animals, these are typically the head itself and the external pinnae, which are specially adapted for this function. The impedance difference between a mammalian head and water is less than it is for air; thus the head will be a much less effective sound reflector underwater. The speed of sound in water is five times that in air, so for a given frequency, sound wavelengths are five times as long. This further diminishes the effectiveness of the head as a reflector. It also reduces the difference in arrival time between the two ears for any off-axis sound, making binaural time comparison more difficult.

Richardson *et al.* (1995) review the directional hearing abilities of marine mammals. Dolphins have excellent directional hearing at high (10s of kHz) frequencies but their hearing at lower frequencies has not been tested. Directional hearing in seals is less precise, and again has only been tested at kHz frequencies. The directional hearing of baleen whales has not been studied but they do at least seem to respond directionally to low frequency vocalisations from conspecifics. Observations showing avoidance of airguns, often at considerable ranges, suggest that marine mammals are able to localise them adequately. However, given the particular difficulties of directional hearing underwater, mentioned above, we might be overestimating the ability of marine mammals to do this if we use the excellent human localisation ability in air as a guide.

There may be situations in which difficult propagation conditions hamper appropriate responses. Some underwater environments are highly reverberant and in these conditions localisation of sound sources may be much more difficult. Deep diving animals, in mid water, may hear two or more discrete sources of noise from a single pulse: the sharp seismic 'crack' from the surface and its more reverberant reflection, the 'bang', from the bottom and have to 'choose' which one to avoid (e.g. Figure 6.7). In some areas where exploration activity is intense, such as the Atlantic Frontier,

several seismic sources may be audible in different locations, either at the same time or intermittently. Potentially, this represents a very confusing situation for a marine mammal trying to avoid a disruptive noise source and it may not always behave appropriately.

Due to the poor propagation of low frequency sound in surface layers and destructive interference from surface reflections, sound levels from seismic sources may often be lower close to the surface than would be predicted by simple spherical spreading models. In deep water, at ranges of tens of miles, convergence zones may occur. These zones are a result of upward acoustic refraction in the water column, an effect due primarily to the dependence of sound-speed on water temperature and pressure (Urick 1983). Convergence zones are regions of sound focussing that occur at regular intervals from a source. In these zones sound intensities can be 10 to 15 dB above the level predicted by simple models. Since these zones only occur at substantial ranges, the sound intensity would not reach the levels required for auditory damage. They could, however, be very disorientating for a displaced animal trying to move away from a seismic source, because in moving away from the direction from which the sound was coming the animal would move into a region of increasing sound level.

In deep water, it is also likely that sound energy will enter the deep sound channel. Once in the sound channel, sound will be ducted, resulting in cylindrical rather than spherical spreading. Using simple models, it is not possible to predict the fraction of the energy from a seismic source that might enter a sound channel, but it should be noted that marine mammals in the sound channel would typically be able to hear the seismic source many hundreds of kilometres away.

The possibility that an animal is not adapted to 'appreciate' the potentially damaging consequences of exposure to airgun noise should also be considered. After all, there are innumerable examples of humans willing to expose themselves to damaging levels of noise: from personal stereos and power tools for example. The damaging effect of transients can be particularly difficult to assess. In humans, the auditory system integrates sound over about 0.5 sec to assess loudness. Transients that are much shorter than this (such as a pulse from an airgun at short ranges where auditory damage could occur) may not be perceived as being particularly loud even though peak pressures are high.

One published example, of humpback whales which remained within an area in which blasting was occurring even though this seemed to result in gross damage to their ears, may be an illustration of this occurring in a marine mammal. Lien *et al.* (1993) made behavioural observations of humpback whales off Newfoundland in an area where

explosives were being used for underwater excavation. Behavioural measures, such as residency, rates of re-sightings of identified animals, movements and overall behaviour showed little change during blasting, suggesting that the animals were not greatly affected by these activities. Two humpbacks were found trapped in fishing gear soon afterwards however, and examination of their ears revealed severe damage consistent with blast injuries (Ketten *et al.*

1993). It would appear that these humpbacks had been severely damaged by exposure to shock waves during the earlier explosions. One alarming and sobering conclusion from this is that a good observational research effort did not spot any dramatic changes in behaviour associated with the infliction of this damage. The authors rightly suggest that caution is needed when interpreting the results of impact studies based on visual monitoring of short-term reactions.

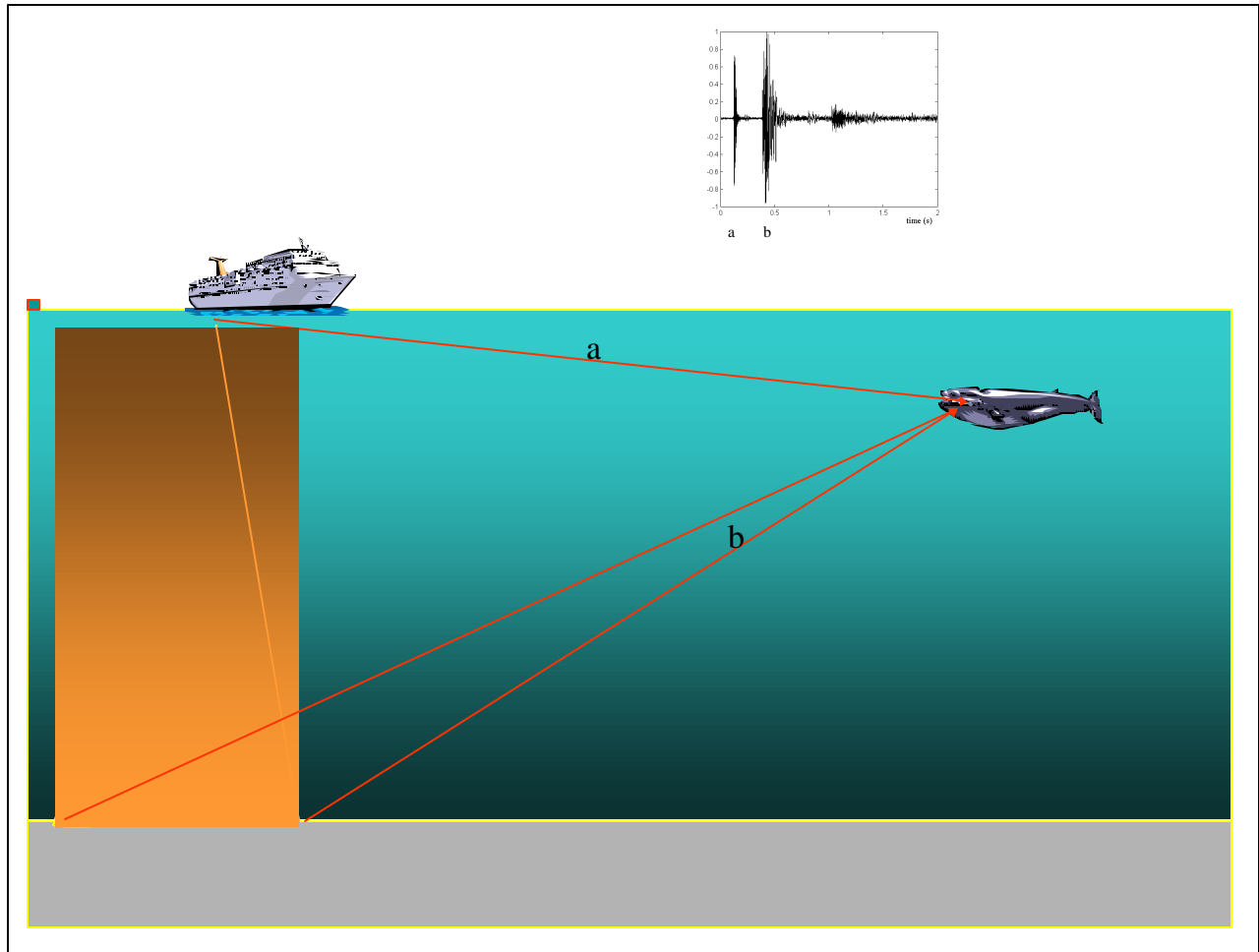


Figure 6.7 A seismic pulse as received by a whale in mid-water. Pulse a is short and sharp and arrives directly from the surface; pulse b is more extended and arrives slightly later from the bottom

6.9 Soft starts

Even if marine mammals were motivated to move away from seismic guns would they be able to do this at a rate fast enough to avoid potential damage? One situation in which such considerations are critical is at the beginning of seismic lines, when guns are first turned on. UK Government voluntary guidelines require ‘soft starts’ to allow animals to move out of the area before the array fires at full rate. ‘Soft starts’ or ‘ramp-ups’ are required mitigation procedures in several other parts of the world as

well (Chapter 7). To achieve a ‘soft start’, seismic operators are advised to increase the power of the airguns over a 30 min period. This is typically done by first turning on the smallest gun and then progressively adding additional guns until the whole array is operational. Peak to peak broadband source levels for a single airgun are typically 220 dB re. 1 μ Pa-m. The power is then increased more or less exponentially to a maximum of 250 dB re. 1 μ Pa-m (typical source level for horizontal propagation). A

critical assumption is that a marine mammal would be able to move away from a source during a 'soft start' at a rate that kept the overall sound exposure below a 'safe' threshold. Is this assumption justified? Figure 6.8 summaries one attempt to investigate this. We have assumed that an airgun array is turned on using a 'UK soft start', as outlined above, and that the target marine mammal swims directly away from the array. The worst case would be if the animal swam away from the seismic vessel down its trackline. Assuming a seismic vessel speed of 5 knots

and a marine mammal escape speed of 8 knots, the two would diverge at a rate of 3 knots. Figure 6.8 shows distances from the source of the 196 dB (possible threshold for auditory damage) and 160 dB (possible threshold for avoidance) as a function of time, for a typical soft start. Also plotted is the distance from the source of a marine mammal swimming away with a relative swim speed of 3 knots. In this case, it is possible for the animal to stay clear of sound exposures at levels of

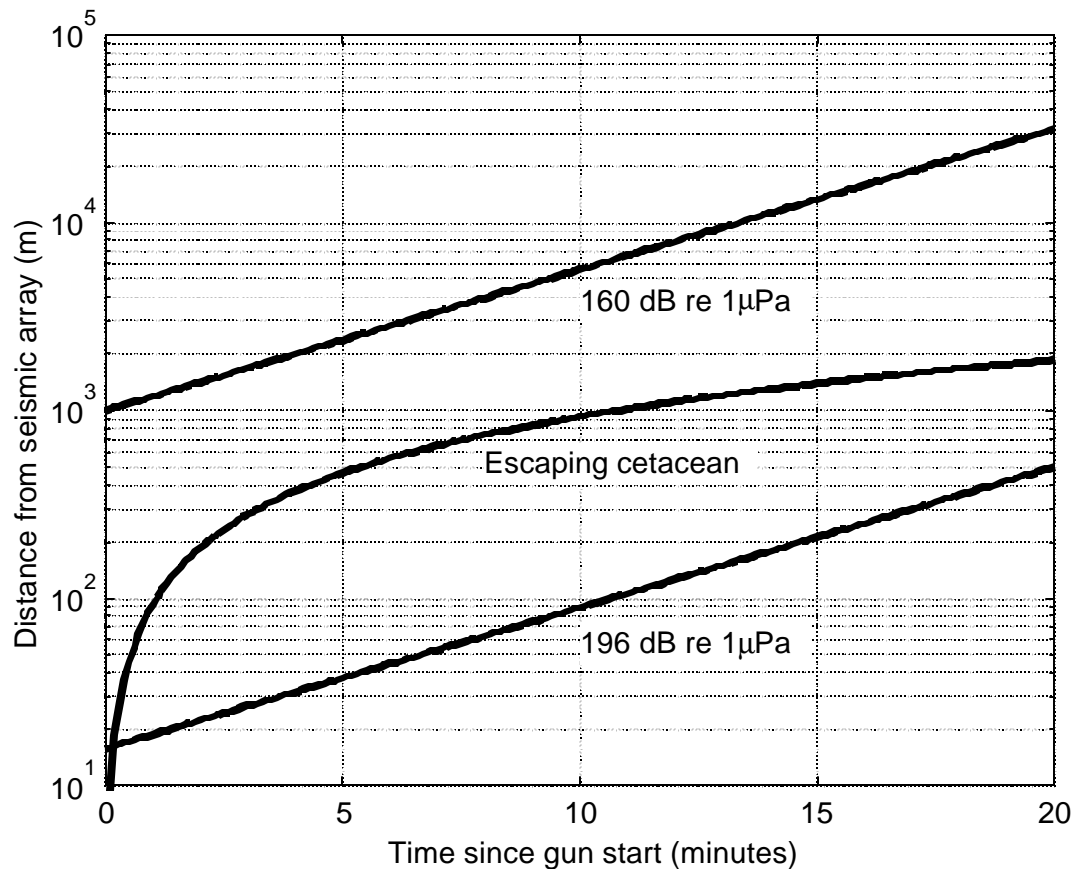


Figure 6.8 Distances from a seismic source during a soft start for 196 and 160 dB isopleths and for a cetacean swimming away from the source with a relative swim speed of 3 knots

196 dB or more. This is just one example however, and, as discussed above, animals may not act appropriately to the source (i.e. not move away) and other constraints for a submerged animal may prohibit them from swimming at speeds sufficient to escape a vessel approaching at 5 knots.

Although soft starts may reduce the risk of an animal being exposed to the high levels of sound that might cause damage, they do increase the total amount of sound released into the marine environment during a survey, and could thus potentially increase the level of lower-level disturbance caused by a seismic survey. More detailed modelling exercises along these lines, and research on the response of animals during 'soft starts', should be undertaken to inform

the design of such mitigation measures to make them more likely to achieve appropriate management criteria (for example, to ensure that the level and number of received pulses should not exceed agreed DRCs, while minimising increases in total noise output).

In this section we have suggested a number of situations in which marine mammals may not perform what might seem, to an informed human observer, to be the obvious course of action to alleviate the effects of airgun noise. This can be due both to an inability on the marine mammal's part to correctly appreciate the situation, and a failure by humans to properly understand the biology of the animals involved or the way in which the noise concerned propagates.

6.10 Spatial and temporal scales

The spatial and temporal scales at which the potential effects of seismic surveys should be investigated are daunting. Sound from airguns may be audible to marine mammals at ranges of several hundreds of kilometres. In some cases (e.g. bowhead whales, Malme *et al.* 1988; and sperm whales, Bowles *et al.* 1994), behavioural responses have been measured at ranges of many tens, or even hundreds, of kilometres from the source. However, few studies have attempted to measure effects at these ranges. Studies tend to focus on smaller numbers of animals close to seismic surveys but it is possible that very substantial

numbers of marine mammals are subject to unmeasured effects, perhaps inducing stress, over huge areas. In the temporal dimension, in some commercially promising regions, such as the Atlantic Frontier and the North Sea, many seismic surveys may be being conducted simultaneously throughout most of the summer months of each year for many years. Long-term studies to assess impacts over these ranges have not been conducted, and in nearly all cases baseline data, from the time before surveys start, is completely lacking.

6.11 Economic significance of seismic disturbance of marine mammals

In addition to strong ethical reasons for wishing to avoid disrupting marine mammal populations with seismic noise, there will also be economic considerations when human commercial utilisation of a marine mammal is potentially

affected. In the North Atlantic, marine mammals are exploited both consumptively (hunting of seals and whaling) and non-consumptively (nature tours and whale watching).

6.11.1 Consumptive utilisation

Consumptive utilisation of marine mammals has declined in most of western Europe, due largely to changing markets and public attitudes. However, commercial whaling persists in Norway and large scale commercial seal hunts continue at a very high level off Canada, Norway, and Russia and on offshore grounds. Small-scale seal hunting is prosecuted in most northern coastal waters from Norway to Canada. considered to be of significant subsistence or cultural value.

There are 'aboriginal' hunts for cetaceans in the Faeroes, Greenland and Canada and there are no signs that the extent of these will diminish in the near future. Changes in distribution, abundance or behaviour of marine mammals that make them less accessible to local hunters will reduce commercially valuable catches that in some cases are also

6.11.2 Non-consumptive utilisation

Wildlife tourism, especially whale watching, has become an increasingly significant economic activity over the last decade. The growth of this business in the North Atlantic and throughout the world has been quite phenomenal. (Some of the prime whale watching areas in the North-east Atlantic are listed in Chapter 5.) Hoyt (1997) estimated that whale watching in Europe alone had revenues of £13.6 million in 1994 and the figure will have increased considerably since then. Whale-watching can be particularly important economically for some remote communities: 'Fungi', a lone 'friendly' dolphin that has

frequented the village of Dingle in County Kerry, Ireland since 1986, attracted 150,000 visitors a year in 1991, providing an estimated annual revenue of £1 million (Hoyt, 1992). The importance of seals as subjects for wildlife tourism has been less well appreciated but Young (1998) estimated the gross annual value of seal watching in the UK and Ireland to be £38 million. Changes in the local population, abundance and distribution, or in the approachability of marine mammals, will affect non-consumptive commercial use of marine mammals.

6.12 Implications for management

Concerns about the conservation of marine mammals have usually focused on cases where a certain number of animals suffer dramatic effects, such as mortality from hunting or fisheries bycatch. Management regimes have been established, with varying levels of success, to address such issues. It is possible that, at short ranges, seismic survey noise could cause some acute problems of this nature. It is also probable that alone, or in combination with other factors, airgun noise will have less dramatic chronic effects such as: excluding marine mammals from important areas at significant times; interfering with their movements, which might be expected to be particularly important during migration; effects contributing to overall habitat degradation; disruption of biologically significant behaviours (such as feeding and breeding) and increased levels of stress. Potentially, very large numbers of animals could be affected in this way. In many cases, these effects will add to or amplify other stresses (both natural and man-made) also impacting individuals or populations. Although at first sight such effects may seem less severe than direct mortality or injury, they affect many more individuals and extend over significant periods of time. We would expect the cumulative or synergistic effects of these to result in reduction in reproductive rates and increases in mortality. For marine mammal species, which in many cases have very low reproductive rates, such sub-lethal effects on large numbers of animals could have greater consequences at the population level than individual mortalities. Chronic problems of this kind are thus a very legitimate conservation concern but they are difficult to manage with existing regimes.

This review has certainly emphasised the paucity of knowledge and the high level of uncertainty surrounding so many aspects of the effects of sound on marine mammals. This is a problem that is common to many conservation issues and which has led to the development and adoption of a precautionary approach in many arenas. The precautionary principle, which has recently been espoused in many international, regional and national agreements (Hey 1991a; Hey 1991b provide reviews), is broadly interpreted to mean that measures to prevent harm should be taken even in the absence of conclusive scientific evidence of cause and effect. Mayer & Simmonds (1996) recently considered the role of precaution in cetacean conservation and used, as one case study, an example of acoustic

disturbance, the 'Heard Island Experiment' - an experiment designed to transmit loud, low frequency sound underwater from Heard Island (near Antarctica) to 18 detection sites around the world. Not surprisingly, the experiment raised concerns about the impacts of these sounds on cetaceans. Indeed, many of the issues that relate to the possible impacts of seismic noises are very similar to those raised by the 'Heard Island Experiment'. This is particularly true of the lack of information about its potential impacts on cetaceans. In the course of the experiment's public review, a substantial ignorance about the effects of noise was admitted and the scientific community was shown to be widely divided in its opinions as to the experiment's potential to harm marine wildlife. One scientist, for example, commented that there was only a vague chance of harm, whilst others suggested that communications could be affected over many thousands of square kilometres of prime whale habitat. Moreover, there was found to be virtually no information about the abundance or normal behaviour of cetaceans in the Heard Island area. In the event, the results of the noise transmissions on the local cetaceans as monitored by observers proved to be equivocal. Mayer & Simmonds (1997) suggested that this could have been predicted beforehand and commented that the scientists undertaking the cetacean monitoring were perhaps taking on too ambitious a task. For example, concerns extended to distant whales in the deep oceans, which clearly could not be monitored effectively. They emphasise that science must not paint a false picture of what it can achieve and, thereby, potentially mislead the public and policy makers.

In view of the uncertainties that still surround the effects of airgun noise on cetaceans, it is important that it should be managed in a precautionary way, to safeguard both individuals and populations. The first goal of the seismic industry should always be to minimise the number of surveys that are conducted and the power of the sources employed. When surveys must be undertaken they should be governed by suitable regulations, incorporating appropriate guidelines for seismic practitioners which, in the absence of good empirical observations, are based on precautionary assumptions about sound propagation and marine mammals auditory sensitivity, and are informed by a detailed understanding of marine mammal behaviour and vulnerabilities.

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