INPUT TO REVISION OF GUIDELINES REGARDING UNDERWATER NOISE FROM OIL AND GAS ACTIVITIES - EFFECTS ON MARINE MAMMALS AND MITIGATION MEASURES

Scientific Report from DCE – Danish Centre for Environment and Energy No. 202 2016

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Data sheet

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Abstract:	Seismic surveys in connection to oil and gas activities have the potential to disturb and injure marine organisms, due to the high sound pressures generated by air guns. An adaptive framework for modelling and assessing the impact on marine mammals in particular is presented, together with a discussion of possible mitigation measures. Other survey methods and sources of loud underwater sound are also briefly discussed.
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Preface

This report was commissioned by the Danish Energy Agency as a background document for their work on revising guidelines for conduction of seismic surveys in Danish waters and other noise-emitting activities related to the exploration for and extraction of oil and gas.

The report thus contains a review of current understanding of how underwater noise may impact marine organisms, in particular marine mammals, and provides scientifically based suggestions for elements to include in impact assessments and suggestions for subsequent monitoring during actual surveys.

This report thus has no legal status and serves only as background material. Current regulatory guidelines of the Danish Energy Agency should be consulted and adhered to when conducting an actual impact assessment.

Summary

This report presents background and suggestions for assessing impact for seismic surveys and other oil and gas related activities, which emit underwater noise. As input to a revision of guidelines for seismic surveys, a common framework for assessment and regulation is presented, developed with the purpose of assuring consistency and transparency and allowing simple updates to evaluate procedures and exposure limits whenever new experimental evidence appears.

Five species of marine mammals are of particular importance for impact assessments in Danish waters and all are protected by the EU Habitats Directive (annex II and/or annex IV). These species are: harbour porpoise, white-beaked dolphin, minke whale, harbour seal and grey seal. Effects on fish are generally unlikely to have significant impact, except during spawning and in particular in fjord systems with limited access to the open sea. Diving birds may be affected by underwater noise but the lack of knowledge about this impact precludes regulatory advice.

Impact of noise are divided into hearing damage (temporary and permanent threshold shifts, TTS and PTS, respectively) and behavioural disturbances. TTS and PTS are likely to occur at lower noise exposures than any other types of physiological injury and are as such good precautionary criteria for injury from underwater noise. Based on an extensive body of experimental results, the consensus is now that the overall best predictor for TTS and PTS is the sound exposure level (SEL), cumulated over a period of at least two hours. Based on experimental data, the thresholds for eliciting TTS and PTS in harbour porpoises by exposure to repeated air gun pulses are estimated to be 175 dB re. 1 μPa^2s and 190 dB re. 1 μPa^2s, respectively. The corresponding thresholds for harbour and grey seals are estimated to be 176 dB re. 1 μPa^2s and 200 dB re. 1 μPa^2s, respectively. All levels are unweighted.

Behavioural reactions to air gun noise are likely to occur at much larger distances than TTS and PTS and thus potentially can affect a much larger number of animals. Based on experimental data from especially pile-driving operations, a behavioural response threshold for porpoises is estimated at 130 dB re. 1 μPa, when expressed as L_{eq} (average over one air gun pulse) or 145 dB re. 1 μPa^2s when expressed as single pulse SEL, both levels unweighted. The corresponding thresholds for harbour seals are associated with considerable uncertainty, and thus tentatively assumed to be identical to the porpoise thresholds.

For both TTS/PTS and behavioural reactions it is stressed that determining and applying appropriate frequency weighting curves is important, but that lack of experimental data and consensus precludes guidance at present.

An impact assessment of underwater noise from seismic surveys should be based on a model that combines accurate modelling of source characteristics, propagation loss, source (ship) behaviour and receiver (animal) behaviour. The output of such a model can, when combined with adequate thresholds for impact from TTS, PTS and behavioural disturbance, as well as information about animal abundance, be used to make predictions about impact ranges and potential areas and number of animals affected. To maximise the

value of assessments and to increase quality of future assessments, the modelling should be accompanied by actual measurements during the survey.

A range of methods is available for mitigating impacts of seismic surveys. As a general rule, the size (source factor) of an air gun array should never be larger than what is required by the purpose of the survey. Furthermore, surveys should, if possible, be conducted at times of the year when animal abundance is low (if such periods exist) and outside the periods when animals are most vulnerable (breeding season and period when mothers have dependent calves). Visual observers (MMOs) and passive acoustic monitoring (PAM) are effective as mitigation in the sense that it protects those animals, which are detected, from injury, although a substantial number of animals are likely to be overlooked at night and during less than ideal observation conditions. Soft start procedures will protect nearby animals from PTS and other injury at the beginning of the transect lines and after shut-downs on lines. The use of a single, small air gun during line changes and turns shorter than the time to complete a soft start procedure, is considered beneficial. In addition to modifying procedures, new techniques, such as the eSource, Vibroseis, and the “popcorn” protocol should be explored and encouraged, as they may offer better possibilities for mitigating effects on marine mammals.

A range of other surveying techniques is used in connection with oil exploration and extraction activities. In terms of potential impact these techniques overlap in terms of predicted impact ranges and form a continuum ranging from unlikely to have any impact (passive instruments such as magnetometers and gravimeters) to very likely to have effects on behaviour and possibly also auditory damage at close range (various techniques for sub-bottom profiling). There is thus no clear gap in terms of magnitude of potential impact between air gun arrays and the other techniques: A sub-bottom profiling survey with a large sparker as sound source may thus have larger impact on marine mammals than a survey with a single, small air gun. The decision to conduct an impact assessment should thus not be based on the type of survey technology, but on the likelihood of significant impact on marine mammals, with this impact being a reflection of emitted noise levels as well as temporal and geographical extent of the survey.

Sammenfatning

Denne rapport indeholder en gennemgang af, hvordan seismiske undersøgelser og andre aktiviteter relateret til olie- og gaseftersøgning og udvinding kan påvirke marine organismer, især havpattedyr, og hvordan disse effekter kan inkluderes i vurdering af effekter af aktiviteterne. Som input til revidering af retningslinjer for seismiske undersøgelser præsenteres en fælles ramme for vurdering og regulering, som er udarbejdet med det formål at sikre kon- sistens og gennemsigtighed i vurderinger og sagsbehandling. Modellen er en rammemodel, således at den løbende kan opdateres, når der fremkom- mer nye eksperimentelle data om f.eks. grænseværdier.

Fem arter af havpattedyr er relevante for konsekvensvurderinger i danske farvande, og alle er omfattet af EU's habitatdirektiv (bilag 2 og/eller bilag 4). Disse arter er marsvin, hvidnæse, vågehval, spættet sæl og gråsæl. Effekter på fisk vurderes generelt ikke at være af betydning. Undtagelser kan være under gydning og i særdeleshed i fjorde med begrænset adgang til havet. Dykkende fugle kan tænkes at blive påvirket af undervandsstøj, men der er ikke tilstrækkelig viden inden for området til at kunne vurdere dette nærmere.

Påvirkning fra støj deles op i høreskader (midlertidig og permanent hørenedsættelse, hhv. TTS og PTS) og adfærdsforstyrrelser. TTS og PTS indtræder sandsynligvis ved lavere lydniveauer end alle andre typer af fysiologiske skader og kan derfor fungere som forsigtighedsbaserede kriterier for skader fra undervandsstøj. Baseret på omfattende eksperimentelle data er der konsensus om, at den samlet set bedste prædiktor for TTS og PTS er lydeksponeringsniveauet (SEL), akkumuleret over en periode på mindst 2 timer. Ud fra forsøg med TTS hos marsvin udsat for pæleramningsstøj vurderes det, at TTS- og PTS-tærskler for støj fra seismiske luftkanoner er hhv. 175 dB re. 1 μPa^2s og 190 dB re. 1 μPa^2s. Tilsvarende tærskler for sæler vurderes til at være hhv. 176 dB re. 1 μPa^2s og 200 dB re. 1 μPa^2s. Alle niveauer er uvægtede.

Adfærdsreaktioner på luftkanon-lyde optræder i langt større afstande fra seismikskibet end TTS og PTS og kan derfor potentielt påvirke et langt større antal dyr. Baseret på eksperimentelle data fra især pæleramning vurderes det, at adfærdstærskelen for marsvin er 130 dB re. 1 μPa, udtrykt som L_{eq} (rms-gennemsnit over en enkelt puls), eller 145 dB re. 1 μPa^2s udtrykt som lydeksponeringsniveauet (SEL) for en enkelt puls. Begge niveauer er uvægtede. Der er betydelig usikkerhed vedrørende de tilsvarende tærskler for sæler. Ud fra en forsigtighedsbetragtning antages de derfor at være de samme som for marsvin.

Både for TTS/PTS og adfærdsreaktioner er det vigtigt at understrege betydningen af at bestemme og anvende den korrekte frekvensvægtning. De eksperimentelle data er imidlertid ikke tilstrækkelige til, at der er opnået konsensus på området, og rådgivning vedrørende frekvensvægtning kan derfor ikke gives for nuværende.

En konsekvensvurdering for undervandsstøj bør baseres på en model, der kombinerer en pålidelig modellering af kildekarakteristik, transmissionstab og bevægelser af skib og modtager (dyrene). Resultaterne fra en sådan model kan, når de kombineres med tærskler for TTS, PTS og adfærdsreaktioner samt information om forekomst (tæthed) af dyrene, anvendes til at forudsige

påvirkningsafstande og antal påvirkede dyr. For at maksimere udbyttet af vurderingerne, også kommende, bør modellering følges op af faktiske målinger under de seismiske undersøgelser.

Flere typer af afværgeforanstaltninger er tilgængelige for at reducere påvirkningen fra seismiske undersøgelser. Som en generel regel bør et luftkanon-array ikke være større, end hvad der kræves for at opfylde formålet med undersøgelsen. Dernæst bør undersøgelserne i videst muligt omfang gennemføres på tider af året, hvor forekomsten af havpattedyr er lav (hvis sådanne perioder findes) og undgå perioder, hvor dyrene er mest sårbare (ynglesæson og dieperiode). Observatører (MMO'er) og passiv akustisk overvågning (PAM) er en effektiv afværgeforanstaltning i den forstand, at de beskytter de dyr, der bliver opdaget af observatører og PAM-systemet, men et betydeligt antal dyr må forventes at blive overset om natten og når observationsbetingelserne ikke er optimale. Gradvis opstart af luftkanoner (soft start) kan beskytte dyr i nærheden af luftkanonerne fra PTS og andre skader ved begyndelsen af transektlinjer og ved opstart efter stop undervejs. Brugen af en enkelt luftkanon under linjeskift anses for at være værdifuld, såfremt linjeskiftet tager kortere tid end en komplet soft start procedure. I tillæg til løbende justeringer af afværgeprocedurer bør det undersøges, om nye teknikker, såsom modificerede luftkanoner (eSource), vibroseis og ”popcorn”-protokoller, kan give større reduktion i påvirkningerne end de nuværende foranstaltninger.

Et antal andre teknikker anvendes til opmåling i forbindelse med olie- og gasproduktion. Påvirkningerne fra disse aktiviteter dækker et bredt spektrum fra fraværende (passive teknikker såsom magnetometre og gravimetre) til en sandsynlig effekt på adfærd og muligvis også høreskader (forskellige teknikker til undersøgelse af den øverste havbund (sub-bottom profiling)). Der er derfor ikke nogen klar adskillelse mellem disse teknikker og luftkanoner, når det kommer til påvirkning: en havbundsundersøgelse med en stor elektrisk lydkilde (sparker) kan således godt tænkes at have en større påvirkning på havpattedyr end en seismisk undersøgelse med en enkelt, lille luftkanon. Skellet mellem hvilke aktiviteter, der bør underlægges en konsekvensvurdering, bør således ikke gå på typen af lydkilde, men på sandsynligheden for at der kan være betydelige effekter på havpattedyr. Denne sandsynlighed vil være en funktion af en række parametre, herunder de udsendte lydtryk, samt udstrækningen af undersøgelsen i tid og rum.

1 Introduction

This report was requested by the Danish Energy Agency as input to their work on developing a legislative framework for regulating biological impacts from underwater noise related to oil and gas activities in Danish waters, with particular emphasis on noise from seismic surveys. The report draws heavily on the seismic guidelines for Greenland (EAMRA 2015) and the regulatory framework of the Greenlandic authorities regulating oil and gas exploration in Greenland. Also the work related to developing guidelines for mitigation of acoustic injury from pile driving in relation to construction of offshore wind farms (Skjellerup et al. 2015, Skjellerup and Tougaard 2016) has been drawn upon.

The purpose of this report is thus to provide input and suggestions for modelling of underwater noise and impact assessment[1] as well as background information justifying these.

Impact assessments can be performed at four different levels:

1. Pressure assessment. In this type of assessment only the magnitude of emissions of disturbing factors is assessed. For underwater noise this amounts to assessing only the noise levels emitted and expected distribution in time and space.

2. Impact range assessment. At this level the potential maximal impact distances for different species of animals are determined.

3. Assessment of number of affected animals. Here the assessment includes information about abundance of protected species, both in time and space, and by factoring in the duration of the planned activities, it is possible to estimate how many animals will be immediately affected by the activities.

4. Population level impact. At this ultimate level the true impact on populations is estimated, for example by measures such as excess mortality or reduction in pup / calf production. By this assessment the potential impact on the long-term conservation status of protected species is possible.

Level 1 is clearly inadequate for an impact assessment, but will typically be conducted during a scoping process, where potentially significant impact is identified. Level 2 is a minimum requirement for an assessment. If impact ranges and effects both are expected to be small, it may be possible to conclude that the likely impact on conservation status of a protected species will be small as well. For non-trivial effects and / or larger impact ranges, it is necessary to proceed to level 3 where the total number of affected animals and the severity of the impact on individuals are factored into an overall assessment of impact. Assessment at level 4 is the ultimate goal, but is rarely attempted for marine mammals because proper methods are lacking at pre-

[1] Throughout this report the term *impact assessment* is used in the literal sense: assessment of impact (on animals); thus not tightly coupled to the more extensive requirements of an Environmental Impact Assessment (EIA), in lieu of the EIA-directive.

sent. Such methods are under development, however, and will eventually become available.

The focus of this report is primarily on level 1 and 2. More specifically, to provide guidance on parameters of noise important for assessment at level 1 and thresholds to be used in assessment of impact ranges at level 2. Assessment at level 3 requires knowledge about abundance of animals, preferably in the form of spatial density distributions. Such density distributions must be based on systematic observations of animals (line transect surveys or other) and by means of adequate spatial modelling be extended to cover the entire geographic area of relevance. Based on impact distances, duration of impact and the modelled density distribution, the expected number of animals affected by the noise can be estimated and should form the basis for the final assessment of the severity of the impact on the relevant population.

1.1 An adaptive framework for regulation of underwater noise

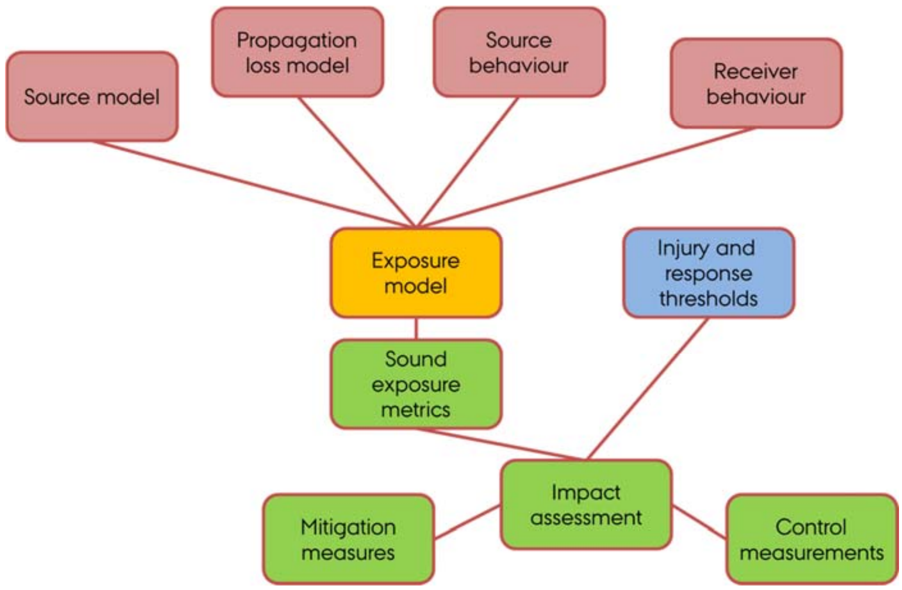


Figure 1.1. Framework for impact assessment of underwater noise. The exposure to animals is modelled on the basis of input variables describing the noise source (e.g. towed air gun array), sound propagation conditions and the behaviour of both source and receiver (animal). The output of the modelling (sound exposure metrics) is then compared to thresholds for acoustic injury and behavioural disturbances, which feeds into the impact assessment, which again could have implications for mitigation measures to reduce the impact. Adapted from Skjellerup et al. (2015).

Figure 1.1 outlines a framework for impact assessment of noisy activities, adapted from the work by Skjellerup et al. (2015). In this framework four inputs (red boxes) are combined in an exposure model, which quantifies the exposure to a particular target species of the assessment. This exposure model provides one or more measures of sound exposure, which in turn can be compared to accepted thresholds for impact (injury and behavioural disturbance, blue box) in the actual assessment. This assessment may, in turn, result in one or more mitigation measures to be applied to the activity in order to reduce impact to acceptable levels.

The framework illustrates that not only the response and injury thresholds are of importance to an impact assessment but also how the modelling of noise exposure is performed. Breaking the impact assessment up into separate parts, highlights the need for standards and transparency in all parts, to allow others to understand and judge the individual steps in the impact assessment and, if required, to replicate the assessment. In addition to being transparent, the framework is also adaptive in the sense that inputs can be adapted to different activities, locations and specific details of the activity, for example, line layout in a seismic survey. Inputs, especially injury and response thresholds, can also be updated as new information becomes available.

1.2 Cumulative effects and the importance of the application process

Large scale seismic surveys have the potential to affect large areas of the ocean and for extended periods of time (months). There is thus considerable potential for cumulative effects if two or more surveys are conducted in the same general area (not necessarily overlapping) or sequentially in time. This cumulative effect should be factored into an assessment, preferably in a way securing equal treatment of applications and not leaving the burden to the second and following applicants. One way of guaranteeing this is to operate with an application procedure with two separate deadlines, as in the Greenlandic regulations (EAMRA 2015): An early deadline, where companies must submit short summary statements of their intentions for the coming season, followed by a later deadline for submission of full applications. If two or more surveys are proposed in the same general area for the coming season, then all companies are informed about the intentions of the other companies and are required to include the other surveys in their assessment.

1.3 Summary

This report presents background and suggestions for conducting and evaluating impact assessments for seismic surveys and other oil and gas related activities, which emit underwater noise. Such assessments can be carried out at four levels: characterising noise sources, estimating impact ranges, quantifying number of affected animals and assessing true impact at population level. This report deals with the first and second level: estimating impact ranges. A common framework for assessment and regulation is presented, with the purpose of assuring consistency and transparency and allowing simple updates to evaluation procedures and exposure limits whenever new experimental evidence appears.

2 Relevant species

The acoustic modelling and in particular choice of acoustic parameters to model depends on the receiver, i.e. the animal. As different species have different hearing and different sensitivity towards underwater noise, this means that some consideration must be given to the species included in the impact assessment before modelling begins, i.e. during the scoping process. A minimum list for Danish waters is provided by the regulation according to the Habitats Directive (European Commission 1992). In addition are the more loosely defined protection implied by the EU Marine Strategy Framework Directive (MSFD) (European Commission 2008), which specifically addresses impact of underwater noise (descriptor 11 of the directive), but is not specific when it comes to species. The MSFD instead operates with the goal of achieving *Good Environmental Status* (GES) in the national and regional seas. Good Environmental Status with respect to underwater noise has not been defined yet, but is linked to the concept of *favourable conservation status* of the Habitats Directive (European Commission 2008).

2.1 Cetaceans (whales, dolphins and porpoises)

All species are included in annex IV of the Habitats Directive, implying that they are protected wherever they occur. A limited number of species occur on a regular basis and in appreciative numbers and should always be included:

- Harbour porpoise (*Phocoena phocoena*) – all Danish waters
- White-beaked dolphin (*Lagenorhynchus albirostris*) – the North Sea and Skagerrak
- Minke whale (*Balaenoptera acutorostrata*) – the North Sea and Skagerrak

A large number of other species can be encountered, especially in the deep parts of the North Sea, such as the slopes of the Norwegian Trench and Skagerrak. Activities in these waters should consider the relevance of such additional species during the scoping process.

Harbour porpoises are also included in annex II of the Habitats Directive, implying an additional level of protection inside designated special areas of conservation (Natura 2000 areas). A full list of these areas can be obtained from the Danish Agency for Water and Nature Management. It is important to stress that the protection implied by the Natura 2000 areas not only relates to activities inside the areas but also activities outside the areas that can make an impact on animals inside the areas. For Danish waters this has particular importance in relation to the large Natura 2000 area designated for harbour porpoises in the German sector of the North Sea, i.e. with direct implications for activities in the adjacent Danish waters.

2.2 Seals

Two species of seals are common in Danish waters and both are included in annex II of the directive, implying particular protection inside the designated Natura 2000 areas:

- Harbour seal (*Phoca vitulina*) – all Danish waters

- Grey seal (*Halichoerus gryphus*) – all Danish waters

The specific information for the relevant Natura 2000 areas should be consulted for additional information on basis for designation and additional regulation attached to the particular areas.

With reference to the Marine Strategy Framework Directive, the impact on these two species should also be assessed for activities outside the Natura 2000 areas.

2.3 Birds

Numerous species of marine birds are protected under the EU Birds Directive. However, the degree to which birds may be negatively affected by underwater noise is entirely unknown and thus no advice can be provided at this point regarding the relevance of birds for modelling of noise impact.

2.4 Fish

Only one species of fish relevant for Danish marine waters is specifically listed in the Habitats Directive:

- Houting (*Coregonus oxyrhinchus*) – the south-eastern Danish North Sea

Houting is an anadromous fish and during the part of its life cycle where it is found in the North Sea, it is thought to be widely dispersed. Furthermore, the limiting factor for attaining favourable conservation status of this species is believed to be access to suitable fresh water streams for breeding. Although houting should always be considered during the scoping process for activities in the south-eastern part of the Danish North Sea, oil and gas related activities are currently not considered to be a threat to this species.

Other species of fish should be considered in the scoping process and must be included if high concentrations of spawning fish or fish larvae are expected to be present in the survey area, especially if this concentration is expected to contain a significant part of a particular breeding stock of the species. This is particularly important in fjord systems but likely of less importance in the open North Sea.

Seismic surveys may affect the behaviour of fish in ways that can affect the fishery (sometimes leading to increase in catches, sometime to decrease), but without affecting the population status of the species. These effects are not treated here.

2.5 Summary

Five species of marine mammals are of particular importance for impact assessments in Danish waters and all are protected by the EU Habitats Directive (annex II and/or annex IV). These species are: harbour porpoise, white-beaked dolphin, minke whale, harbour seal and grey seal.

Diving birds may be affected by underwater noise but the lack of knowledge about this impact precludes regulatory advice.

Only one relevant species of fish is protected by the Habitats Directive, the houting. Negative impact from oil and gas activities on this species is not expected, but not excluded. Effects on other fish are generally unlikely, except during spawning and in particular in fjord systems with limited access to the open sea. In most cases, effects on fish can thus be excluded during the scoping process.

3 Effects of noise and proposed thresholds for impact on marine mammals

It is generally accepted that underwater noise from oil exploration and extraction activities has potential to impact the marine ecosystem (Turl 1982, Richardson et al. 1995, OSPAR Commission 2009). This impact can occur through a number of processes and usually three main issues are considered. This is physical injury and damage to hearing organs, disturbance of animal behaviour, and masking of other sounds. In addition to these three issues are more general physiological reactions such as acute and chronic stress (e.g. Wright et al. 2007), which so far has been difficult to deal with experimentally and therefore most often excluded from assessments.

No matter how the detrimental effects of noise are mediated, they will impact individual animals in the first place and in turn, if a sufficient fraction of a population is affected, also translate into population level effects. Protection can thus be assessed and regulated at two stages.

First stage is the individual animal. Some activities are so loud that they have potential to severely injure or even kill animals and especially for large marine vertebrates (turtles, birds and mammals) this may be undesirable, even if the number of animals killed is not large enough to have any appreciable population effect. In this case, the objective of regulation is to protect individuals from harm and ideally there is no lower limit to the acceptable number of impacted animals.

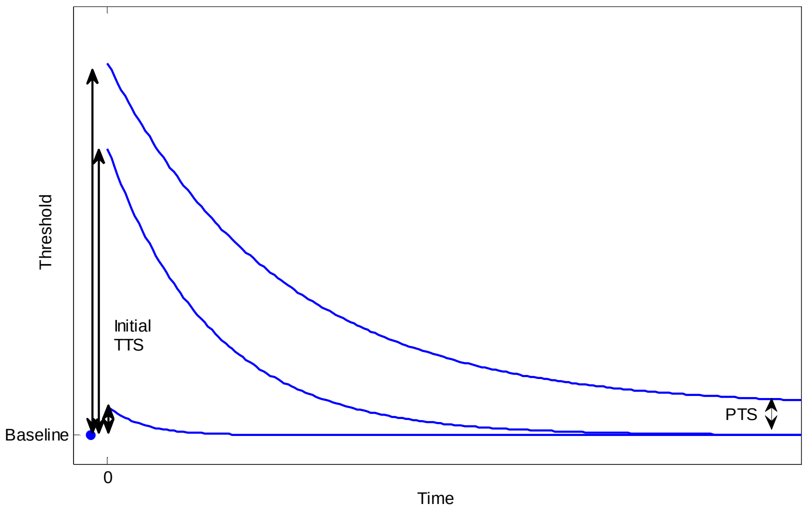
Second stage of impact is the population level. Here the objective of regulation is to protect a small or large population of animals from impact, i.e. to assure that the population remains in favourable conservation status, or if not already in a favourable status then at least assure that the conservation status is not further compromised by the noise. In this case, the limit on how many animals can be impacted depends critically on the magnitude of the impact, the number of individuals affected and the conservation status of the population. A large, healthy population can thus accommodate a much larger disturbance than a small and vulnerable population. This form of assessment is ideally performed by judging the population impact (level 4 from the Introduction), but in practice often performed as a judgement of the fraction of a population affected by the impact (level 3 from the Introduction).

Modelling of noise impact should allow assessment of injury and behavioural disturbance to relevant species of marine animals. Ideally also masking should be included, but as the current level of knowledge about conditions where masking occurs outside strictly experimental settings and how masking affects short-term and long-term survival of individuals, it is not possible to provide guidance on thresholds (see Erbe et al. 2016 for a recent review). The following will thus focus entirely on auditory injury and behavioural disturbances.

3.1 Injury

For marine mammals it is generally accepted that the auditory system is the most sensitive organ to acoustic injury, meaning that injury to the auditory system will occur at lower levels than injuries to other tissues (see e.g. Southall et al. 2007). Furthermore, noise-induced hearing impairment (threshold shifts) is likewise accepted as precautionary proxies for more widespread injuries to the auditory system. Noise-induced threshold shifts are temporary reductions in hearing sensitivity following exposure to loud noise (commonly experienced by humans as reduced hearing following rock concerts, etc.). This temporary threshold shift (TTS) disappears with time, depending on the severity of the impact. Small amounts of TTS will disappear in a matter of minutes, extending to hours or even days for very large TTS. A schematic illustration of the time course of TTS is shown in *Figure 3.1*. The amount of TTS immediately following the noise exposure is referred to as *initial TTS*. It expresses the amount by which the hearing threshold is elevated and is measured in dB. The larger the initial TTS, the longer the recovery period.

Figure 3.1. Schematic illustration of the time course in recovery of TTS. Zero on the time axis is the end of the noise that caused the TTS (the fatiguing noise). Gradually the threshold returns to baseline level, except for very large amounts of initial TTS where a smaller permanent shift (PTS) may persist.



At higher levels of noise exposure, the hearing threshold does not recover fully, but leaves a small or large amount of permanent threshold shift (PTS), see *Figure 3.1*. This permanent threshold shift is a result of damage to the sensory cells in the inner ear (Kujawa and Liberman 2009). An initial TTS of 50 dB or higher is generally considered to carry a significantly increased risk of generating a PTS (Ketten 2012). Lower levels of TTS can, if repeatedly induced, also lead to PTS (Kujawa and Liberman 2009).

The long-term consequences of permanent hearing loss in marine mammals are unknown, but with reference to Section 2 above it seems fair to assume that a national or regional sea cannot be in *Good Environmental Status* if a significant proportion of animals of protected species has noise-inflicted permanent hearing loss, even if the consequences for the population as a whole may be small.

In order to evaluate the output of the exposure model in terms of impact on animals, it is required to have thresholds for TTS and PTS to compare against. Deriving such thresholds is by no means an easy task and has been the subject of a large effort from many sides (see review by Finneran 2015) and much controversy (see e.g. Finneran 2015, Tougaard et al. 2015). No current consensus on general thresholds for TTS and PTS can thus be said to exist. Matters are simplified somewhat, however, if one restricts to only one type of sound, such as air gun noise or pile-driving noise and limits the discussion to only species for which sufficient data are available. A comparatively large effort has gone into investigating TTS caused by low frequency noise, including noise from pile driving, in harbour seals and harbour porpoises, as they are key species in many impact assessments. TTS is in general localised to frequencies around and immediately above the frequency range of the noise which caused the TTS. This means that TTS induced by seismic air guns and pile driving typically only affects the hearing at low frequencies (Kastelein et al. 2013b).

As PTS thresholds for ethical reasons cannot be measured directly in experiments, the agreed approach to estimate thresholds for PTS is by extrapolation from TTS thresholds to the noise exposure predicted to induce 50 dB of TTS and thus a significant risk of PTS. This extrapolation is not trivial, however, as it is complicated by the fact that the relationship between exposure and amount of initial TTS is not proportional. Thus, one dB of added noise above the threshold can induce more than one dB of additional TTS, see *Figure 3.2*. The slope of the TTS growth-curve differs from experiment to experiment and slopes as high as 4 dB of TTS per dB of additional noise have been observed in a harbour porpoise (Lucke et al. 2009).

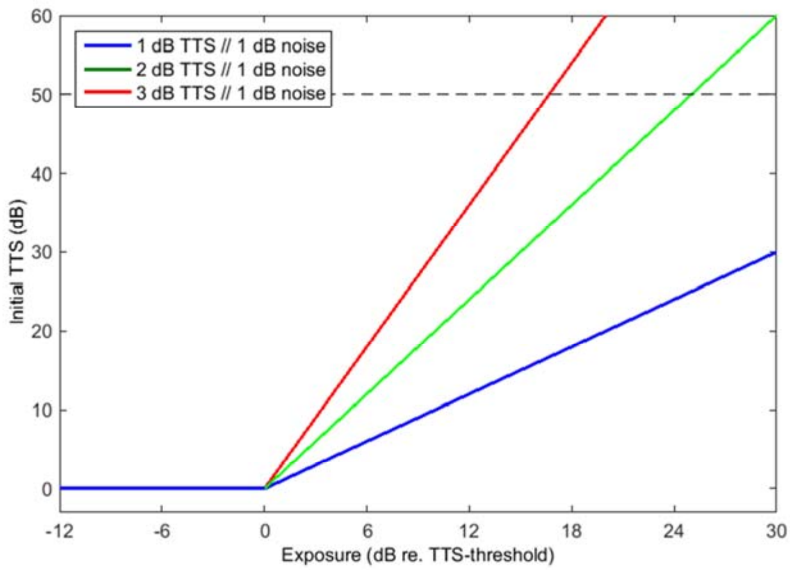


Figure 3.2. Schematic illustration of the growth of initial TTS with increasing noise exposure. Three different slopes are indicated. Note that the real curves are not necessarily linear. Broken line indicates threshold for inducing PTS, assumed to be at 50 dB initial TTS.

Two aspects of TTS and PTS are of central importance. The first aspect is the frequency spectrum of the noise causing TTS/PTS (often referred to as the *fatiguing noise*), which leads to the question of how to account for differences in spectra of different types of noise through frequency weighting. The second aspect is the cumulative nature of TTS/PTS. It is well known that the duration of exposures and the duty cycle (proportion of time during an exposure where the sound is on during intermittent exposures, such as air guns or pile driving) have a large influence on the amount of TTS/PTS induced, but no simple model is available that can predict this relationship.

3.1.1 Importance of frequency

Animals do not hear equally well at all frequencies, which is reflected in the common U-shape of audiograms. Substantial uncertainty is connected to how this fact should be handled when assessing risk for inflicting TTS and PTS. Southall et al. (2007) proposed that frequencies should be weighted with a fairly broad weighting function (M-weighting) which only removes very low and very high frequencies, well outside the range of best hearing for the animals. Separate weighting functions were developed for different groups of marine mammals. Others have proposed a more restrictive weighting with a weighting filter function resembling the inversed audiogram (e.g. Terhune

2013, Tougaard et al. 2015, National Marine Fisheries Service 2016) and several other intermediate forms (Finneran and Schlundt 2013, NOAA 2013). See *Figure 3.3* for examples. There is thus not agreement on how to perform frequency weighting when deriving exposure limits and calculating exposure levels. However, as long as we are only concerned with seismic air gun noise, this disagreement is not critically important, as the individual air gun pulses are very stereotypic within the same survey and even relatively stereotypic among different surveys. The different parameters such as peak level, rms-average and single pulse Sound Exposure Level (SEL) are thus highly correlated, as are weighted and unweighted levels. As long as all parameters are used consistently across the process of determining reaction thresholds to assessment of impact, it is possible to conduct regulation with any of the measures. It is thus important that TTS and behavioural thresholds used as basis for the regulation are derived from experiments with signals resembling real air gun pulses as closely as possible.

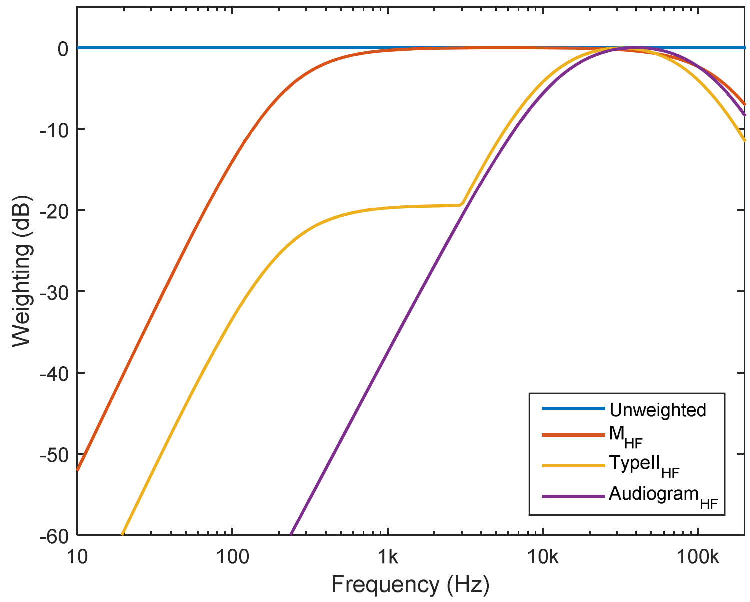


Figure 3.3. Four different types of frequency weighting proposed for high-frequency cetaceans, such as harbour porpoise. Unweighted, M_{HF} (Southall et al. 2007), Type II_{HF} (Finneran and Jenkins 2012) and HF audiogram (National Marine Fisheries Service 2016). Similar weighting curves exist for mid-frequency cetaceans (incl. dolphins), low-frequency cetaceans (baleen whales) and seals.

The only real concern connected to using unweighted levels in regulation of seismic noise is that it may impede development of technologies aiming at reducing the energy at higher frequencies, such as the eSource (Norton 2015). Reducing the energy content above 1 kHz will have very little effect on the unweighted levels, as most energy is below 1 kHz in the first place, but the effect on audiogram-weighted levels will be very significant.

3.1.2 Equal energy hypothesis

A substantial effort has gone into quantifying sound levels required to elicit TTS in marine mammals. The initial experiments were primarily conducted on bottlenose dolphins, belugas and sea lions (all reviewed by Southall et al. 2007), but recently also a large number of results from other species are available, most notably harbour seals and harbour porpoises (see comprehensive review by Finneran 2015). The initial recommendations of Southall et al. (2007) reflected an uncertainty as to what single acoustic parameter best correlated with amount of TTS induced and resulted in a dual criterion: one expressed as instantaneous peak pressure and another as acoustic energy of the sound (integral of pressure squared over time, see below). In the reviews of Tougaard et al. (2015) and Finneran (2015) this uncertainty is no longer present and it is generally accepted that other things being equal, the amount of TTS correlates well with the acoustic energy of the fatiguing noise. The acoustic energy is most often expressed as the cumulated sound exposure level (SEL_{cum}), given as:

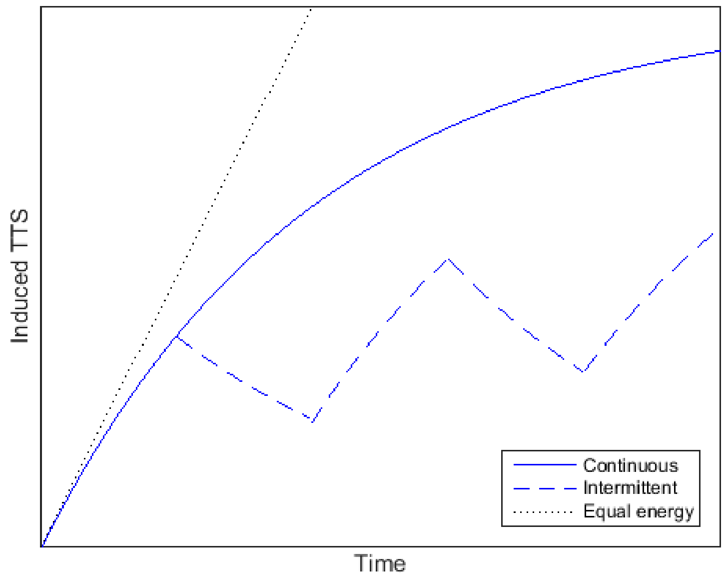
$$SEL_{cum} = 10 \log \int_0^T \frac{p^2(t)}{p_0^2} dt \qquad \text{Equation 1}$$

where p(t) is the instantaneous pressure at time t of a signal of duration T and p_0 is the reference pressure (1 µPa in water). The unit of SEL is thus dB re. 1µPa^{2}s. It is possible to show that this is indeed a unit of energy, being proportional to Jm^{-2} by means of a constant depending on the acoustic impedance of water.

The integration period T should equal the duration of the fatiguing noise up to some limit. This limit is debated. In human audiometry it is customary to use 24 hours, in conjunction with the sensible assumption that people are often exposed to the fatiguing noise during their workday and then spend the night resting in a quiet place. This assumption is less relevant for marine mammals, but the 24 h maximum was retained by Southall et al. (2007), stressing that it is likely to be very conservative (in the sense that it leads to overprotection).

The simple assumption that SEL determines the TTS induced (often referred to as the *equal energy hypothesis*) has been challenged in several experiments where the fatiguing noise was intermittent rather than continuous (e.g. Finneran et al. 2010) and in these cases the amount of TTS induced is less than predicted by the equal energy hypothesis. The TTS induced, however, is still above the TTS induced by a single pulse of a pulse series, demonstrating that the energy does add up across the individual pulses of a pulse train. This phenomenon can be explained if development and recovery from TTS are viewed as two competing processes (see *Figure 3.4*). According to this understanding, there is some recovery from TTS in the silent intervals between pulses, leading to a smaller overall TTS induced compared to a continuous noise with the same total SEL. This simple model can also help identify an upper limit to the integration period (T in equation 1 above). Thus, if it is assumed that recovery begins from the onset of the fatiguing noise, then a steady state will be established after some time where additional energy does not cause any additional TTS, giving the upper limit to T. Experiments on harbour porpoises have not shown clear indication of an upper limit to T for exposures up to two hours (Kastelein et al. 2014).

Figure 3.4. Conceptual model for growth of TTS with exposure time for continuous and intermittent noise exposure at constant intensity. For short durations there is an almost linear increase in induced TTS with time (equal energy hypothesis). With increasing duration the curve levels out as a steady state is established between the process causing TTS and the recovery process. Because of recovery between pulses, the TTS induced by an intermittent noise is less than for the continuous sound.



3.1.3 TTS and PTS in harbour porpoises

A threshold for inducing PTS in high-frequency cetaceans, including harbour porpoises, was proposed by Southall et al. (2007). However, this threshold was based solely on experimental data from mid-frequency cetaceans (bottlenose dolphin and beluga) and is no longer considered representative. Only one study is directly relevant to PTS and this was performed on a sister species to the harbour porpoise, the finless porpoise (*Table 3.1*). Popov et al. (2011) were able to induce very high levels of TTS (45 dB, considered close to the point where PTS is induced) by presenting octave band noise centred on 45 kHz at a total SEL of 183 dB re 1µPa²s. The energy in this noise was, however, at a considerably higher frequency than the main energy of seismic air gun noise. As the hearing of porpoises at 45 kHz is much better than at frequencies below a few kHz where the air gun energy is present, it seems likely that this proposed threshold underestimates the threshold for inducing PTS by air gun noise, i.e. the threshold for PTS for air gun noise is likely to be higher than 183 dB re. 1 µPa²s.

Table 3.1. Experiments on porpoises relevant for determining PTS and TTS thresholds for air gun noise.

	Reference	Threshold	Sound type
PTS	Popov et al. (2011)	>183 dB SEL[1]	45 kHz octave band noise
TTS	Lucke et al. (2009)	165 dB SEL	Single pulse from 20 in^3 sleeve gun
	Kastelein et al. (2015b)	180 dB SEL	1h of pile-driving pulses playback

[1] Measured as severe TTS on a finless porpoise, likely close to the level inflicting PTS.

Several studies of TTS in harbour porpoises are available (*Table 3.1*). However, the study of Lucke et al. (2009) is the only one directly concerned with air gun noise. Lucke et al. (2009) measured TTS induced by exposure to single air gun pulses, generated from a small 20 in³ sleeve gun at a received SEL of 165 dB re. 1 µPa²s. However, only a single air gun pulse was used as fatiguing stimulus, which means that the threshold derived may not be valid if extrapolated to cumulative SEL across multiple pulses, as would be the case for an animal exposed to air gun noise from a real seismic survey. This means that the threshold of Lucke et al. (2009) probably should be considered too low, when applied to repetitive air gun pulses, because, as indicated above, there is partial recovery from TTS between repetitive pulses. The total energy cumulated across several pulses required to induce TTS is thus expected to be higher than if all energy is delivered in a single pulse.

The same problem with extrapolation applies to pile-driving noise, which is also repetitive and with a frequency spectrum not unlike that from seismic air guns. Thus, the threshold for inducing TTS from repetitive stimuli was addressed in the study of Kastelein et al. (2015b). They exposed a single harbour porpoise to 1 hour of pile-driving pulses (2760 single pulses) and were able to induce TTS at an estimated received and cumulated SEL of 180 dB re. 1 μPa²s. There is, however, considerable uncertainty connected to this threshold estimate. The uncertainty arises because the exposed porpoise swam freely in a 8 m by 12 m pool, 2 m deep during exposure to the fatiguing noise and the cumulated noise the porpoise was exposed to was estimated from the average noise level in the pool. This average was made over a large number of measurements at different depths and positions in the pool, excluding only the measurements less than 2 m from the loudspeaker. As the porpoise clearly changed its swimming pattern between pre-exposure and exposure (seen in figure 4 in Kastelein et al. 2015b), there is a possibility that the animal actively sought swimming paths in the pool with less than average sound pressure when the noise was on. This would lead to an overestimation of the received SEL and hence an overestimation of the threshold. Until further experiments can elucidate this, it thus seems prudent in a management context to precautionary consider the TTS threshold of Kastelein et al. (2015b) as too high.

An alternative and precautionary threshold is suggested below. Instead of taking the mean of all noise measurements in the pool beyond 2 m from the loudspeaker, only the lower quartile of the measurements is used (see *Figure 3.5*). This results in an average of the lower quartile of 140 dB re. 1 μPa²s per pulse, or **a TTS threshold equal to a total cumulated SEL of 175 dB re. 1 μPa²s**.

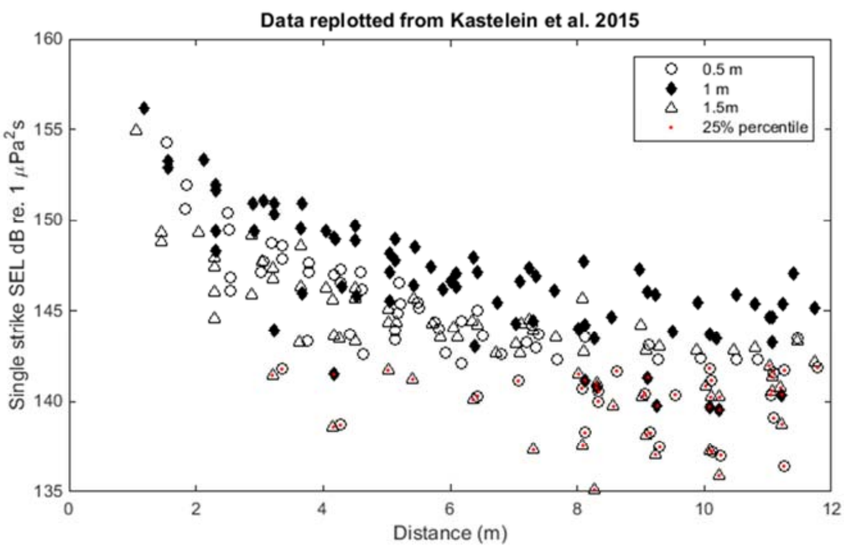


Figure 3.5. Noise measurements from Kastelein et al. (2015b) replotted and lower quartile indicated.

To derive an estimate for a PTS threshold from this value, 15 dB is added, following Southall et al. (2007), resulting **in a PTS threshold for repeated pulses of 190 dB re. 1 μPa²s**, considered valid also for air gun pulses. This value may not be valid for exposures shorter than 1 hour, the exposure duration used by Kastelein et al. (2015b), but can safely be extrapolated to longer exposures, as the assumption behind this latter extrapolation is precautionary.

3.1.4 TTS and PTS in seals

Southall et al. (2007) estimated TTS and PTS thresholds for seals in general, but these estimates were based on data from bottlenose dolphins, belugas and California sea lions. However, since 2007 actual measurements from harbour seals have become available and are used here instead to estimate thresholds.

PTS was induced in a harbour seal due to an experimental error by Kastak et al. (2008). This means that an actual measurement is available. In fact, a second experiment (in a different facility and on a different animal) produced a very strong TTS (44 dB) by accidentally exposing the seal to 199 dB re 1µPa^{2}s (Kastelein et al. 2013a), which is considered to have been very close to inducing PTS. By combining the two experiments a **threshold for PTS in harbour seals is tentatively set to 200 dB re. 1 µPa^{2}s** (*Table 3.2*).

TTS was induced in two harbour seals with octave band noise centred on 2.5 kHz and 4 kHz, respectively. Simply taking the mean of the thresholds produces an **estimated threshold for TTS of 176 dB re. 1 µPa^{2}s**.

Table 3.2. Experiments on harbour seals relevant for determining TTS and PTS thresholds for air gun noise.

	Reference	Threshold	Sound type
TTS	Kastak et al. (2005)	182 dB SEL	2.5 kHz octave band noise
	Kastelein et al. (2012)	169-176 dB SEL	4 kHz octave band noise
PTS	Kastak et al. (2008)	202 dB SEL	4.1 kHz pure tone
	Kastelein et al. (2013a)	>199 dB SEL[1]	4 kHz octave band noise

[1] Severe TTS, likely on the brink of inducing PTS.

3.1.5 TTS and PTS in other species

No data on TTS and PTS are available for white-beaked dolphins. Until such data or other, more relevant indirect data become available, results from the bottlenose dolphin (*Tursiops truncatus*) may be used instead. See Finneran (2015) for a summary. However, as bottlenose dolphins consistently appear to be less sensitive to TTS and PTS than harbour porpoises, any regulation based on harbour porpoises is thus likely to offer protection of white-beaked dolphins as well.

No information is available on the sensitivity of minke whales. In fact, no direct information is available on the hearing ability or sensitivity of noise for any mysticete species. It is thus not possible to provide any guidance regarding TTS and PTS for minke whales.

There are no results available from grey seals or any other true seals of similar size as grey seals. Data available from California sea lions and northern elephant seals (Kastak et al. 1999, Kastak et al. 2005) are considered less likely to be representative for grey seals than the harbour seal data. Consequently the results from harbour seals should be considered valid for grey seals until specific data for grey seals become available.

3.2 Disturbance of behaviour

Noise which is not loud enough to induce TTS or PTS can still have an impact on marine mammals, as it may affect and alter the behaviour of the animals which again can carry implications for the long-term survival and reproductive success of individual animals. Thereby, if a sufficiently large number of individuals is affected, also the status of the population can be affected (see *Figure 3.6*). Effects come as two different types. The most direct effect is through flight reactions to the noise in which case direct mortalities could be the result, as a fleeing animal may be caught in a gill net (Wright et al. 2013) or a small and not yet independent calf may become separated from its mother. More common, however, is probably the less severe effects where displacement of animals to less favourable areas or disturbance to feeding or mating behaviour will lead to a reduced energy intake and reduced mating success, which in turn again affects the population. The sequence of events is illustrated in *Figure 3.6* where it is also suggested how regulation of impact through behavioural effects of noise could be approached. It seems desirable to seek a population-based criterion for noise exposure so that:

- if the conservation status is favourable, the population size must not be negatively affected
- if the conservation status is not favourable, the growth of the population must not be affected, i.e. the ability to achieve good conservation status must not be compromised
- the long term survival of local populations must not be compromised

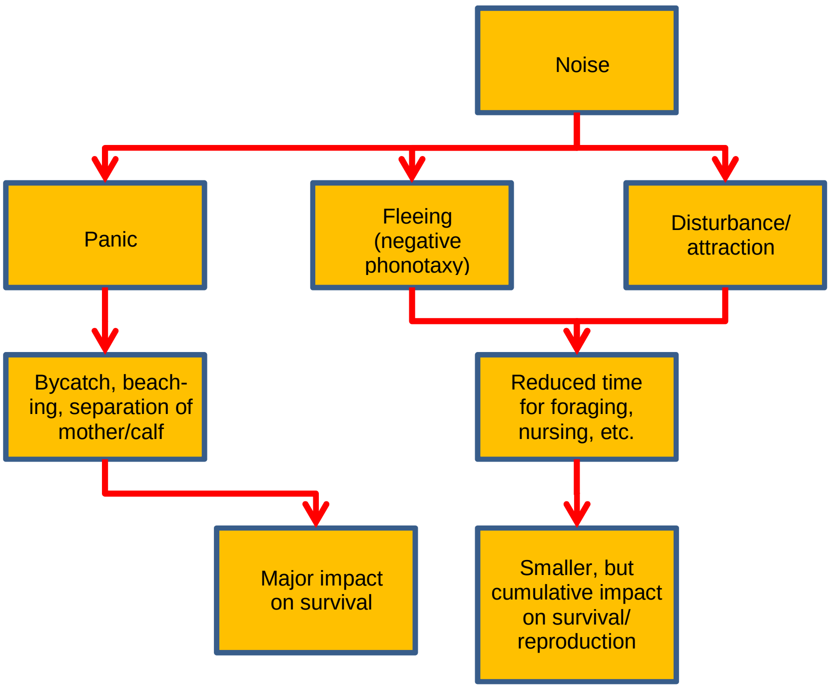


Figure 3.6. Schematic illustration of mechanisms by which noise-induced changes to behaviour can lead to effects on short-term and long-term survival and reproduction (fitness) in marine mammals.

Based on independent information about the conservation status of the population, an acceptable limit of disturbance may be determined as some small, additional mortality permitted by the activity under evaluation (seismic survey, pile driving or other). Given a firm understanding of how immediate behavioural changes in response to a given noise type and level (displacement and changes to foraging and mating behaviour) can translate into population level effects, it becomes possible to go back up through the model (see *Figure 3.7*), combine this with information about sound levels, sound transmission and animal densities and then derive a maximum tolerated sound exposure (exposure limit) for the given activity. However, the knowledge about how immediate, short-term changes to behaviour are translated into population level effects is so incomplete for seals and harbour porpoises that such a method of regulation is completely unrealistic within the near future. At present it is thus not possible to derive exposure limits based on management objectives for the conservation status of the population. Furthermore, as the uncertainties of current monitoring methods are considerable and the natural variation very large, it is unlikely that it will be possible to detect changes in population size or growth rates directly and unequivocally relate these to a noise impact. Assessment of impact on populations thus must be performed largely through expert judgment.

In the absence of a population-based criterion, it is only possible to make a criteria relating to how many animals are affected by the noise, without knowledge of the consequences (corresponding to level 3 in section 1 above). Other things being equal, the more animals which are affected and the longer the impact lasts, the larger the impact on the population must be.

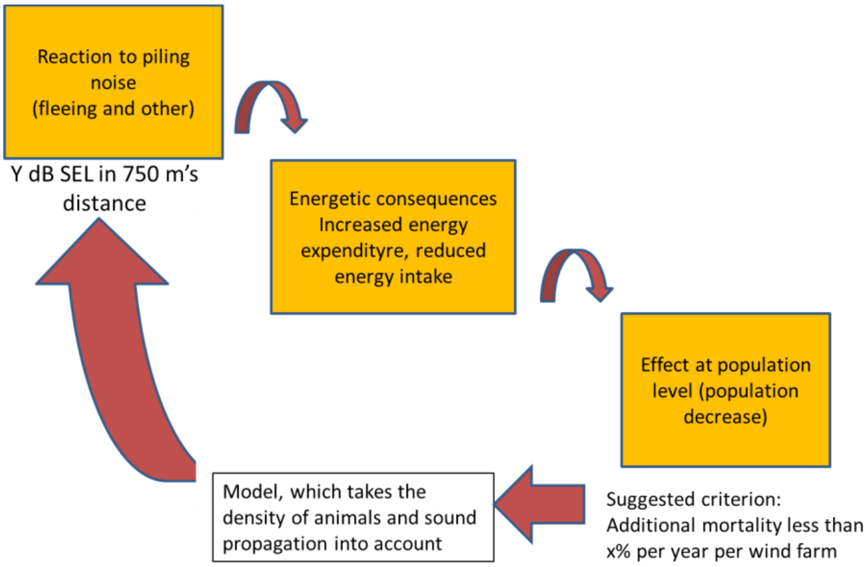


Figure 3.7. Sequence of events leading from noise exposure to population level effects and suggestions as to how a population-based exposure criterion could be fed backwards up the chain and lead to an exposure limit. Model modified from the PCAD model of National Research Council (2005)

3.2.1 Criteria for behavioural effects

When it comes to determining thresholds for behavioural reactions to noise there is first of all considerable disagreement among experts on the best noise measure to use. There is, however, general support to the suggestion that sound pressure level ($L_{eq,}$ see below) is a better overall predictor for reactions than for example sound energy cumulated over long periods (SEL). As was the case for TTS and PTS thresholds, there is also not agreement on how to perform frequency weighting when computing sound levels. In the same way as for TTS/PTS, however, as long as we are only concerned with seismic air gun noise, this disagreement is not critical, provided that parameters are used consistently across the process from determining reaction thresholds to assessment of impact.

3.2.2 Behavioural reaction thresholds for porpoises

Only one study on effects of a seismic survey on porpoises has sufficient information to estimate a threshold (Thompson et al. 2013). Several other studies are available where the thresholds for reaction to pile-driving noise could be estimated. These are summarized in *Table 3.3*. Thresholds are specified in different units: two as single pulse SEL (single pulse energy) and four as L_{eq}. L_{eq} is also referred to as the rms-average and is given as

$$L_{eq} = 20\log\sqrt{\frac{1}{T}\int_0^T \frac{p^2}{p_0^2}dt} \qquad \text{Equation 2}$$

where T is the pulse duration. The pulse duration can be difficult to determine for signals with poorly defined onset and / or offset, but is then often defined as the duration of a window containing 90 % of the pulse energy (Madsen 2005). The unit of L_{eq} is µPa and values thus cannot be directly compared to SEL, which has the unit µPa²s. There is some evidence that the relevant metric for comparison of thresholds for behavioural reactions is L_{eq}, averaged over a period equal to the integration time of the mammalian ear, i.e. roughly 125 ms (Tougaard et al. 2015). The duration of air gun pulses and pile-driving pulses is close to 125 ms. Therefore, the L_{eq} measured over the pulse duration is almost identical to $L_{eq(125ms)}$. L_{eq} over the entire pulse relates to single pulse SEL as:

$$SEL_{single\ pulse} = L_{eq} + 10\log_{10} d \qquad \text{Equation 3}$$

Based on the studies presented in *Table 3.3*, tentative thresholds for negative phonotaxis (fleeing) in response to seismic air gun noise and pile-driving noise are set at 145 dB re. 1 µPa²s single pulse SEL (unweighted), when expressed as SEL, or alternatively 130 dB re. 1 µPa (L_{eq}, unweighted), if expressed as sound pressure level.

Table 3.3. Studies of reactions of porpoises to seismic surveys and pile-driving sounds. Unit in four of the studies is L_{eq} (rms-average sound pressure level) (unweighted) whereas it was single pulse SEL, unweighted, in two studies. Values are thus not directly comparable.

Reference	Threshold dB re. 1 µPa²s (SEL)	Threshold dB re. 1 µPa (L_{eq})	Study	Comments
Thompson et al. (2013)	145-151		Small-scale seismic survey	470 in³ array in Moray Firth
Tougaard et al. (2009)		<130	Pile driving Horns Reef I	A threshold was not established
Brandt et al. (2011)		149	Pile driving Horns Reef II	Likely overestimated, as excess attenuation of reef was not included
Tougaard et al. (2012)		130	Pile driving play back	Not a real pile driving
Dähne et al. (2013)	140		Pile driving at Alpha Ventus	Supported by aerial surveys
(Kastelein et al. 2013c)		>136	Pile driving play back	In captivity

3.2.3 Behavioural reaction thresholds for seals

Very limited information is available on the reactions of seals to pile driving and even less for seismic surveys. A single study on ringed seals in the Arctic (Blackwell et al. 2004) studied reactions (or rather the absence of reactions) of ringed seals to conductor tube piling on an artificial island, one study looked at reactions to real pile driving (Russell et al. 2016) and two other studies used Lofitech seal scarers as signals (Gordon et al. 2015, Kastelein et al. 2015a). See *Table 3.4*.

Table 3.4. Results of three field studies and one study from captivity where seal reactions to pile driving and seal scarer sounds were investigated.

Reference	Threshold dB re. 1 μPa²s	Threshold dB re. 1 μPa	Study	Comments
(Blackwell et al. 2004)	>145	>151	Pile driving at Northstar Island, Alaska	No reaction from ringed seals in the water. Signals likely low pass filtered
(Russell et al. 2016)		146-158	Pile driving in the Wash, U.K.	Evasive reactions seen on tracked seals
(Kastelein et al. 2015a)		~130	Captivity	15 kHz seal scarer signal
(Gordon et al. 2015)		~130	In the wild	15 kHz seal scarer signal

These studies suggest that seals may be less sensitive than harbour porpoises. However, as the information is limited, it is tentatively suggested to use the same thresholds for behavioural reactions in seals as in porpoises: 145 dB re. 1 μPa²s single pulse SEL (unweighted), when expressed as SEL, or alternatively 130 dB re. 1 μPa (L_{eq}, unweighted), if expressed as sound pressure level.

3.3 Summary

Temporary and permanent threshold shifts (TTS and PTS, respectively) are likely to occur at low noise exposures than any other types of physiological injury and are as such good precautionary criteria for injury from underwater noise. Based on an extensive body of experimental results, the consensus is now that the overall best predictor for TTS and PTS is the sound exposure level (SEL), cumulated over a period of at least two hours. Based on experimental data, the thresholds for eliciting TTS and PTS in harbour porpoises by exposure to repeated air gun pulses are estimated to be 175 dB re. 1 μPa²s and 190 dB re. 1 μPa²s, respectively. The corresponding thresholds for harbour and grey seals are estimated to be 176 dB re. 1 μPa²s and 200 dB re. 1 μPa²s, respectively. Although the importance of frequency weighting is acknowledged, the current understanding of frequency weighting does not allow for advice on this issue and as thresholds are based on experiments with signals in roughly the same frequency range as air gun pulses, the application of weighting to thresholds is unlikely to change these considerably.

Table 3.5. Estimated thresholds for inducing TTS and PTS, respectively, by exposure to repeated air gun pulses.

Species	TTS threshold dB re. 1 μPa²s	PTS Threshold dB re. 1 μPa
Harbour porpoise	175	190
Harbour and grey seal	176	200

Behavioural reactions to air gun noise are likely to occur at much larger distances than TTS and PTS and thus potentially can affect a much larger number of animals. The experimental data support the use of sound pressure level (L_{eq}), averaged over a short interval (125 ms) as a common measure for derivation of thresholds for behavioural reactions. As air gun pulses are short and stereotypic, it is permissible to convert thresholds measured as L_{eq} into single pulse sound exposure level (SEL). Based on experimental data from especially pile-driving operations, a behavioural response threshold for porpoises is estimated at 130 dB re. 1 μPa, when expressed as L_{eq}, or 145 dB re. 1 μPa²s when expressed as single pulse SEL, both levels unweighted. The corresponding thresholds for harbour seals are associated with considerable uncertainty, and thus tentatively assumed to be identical to the porpoise thresholds. As for TTS/PTS, the significance of frequency weighting is acknowledged, but not taken into account on the ground that thresholds were only derived from experiments with low frequency noise.

4 Modelling sound exposure from seismic air gun arrays

The purpose of the modelling is to provide accurate predictions of the noise exposure experienced by various marine organisms around the seismic vessel and at various ranges. These predictions can then form the basis of the impact assessment, by comparison with thresholds for impact and be used to evaluate likely effectiveness of possible mitigation measures taken to reduce the impact (see section 5 below). A modelling made months in advance of a seismic operation must necessarily be based on best available estimates of survey design available at the time of modelling and use measured or modelled hydrographic information likely to be representative of those encountered during the actual survey. An important part of the modelling is thus also a post hoc comparison of predictions to actual measurements of radiated noise. This serves two purposes: documenting compliance with conditions of the permit and providing input for improved modelling in connection with subsequent activities. The aim of the latter is to make sure that the quality and accuracy of noise propagation models continuously improve.

4.1 Requirements of the modelling

The modelling should take into account that it serves a dual purpose: assessment of injury, which is likely to occur only at high noise levels close to the array, and behavioural disturbances, likely to occur at much larger distances from the array. In practice, this means that it will often be advantageous to use one type of model to estimate noise levels in the near field of the array and another type of model for larger distances, where the array can be treated as a point source.

4.1.1 Source model

For estimating the number of animals likely to be exposed to sound levels capable of inducing PTS, it is necessary to treat each airgun (or cluster of closely spaced airguns) as separate sources. The output from each gun or cluster can be modelled with appropriate software or actual near-field recordings can be used. For estimating TTS and behavioural disturbances at larger distances from the array, the entire airgun array can be modelled as a point source, realizing that sound pressure levels then cannot be accurately predicted close to the array. Source characteristics can be modelled by appropriate software as for the near-field measurements or measured from a real array at a horizontal distance large enough to be well beyond the Fresnel near field of the array and at a depth sufficiently large to reduce the effect of attenuation from Lloyd's mirror[2].

The source models should not only be restricted to the frequency range relevant for the seismic survey itself and where the main energy of the airgun

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[2] Lloyd's mirror is the phenomenon that the underside of the sea surface acts as an almost perfect phase-inverting acoustic mirror. This means that at large distances from a sound source, the sound propagated in a direct path from the source will interfere negatively with the reflected surface signal, greatly reducing the sound level. This effect is frequency dependent, such that the critical depth range where the effect is appreciable extends down to a few wavelengths of the signal (Urick 1983).

pulse is present, but should be extended to cover frequencies where there is appreciative noise energy above ambient noise. In practice this means that the upper frequency limit of the modelling should be high enough not to be a limiting factor for determination of impact ranges, or, expressed otherwise: it should not be possible to model larger impact ranges, simply by increasing the bandwidth of the modelled signal. In practice this means including frequencies up to at least 48 kHz.

The source models shall include a detailed description of the method used for estimating source properties and as minimum report the following parameters:

- Noise source strength as L_{eq} measured over the duration containing 90 % of the pulse energy (Madsen 2005), unweighted.

- Peak-to-peak pressure, and/or zero-to-peak pressure (source factor) (unweighted).

- Single pulse SEL (broadband, unweighted).

- Average frequency spectra of single pulses, expressed both as sound pressure level in 1/3 octave bands and as power spectrum density levels.

All levels should be back propagated to a distance of 1 m from an assumed point source. Levels are thus expressed as point source equivalent source levels.

4.1.2 Transmission loss model

The sound propagation models should be suitable for the tasks: modelling injury at close range and behavioural disturbance at long range, respectively. In both cases, models should include estimation of the frequency spectrum of transmitted noise with distance. The bandwidth of the transmission loss model should not be lower than for the source model, cf. section 4.1.1 above.

The transmission loss models shall

- Employ sound velocity profiles based on measured and/or modelled hydrographical conditions and thus likely to be representative for the actual sound velocity profiles in the survey area at the expected time of the survey.

- Include volume attenuation for modelling of frequencies higher than 2 kHz.

- Take into account the influence of the bathymetry in the survey area.

- Take into account the acoustic properties of the topmost sea bed sediment.

- Model the boundary conditions at the surface either presuming calm waters or including an appropriate surface roughness parameter.

4.1.3 Source behaviour

The behaviour of the airgun array should be included in the modelling, which means that towing speed and shot intervals should be incorporated. Also, if a double and alternating array is used both arrays must be included in the modelling in a suitable way. It is not required that the acoustic exposure from the entire proposed survey is modelled. The modelling can be restricted to a limited, but representative number of transect lines, or, if the lines are very long, representative sections of the transect lines. The cumulative impact, however, should be scaled up from the representative sections to cover the entire survey.

The modelling of source behaviour shall:

- Model exposure from representative transect lines, or, if the lines are longer than 50 km, representative segments of the transect lines.

- Include all airgun pulses of each segment in the cumulative noise exposure model (see below). However, the transmission loss model need not be recalculated for every single shot but can be extrapolated to cover larger regions with comparable bathymetry, hydrography and sediment properties.

- Include modelling of soft start procedures.

4.1.4 Receiver behaviour

The behaviour of receivers (animals) is essential to include in a model of exposure. A worst case assumption of a stationary animal can be made, but this is likely to overestimate the extent of especially the TTS / PTS zones considerably and it may be useful to include a simple model for animal escape, including a threshold for reaction followed by movement away from the source, either in a straight line perpendicular to the track line or radially away from the sound source.

The receiver behaviour model shall either:

- Assume stationary receivers (animals) – unrealistic worst case.

or:

- Include evasive movement of receivers (animals) with realistic assumptions on response thresholds and escape behaviour.

Documentation must include detailed description of assumptions in the model, including response thresholds, flee speed, flee direction and variance in these parameters, if this is included in the model.

4.1.5 Bringing it all together – exposure model

An example of an exposure model incorporating the elements from above is given in the following. The assumptions are deliberately simplified, thus unlikely to be realistic and serve only the purpose of illustrating how a model can be constructed.

Source signal is assumed to be a 1 s pulse with L_{eq} at 1 m of 230 dB re. 1 µPa²s. L_{eq} is related to SEL by equation 4:

$$SEL = L_{eq} + 10\log_{10} d \qquad \text{Equation 4}$$

where d is the duration of the pulse. As duration is 1 s (for simplicity; real airgun pulses are significantly shorter), the single pulse SEL is equal to L_{eq}.

Transmission loss (TL) is modelled as a simple spherical spreading plus absorption, α:

$$TL = 20\log_{10} r + \alpha r \qquad \text{Equation 5}$$

where α is set to 0.0004 dB/km, as derived by Bailey et al. (2010) for pile-driving pulses in the Moray Firth.

Source movement is modelled as a seismic vessel moving with a speed of 2.5 m/s (approx. 5 knots) with a shot rate of 1 shot every 5 seconds.

Receiver (animal) movement is modelled as a movement in a straight line perpendicular to the transect line with a speed of 1.5 m/s, beginning at a received single pulse SEL of 145 dB re. 1 μPa²s.

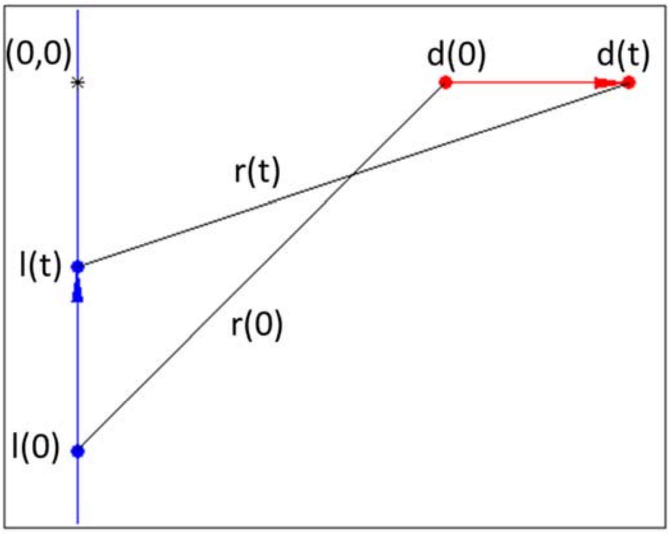

Figure 4.1. Illustration of the relative movements of survey vessel (blue) and receiver (fleeing animal, red). During the time interval t, the ship moves the distance l(0)-l(t), whereas the receiving animal moves distance d(0)-d(t) in the direction perpendicular to the transect line. r is the radial distance from survey vessel to receiver at time t.

The ship moves along the transect line with constant speed v_{ship}. The receiver swims with a speed of $v_{receiver}$ and starts reacting at t=0, when the ship is at distance l(0) from the point where the animal is abeam (perpendicular to the transect line) and the animal is at the perpendicular distance d(0) from the transect line. The radial distance from ship to receiver at time t is given as:

$$r(t) = \sqrt{\left(l_0 - t \cdot v_{ship}\right)^2 + (d_0 + t \cdot v_{receiver})^2} \qquad \text{Equation 6}$$

The ship fires shots with interval period p, which means that the radial distance at time of the i'th shot is:

$$r_i = r((i-1) \cdot p) \qquad \text{Equation 7}$$

The single pulse SEL of the i'th shot is

$$RL_i = SL - TL(r_i) \qquad \text{Equation 8}$$

where SL is the source level of the pulses, back propagated to 1 m distance from the array.

We now have what is needed to calculate the cumulated SEL at the receiver after receiving n shots:

$$SEL_{cum}(n) = 10\log_{10}\sum_{i=1}^{n} 10^{\frac{(SL-TL(r_i))}{10}} \qquad \text{Equation 9}$$

The output of the model is illustrated in *Figure 4.2* for three different initial positions of the receiver (porpoise): 0m, 1,000m and 2,000m perpendicular distance from the transect line. The porpoise begins to react when the received single pulse SEL exceeds 145 dB SEL, which happens at a radial distance of roughly 11 km. This distance is the extent of the behavioural disturbance zone.

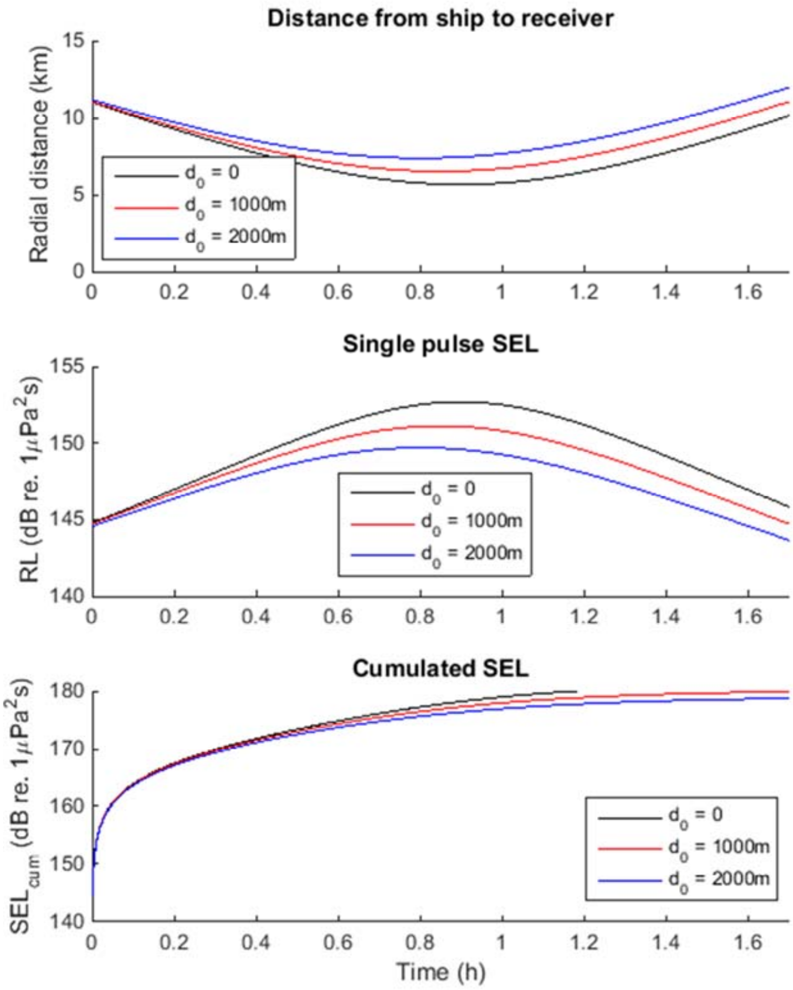

Figure 4.2. Output of the simple exposure model developed in section 4.1.5 assuming three different starting positions of the receiver (perpendicular distance to survey transect line). See text for additional assumptions.

The cumulated SEL builds up over the course of the nearly two hours it takes from the porpoise starts reacting to the point where it is behind the ship in a distance where it no longer is presumed to react to the ship. In the beginning SEL increases rapidly and then levels out gradually, as the ship passes the point of closest approach to the porpoise (the point with maximum RL). It is noteworthy that the final SEL_{cum} differs only by a few dB between the scenario with a porpoise on the transect line and the scenario with an initial perpendicular distance of two km to the transect line.

In all three scenarios, the final SEL_{cum} just exceeds the threshold for inducing TTS (section 3.1.3), indicating that porpoises under this scenario would be likely to develop mild TTS as a consequence of the seismic survey. None of the scenarios results in SEL_{cum} exceeding the threshold for PTS. Even the animal initially on the transect line will move sufficiently far away from the survey ship over the almost one hour it takes for the ship to reach the point of closest approach. This is a central observation, because it means that PTS is unlikely to be induced in porpoises under this particular scenario once the ship is moving and the array is firing. The seismic signals thus can be said to have a self-mitigating effect, in that they deter animals from the ship at much lower levels than the levels required to induce PTS. Exposure during ramp up will be different, however, as animals could be much closer to the ship at start-up of the survey and it is thus the beginning of each line that carries the highest risk of inducing PTS in porpoises. The nature of a soft start protocol and efficiency of pre-start procedures are thus critically important and should be modelled separately.

4.1.6 Cumulative effects

If more than one seismic survey vessel operates within the same area (either as part of the same survey or as independent surveys), the combined impact of all survey vessels should be considered and included in the modelling. For an example of how this can be done, see for example Shell's environmental impact assessment for the Anu and Napu licence blocs, Baffin Bay (Anon. 2012). The key elements are that mapping of impacted areas and estimates of total exposure time (total duration of surveys) include contributions from all vessels likely to operate in the area during the same season. The extent of the area where cumulative impact should be assessed is determined not only by the maximum impact ranges of each vessel, but also whether the different surveys are likely to impact the same population of animals.

4.2 Measurements

Modelling results should preferably be verified by actual acoustic measurements during the seismic survey. A measurement programme could be suggested together with the impact assessment, designed to allow a validation of the transmission loss model and perform a post hoc evaluation of the predicted exposure to animals and Natura 2000 areas.

Preferably acoustic measurements should be made from moored recording stations, as this will secure longer time series. These stations should be placed both inside and outside the survey area, assuring that recordings are obtained from a wide range of distances from the array. Distances should cover the range to and beyond the behavioural impact range predicted in the impact assessment.

Alternatively, acoustic measurements can be made from one or more designated vessels or from support vessels to the survey ship.

To fulfil the purpose, measurements shall

- Have sufficient dynamic range to allow determination of L_{eq}, peak-to-peak pressure and SEL for individual air gun pulses without clipping of signals.

- Have sufficient bandwidth to cover the frequency range used in modelling, in no case less than between 12.5 Hz to 20 kHz, preferably higher.

- Employ calibrated omnidirectional hydrophones with a sensitivity deviation of less than ±2 dB up to 40 kHz in the horizontal plane and less than ±3 dB up to 40 kHz in the vertical plane. It is recommended that a calibration signal is recorded within all recordings.

- Obtain sufficient number of recordings under different conditions (distances from ship, weather conditions, depths, etc.) to provide a statistically valid representation of the exposure to animals in the affected areas.

- Cover ranges from approximately two km from the airgun array to beyond the predicted maximum impact range.

- Be performed at two different depths, at 66 % and 33 % water depth (but in no case less than two m below the sea surface).

- Be recorded and stored in a lossless format, such as WAV.

4.3 Deliverables for modelling and measurements

In order to fulfill the objectives outlined above, the modelling and subsequent measurements should include the following:

- Detailed information about the signal used as basis for modelling impact, including power density spectrum, zero-to-peak pressure (source factor), L_{eq}, including specification of averaging window, and single pulse SEL, unweighted.

- Representative examples of sound speed profiles used in modelling propagation loss.

- Maps of sea floor characteristics used in modelling: bathymetry and acoustic properties. Acoustic properties can be shown as maps of sediment types with a table listing associated acoustic properties of sediment classes.

- Information about modelling of sea surface roughness.

- Representative maps of modelled propagation of sound from air gun arrays, showing single pulse SEL and L_{eq} (both unweighted). Maps should extend in all directions beyond the maximal distance of predicted impact.

- Representative examples of power density spectra of propagated signals with increasing distance out to beyond the maximal distance of predicted impact.

- Sufficiently detailed description of the animal movement model to allow independent replication of the modelling.

- Maps illustrating the spatial extent of the zones of impact (PTS, TTS and behavioural reactions) around the survey transect.

- Estimates of the number of affected marine mammals, divided into species, and an assessment of the potential impact on the animals. Particular attention should be on effects on the conservation status (population level) for annex 4 species and effects inside Natura 2000 areas for annex 2 species.

Reporting on measurements should include:

- calculated and measured 90 % energy duration, L_{eq} and SEL for single air gun pulses as a function of distance to survey ship
- hydrophone data and calibration
- sample rate / frequency range of data logger
- positions of measurement stations and hydrophone depths
- evaluation of correspondence between modelled and recorded sound levels and a discussion of possible explanations for significant deviations.

Raw recordings must be stored safely and should be handed over to the responsible agency upon request.

4.4 Evaluation of assessments and measurements

The impact assessment should be evaluated by the responsible agency with particular attention to the requirements in lieu of the EU Habitats Directive. A satisfactory modelling of impact should be based on realistic assumptions regarding sound propagation, including all parameters listed above in section 4.1. Whenever parameters are estimated, rather than based on actual measurements, they must be estimated using sufficiently precautionary assumptions, to assure that impact is never underestimated.

Successful measurements should be accurate and representative of the noise emitted during the entire survey and allow for a validation of the noise modelling performed for the impact assessment. This means that they should be obtained from strategic and / or representative locations to allow direct comparison with the model predictions and to be able to understand limitations in the modelling. This will allow for better models for subsequent impact assessments.

It is thus not a goal to obtain a 1:1 match between predictions and measurements; as such a match can never be expected. Rather, it is a goal to obtain sufficient information about the nature of deviations to identify the weak and / or inaccurate input parameters in the modelling, allowing greater attention to these parameters in subsequent modelling.

4.5 Summary

An impact assessment of underwater noise from seismic surveys should be based on a model that combines accurate modelling of source characteristics, propagation loss, source (ship) behaviour and receiver (animal) behaviour. The output of such a model can, when combined with adequate thresholds for impact from TTS, PTS and behavioural disturbance, as well as information about animal abundance, be used to make predictions about impact ranges and potential areas and number of animals affected.

To maximise the value of assessments and to increase quality of future assessments, the modelling should be accompanied by actual measurements during the survey. The immediate value of the measurements is to allow documentation of compliance with conditions set in the permit, but the long-term value of the measurements is that they will allow validation of the noise impact model and hence improve the quality of modelling efforts in future impact assessments.

5 Mitigation measures

The potential impact on marine mammals during conduction of a seismic survey can be reduced to variable degrees through different mitigating efforts. Some mitigation measures can reduce the likely number of animals exposed to both TTS / PTS and behavioural disturbance, whereas other measures only affects one type of impact.

In general, there are three levels of reducing impact from underwater noise:

1. Reduction of generated noise levels

2. Reduction of transmitted noise levels

3. Reduction of received noise levels and / or number of animals exposed to the noise

Reduction of the generated noise has obvious benefits with respect to all impacts, as impact ranges and thus number of affected animals decreases with a decrease in generated noise. The immediate consequence of this is that the size of airgun arrays (or more relevant, the combined source factor of the array) should never be larger than required in order to fulfil the objectives of the survey. Even small reductions in source factor can be of importance. Assuming simple spherical spreading loss, a reduction of the source factor by 6 dB will reduce the impacted area by 75 %.

Reduction of transmitted noise can be obtained for stationary sources, such as pile driving, where it is possible to attenuate the noise with up to 20 dB by means of for example bubble curtains (e.g. Caltrans 2009, Lucke et al. 2011). Such an approach appears less realistic for moving sources, such as airgun arrays.

Reduction of the noise received by animals and the number of animals exposed can be achieved in various ways. This can be simply by restricting surveys to times of the year where fewer animals are present, or, for mitigation of injury, PTS and partly TTS, by marine mammal observers coupled with procedures for shut down of the airguns if animals come too close (see for example JNCC (2010), EAMRA (2015)).

In most cases the different mitigation measures can be combined, to achieve a higher degree of mitigation.

5.1 Time-area restrictions

A simple, yet efficient way to reduce impact on marine mammals is to conduct surveys at times of the year where there are no or fewer animals in the seismic survey area, given that such periods exist. Also, the severity of impact can be reduced by avoiding times of the year where the individual species are most vulnerable to disturbance. This would typically be during mating and breeding seasons.

5.1.1 Harbour porpoises

Harbour porpoises are present year round in the North Sea (Reid et al. 2003) and although there are strong indications of seasonal movements within the North Sea (Camphuysen 2004, Gilles et al. 2009, Sveegaard et al. 2011), there is insufficient evidence to allow identification of periods where the abundance in the Danish sector is lower than at other times of the year.

Vulnerability is likely to be largest during the summer and autumn months. Porpoise calving and mating is in May to August, peaking in June-July (Sørensen and Kinze 1994). The calf remains dependent on the mother for many months after birth (Lockyer 1995).

5.1.2 Seals

Harbour seals generally have a coastal distribution (Tougaard et al. 2008, Herr et al. 2009), but can be encountered across the entire North Sea. During the breeding and moulting season in summer (June through August) harbour seals are more associated with haul-out sites along the coast (Leopold et al. 1997) and abundance in the central part of the North Sea is reduced.

Grey seals are present all over the North Sea, but more associated with haul-out sites in winter months where they breed and moult.

5.1.3 Minke whales and white-beaked dolphins

Minke whales are present in the Danish part of the North Sea (Kinze et al. 2003), albeit not as abundant as in the western part of the North Sea (Reid et al. 2003). They appear to be present year round (Kinze et al. 2003, Reid et al. 2003), but too little is known about their distribution to conclude on possible annual patterns. Almost nothing is known about the reproductive biology of mike whales and it is entirely unknown where they mate and give birth to their calves.

Almost the same can be said about the white-beaked dolphin. They are present especially in the northern part of the North Sea, presumably year round (Kinze et al. 2003, Reid et al. 2003). Little is known about their reproduction, but it is assumed that calving occurs during summer months (Galatius and Kinze 2016).

5.2 Visual observers and passive acoustic monitoring

Marine mammal observers (MMOs) and passive acoustic monitoring (PAM) are mandatory according to guidelines and regulations for seismic surveys in many countries, including the UK (JNCC 2010) and Greenland (EAMRA 2015). The rationale behind observer systems is that visual observers or operators on real-time passive acoustic monitoring systems can alert the crew of the ship of the presence of marine mammals inside a designated safety zone, allowing the crew to act accordingly. The extent of the safety zone is usually determined as the zone where short exposures can lead to PTS or other injury and is usually in the range of a few hundred metres to one km. Under many regulations, ships are required to shut down the airgun array if marine mammals are encountered inside the safety zone, which typically extends some hundreds of metres around the airgun array. A shutdown has obvious beneficial effects on the encountered animals, as their exposure to noise diminishes immediately, removing the risk of acoustic injury. Visual observers and PAM are thus an effective mitigation measure with respect to acoustic injury in the sense that when a shutdown is performed, it will remove the risk. A debated question, however, is whether visual observers and PAM are efficient mitigation measures. There are at least two issues: they do not mitigate behavioural disturbances and they do not protect marine mammals that are present inside the safety zone, but are overlooked by MMOs and PAM. Visual observations are not possible at night and during foggy or misty weather and especially for the small cetaceans, such as porpoises, there is a sharp decline in detection rates with even small increases in sea state (wave height). Essentially no porpoises are observed at sea state 3 and above (Teilmann 2003), a condition often present in the North Sea. The same is likely to apply for seals.

Acoustic detections with PAM is not dependent on light and less affected by weather, but for seals and baleen whales that do not vocalise regularly in the same way as echolocating toothed whales, the absence of sounds is far from evidence that no animals are present. Even for odontocetes detection range of PAM systems is less than 100 % even at close range and for porpoises it decreases sharply to zero around 100-200 meter from the detecting hydrophone (Kyhn et al. 2011).

All in all this means that MMOs and PAM cannot guarantee that seals and small odontocetes are not present inside the safety zone, unless surveys are conducted only under ideal conditions (i.e. daylight and sea state 0-1), which is unrealistic. Visual monitoring during daylight hours for minke whales is likely to be more efficient, as they are much easier to see.

5.3 Soft start and line change protocols

It is common practice in many seismic regulations to ask for a gradual increase of sound emissions from air guns (soft start) when beginning a new transect line or after a stop in transmissions for whatever reason (technical, navigational or due to a shutdown because of a marine mammal sighting). The rationale behind a soft start is to provide a gradually increasing sound level, alerting any nearby marine mammals and giving them opportunity to move to safe distances before the array starts transmitting at full power and in this way protect them from developing PTS or sustaining other injuries. The beneficial effects of soft start have never been documented experimentally, however, and recently critique has been raised of the fundamental logic behind current soft start procedures (McCauley et al. 2015). A central point of critique is that the increase in noise energy from a protocol where one air gun is added at a time over a course of 20-30 minutes does not constitute a linear increase in neither sound pressure level, nor cumulated SEL. The first air gun contributes disproportionally to the overall level, due to the logarithmic nature of the dB scale. Adding a second air gun will increase the sound pressure level and the single pulse SEL by 3 dB, but adding a third air gun will only increase the sound pressure level and SEL by 1.8 dB and adding air gun number 15 to an array of 14 air guns of the same size only adds 0.3 dB to the overall sound pressure level and the mean single pulse. The discussion of the implications of this for the effectiveness of soft start protocols as mitigation measures is ongoing and it is thus at present not prudent to provide guidance on the issue of how a soft start protocol should be designed optimally to achieve the objectives with respect to the best protection of animals from acquiring PTS or other injuries.

A secondary issue related to soft starts is possible protocols related to line changes in the survey. A general guiding rule of mitigation should be to limit noise emissions to only what is required to fulfil the objectives of the survey. It is thus reasonable to ask for a shutdown of arrays whenever data are not collected. This includes most importantly whenever the survey vessel is turning and/or changing from one transect line to another. Start-up of the array when arriving to the start of the new line should be conducted with a soft start procedure. However, it makes sense to modify the protocol for turns and line changes that take less time to complete than the duration of a complete soft start procedure (typically 20 or 30 minutes). In those circumstances, it is suggested not to shut down the array completely, but to keep a single, small gun active. This single air gun, often referred to as a mitigation gun (EAMRA 2015), has the role of alerting marine mammals to the presence of the seismic vessel and prevent them from entering the safety zone around the array before the onset of all air guns and allowing operation to commence at full power without going through soft start procedures once the start of the new line is reached.

5.4 Alternative seismic sources and techniques

A number of experimental techniques and analysis methods are available. This includes a modified air gun called the eSource (Norton 2015), which allows for better control of high frequency noise emissions (presumed to be the problematic part of the noise for marine mammals); the Vibroseis seismic source (Jenkerson et al. 2015), which is an alternative seismic source producing continuous noise rather than impulsive noise and the so called ”popcorn” analysis protocol (Abma 2015), in which air guns in the array are not fired simultaneously (limiting the peak levels emitted), but the peak is restored afterwards by signal processing of the received echoes. The experience with these new alternatives is limited and no guidance can thus be provided at present, but the development should be followed closely and operators should be encouraged to conduct experiments with the new types of sources.

5.5 Summary

A range of methods is available for mitigating impacts of seismic surveys. As a general rule, the size (source factor) of an air gun array should never be larger than what is required by the purpose of the survey. Furthermore, surveys should, if possible, be conducted at times of the year when animal abundance is low (if such periods exist) and outside the periods when animals are most vulnerable (breeding season and period when mothers have dependent calves).

Visual observers (MMOs) and passive acoustic monitoring (PAM) are effective as mitigation in the sense that it protects those animals, which are detected, from injury. The methods are not efficient, however, in the sense that the likelihood that animals will remain undetected and hence exposed to loud noise inside the safety zone, is very high, particularly for seals and porpoises and especially during periods of darkness and high sea states. Currently no techniques are available that will offer this protection to full extent, leaving MMOs and PAM as only incomplete mitigation measures.

Although generally considered “best practice”, benefits of soft start procedures during start-up of air gun arrays have not been documented and the optimal protocol for these is currently disputed. However, they will protect nearby animals from PTS and other injury at the beginning of the transect lines and after shut-downs on lines. There is a need for further evaluation of the effectiveness of soft starts and whether revised protocols can provide the same or additional protection of marine mammals from potentially injuring sound levels.

The use of a single, small air gun during line changes and turns shorter than the time to complete a soft start procedure, is considered beneficial.

New techniques, such as the eSource, Vibroseis, and the “popcorn” protocol may offer better possibilities for mitigating effects on marine mammals, but experience is still limited.

6 Pile driving

Pile driving of structures such as conductor pipes and jacket structures can generate very loud noise, not unlike the noise from seismic air guns. Much of the requirements of the modelling are thus similar to modelling of air gun noise, with one important exception. This relates to the fact that the noise source during pile driving is stationary, in opposition to a moving seismic vessel. This means that animals close to the pile-driving site at onset of piling can be exposed to significant levels of noise before they are able to swim sufficiently far away from the piling site.

The requirements for predictive modelling and measurements have already been established for pile driving related to offshore wind farm construction (Skjellerup et al. 2015, Skjellerup and Tougaard 2016). These recommendations should be consulted and applied to pile driving in connection to offshore oil and gas installations.

The key elements of the guidelines are a specified method to estimate the sound exposure experienced by marine mammals around the piling site and methods to evaluate the mitigation measures required. The modelling is conceptually similar to the modelling of cumulative exposure in section 4 above: sound exposure level is to be summed over the entire duration of the activity (piling of one monopile), taking into account that the animals react to the sounds by fleeing. The effect of mitigating measures, such as the use of deterrent devices (seal scarers) prior to pile driving, in order to deter animals from the vicinity of the piling site, should also be included in the exposure model. Thus, the modelling is to proceed in several steps where first the need of deterrent devises is addressed, and if these measures are insufficient, the level of additional source reduction required is determined. This additional reduction can be achieved by other means, such as air bubble curtains.

7 Other surveying techniques

Seismic survey with an air gun array is only one among a suite of survey techniques used in oil and gas exploration and extraction. It is beyond the scope of this report to enter a full discussion of these techniques but for completeness follows a short description of selected techniques and some of the issues with respect to potential impact attached to these.

7.1 Vertical seismic profiling

In vertical seismic profiling one or more hydrophones are lowered into a well and a seismic signal is transmitted from one or more air guns in the water above the well, with the aim of verifying the coupling between acoustic signatures and geological strata. As the recorded signals are directly transmitted and not echo bouncing off structures deep in the sea bed, the required source strength is much lower than for regular seismic profiling. Also the duration of the transmissions is very short compared to surveys covering larger areas. The sounds from the air guns used for vertical seismic profiling are no doubt capable of disturbing behaviour of marine mammals and thus an impact should not be excluded beforehand, but impact ranges are expected to be much smaller than for large air gun arrays.

7.2 Sub-bottom profiling

A number of techniques are available for seismic surveys targeting only the uppermost layers of the sea bed and used for various surveys including search for shallow gas pockets and planning of pipe lines and / or platform structures on the sea bed. These techniques include so-called “sparkers”, where sounds are generated by electric sparks; “boomers”, where an electrodynamic sound source is used and “chirpers” which use piezoceramic transducers, but also very small air gun arrays (down to a single small sleeve gun) can be used. They thus constitute the lower end of a continuum of seismic sound sources, which end with the largest 4000+ inch^3 arrays used for surveys targeting very deep structures in the ocean bed. Very little information is available about the noise emissions from these sound sources (see Hermannsen et al. 2015 for a discussion of effects of a single sleeve gun), but sound levels are considerable and effects on behaviour of marine mammals is clearly to be expected in the vicinity of the sound sources. TTS / PTS also cannot be ruled out without further evaluation. It is, however, beyond the scope of this document to assess this further.

7.3 Echo sounders and multi-beam sonars

Echo sounders are instrumental to safe navigation and their use is mandated by general regulations surrounding navigation. The possibilities for regulating their use based on environmental concern are thus restricted. Echo sounders use a wide range of different frequencies and depending on the frequency used can have a small or large potential impact on marine mammals. Common, however, for echo sounders is that they typically emit their powerful sound in a narrow beam vertically towards the sea floor, restricting the sound propagation away from the ship. Deep water echo sounders typically operate at low frequencies (38 kHz is common), but can be down to 10 kHz, while echo sounders with greater resolution but for shallower depths (fish finders) can operate at higher frequencies, typically 120 kHz but can be beyond 200 kHz.

As harbour porpoises and other odontocetes have their upper hearing limit somewhere between 150 and 180 kHz, it is unlikely that echo sounders operating above 180 kHz will have any significant effect. Echo sounders operating at lower frequencies are likely to have disturbing effects on marine mammals, but the extent of this disturbance has not been well studied. Because of the directional beam, however, impact ranges around the ship are expected to be relatively small.

The sounds from sonars, whether hull mounted or towed systems, are comparable to echo sounder signals, but the fact that they are often directed forwards or sideways from the ship means that the impact ranges are expected to be larger than for echo sounders. There are numerous examples of strandings of whales (in particular species of beaked whales) associated with the use of sonar (Frantzis 1998, Evans and England 2001, Filadelfo et al. 2009). All have been very powerful military sonars, however, and conclusions should not be transferred to less powerful side scan sonars, which are also operated in a totally different way than navy sonars during active submarine hunting. There is one example, however, of a mass stranding of melon-headed whales on the coast of Madagascar, likely associated with the operation of a (very powerful) bathymetric multi-beam sonar (Southall et al. 2013). As for echo sounders it is expected that sonars operating at frequencies above 180 kHz will have no significant impact on marine mammals.

7.4 Electromagnetic measurements (CSEM)

In controlled source electromagnetic surveys (CSEM) the physical properties of the sea bed are investigated by emission of a strong electromagnetic signal from a streamer (antenna) towed close to the sea bed. The frequency of the signals are very low, below 1 Hz, but with higher harmonics.

Experience with the technique is limited, but environmental impact has been assessed to be negligible by several authors (Fechhelm 2005, Constable 2010, LGL Limited 2014).

7.5 Magnetometers and gravimeters

The sea bed can also be studied with passive instruments such as magnetometers and gravimeters that measure variation in the earth's magnetic and gravitational fields, respectively. As these instruments do not emit sound, except perhaps for controlling the position of the instrument above the sea floor, the potential impact on marine mammals is likely reduced to the disturbing effects of the vessel itself.

7.6 Summary

A range of other surveying techniques is used in connection with oil exploration and extraction activities. In terms of potential impact these techniques overlap in terms of predicted impact ranges and form a continuum from range from unlikely to have any impact (passive instruments such as magnetometers and gravimeters) to very likely to have effects on behaviour and possibly also auditory damage at close range (various techniques for sub-bottom profiling). There is thus no clear gap in terms of magnitude of potential impact between air gun arrays and the other techniques: A sub-bottom profiling survey with a large sparker as sound source may thus have larger impact on marine mammals than a survey with a single, small air gun. Determining whether or not to conduct an impact assessment should thus not be based on the survey technology, but on the likelihood of significant impact on marine mammals, with this impact being a reflection of emitted noise levels as well as temporal and geographical extent of the survey.

8 References

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INPUT TO REVISION OF GUIDELINES REGARDING UNDERWATER NOISE FROM OIL AND GAS ACTIVITIES - EFFECTS ON MARINE MAMMALS AND MITIGATION MEASURES

Seismic surveys in connection to oil and gas activities have the potential to disturb and injure marine organisms, due to the high sound pressures generated by air guns. An adaptive framework for modelling and assessing the impact on marine mammals in particular is presented, together with a discussion of possible mitigation measures. Other survey methods and sources of loud underwater sound are also briefly discussed.

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