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Cefas contract report: C6082

ENV.D.2/FRA/2012/2005: Impacts of noise and use of propagation models to predict the recipient side of noise

Supplementary Annexes

Issue date: May 2015

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ENV.D.2/FRA/2012/0025: Impacts of noise and use of propagation models to predict the recipient side of noise

Supplementary Annexes

Issue date: May 2015

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Task 1: Current Noise Legislation and Mitigation Initiatives

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Issue date: 17 June 2014

National Physical Laboratory

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Cefas Document Control

Title: ENV.D.2/FRA/2012/0025: Impacts of noise and use of propagation models to predict the recipient side of noise

Task 1: Current Noise Legislation and Mitigation Initiatives

Submitted to:	Paula Valcarce-Arenas (DG Environment)
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Approved by & date:	K. Baker 30/11/ 2014
Version:	2.1

Version Control History			
Author	**Date**	**Comment**	**Version**
S. Watts	30/05/2014		1
J.F. Borsani	17/05/2014	Added section 3.4	2
K. Baker	30/11/2014	Authorship revised	2.1

Title: ENV.D.2/FRA/2012/0025: Impacts of noise and use of propagation models to predict the recipient side of noise

Task 1: Current Noise Legislation and Mitigation Initiatives

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Issue date: 30 May 2014

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1 Introduction

The purpose of this review is to highlight the current noise legislation and mitigation initiatives that are currently in place. This document aims to highlight the variation in noise mitigation measures that are imposed with a variety of legislative and enforcement frameworks. Key drivers to developing European legislation are Member states responsibility to implement the Marine Strategy Framework Directive. Much of the current legislation and best practice focuses on mitigating the impact of underwater noise on marine mammals with less legislative focus on other species which may also be affected by acoustic stimulus. A detailed review of the biological impact of underwater noise is given later as part of this literature review.

1.1 Methods of reducing or mitigating the effects of underwater noise

Specific methods used to reduce and mitigate the effects of anthropogenic underwater noise vary from country to country. However, the general approaches can be grouped into the following categories:

- **Location and timing -**Avoiding particular sounds at places and times of known higher sensitivity.
- **Mitigation equipment** -Acoustic barriers are being considered in some European countries as a method of absorbing some of the sound associated with pile driving.
- **The Source** -A stipulated technique for pile installation or a minimum practical output power level is used.

1.1.1 Mitigation Procedures

1 **Mitigation zone/ Exclusion Zones** -Real-time mitigation around the radius of a sound source, either prior to the noise emitting activity commencing or throughout the duration of the activity (e.g. UK, Australia). A mitigation zone is observed by a Marine Mammal Observer (MMO) but passive techniques can also be used as support such as Passive Acoustic Monitoring (PAM) and Acoustic Mitigation Devices (AMDs).

2 **Pre start up visual Observation -**A period of observation 30 minutes prior to operations or 1 hour prior to the use of explosives (JNCC guidelines, 2010), if marine mammals are not detected then operations can commence.

3 **Passive Acoustic Monitoring (PAM)** -This is a recommendation in addition to MMO's, particular during times of poor visibility (e.g. New Zealand)

4 **Low Power and Shut Down Zones** -If animals enter these zones then operators switch to low power or shut down operations (e.g. USA) (Erbe, 2013)

5 **Operational procedures** -e.g. soft start (ramp up) is a method of providing source level control by incrementally increasing the sound to allow sensitive species to avoid the area (JNCC seismic survey guidelines, 2010).

6 **Acoustic Mitigation Devices** – These devices are a deterrent by releasing safe sounds to ensure that marine mammals are not present in the area where loud noises are being produced.

2 International Mandatory/Legislative Requirements

The following sections highlight a variety of noise legislation and best practice recommendations. These are characterised under mandatory legislation requirements and best practice techniques both at a national and an international level.

2.1 Marine Strategy Framework Directive (MSFD)

The Directive requires Member States to develop an ecosystem based approach to marine management. It uses 11 qualitative high-level descriptors to achieve 'Good Environmental Status (GES)', with the indicators under the 11th descriptor addressing impulsive sound (11.1) and continuous ambient sound (11.2). Currently the majority of monitoring of underwater noise has been undertaken at a project or species level (Van der Graaf et al, 2012) with future focus on a broader assessment.

The latest TSG noise report provides monitoring guidance for Member States to monitor underwater noise in European Seas, for filling their MSFD requirements. The report focuses on address current ambiguities and uncertainties that may currently hinder monitoring. It highlights the need for further scientific and technical progress to support the further development of this descriptor, including improved understanding of the impacts of the introduction of energy to marine life and the relevant noise and frequency levels. (TSG Noise, 2013). This acts as a European driver to noise mitigation and legislative requirements.

Currently, the MSFD is the only truly effective legislation that addresses directly the issue of noise. With the aim of reaching GES for noise through setting appropriate targets member states will have to actually regulate the emission of underwater noise in a variety of ways. Currently monitoring programmes and studies are being evaluated at the member state level.

The Helsinki Commission (HELCOM) has been set up to protect the marine environment of the Baltic Sea from all sources of pollution by intergovernmental co operation. The CORESET project by the commission is developing a set of indicators to assess the effectiveness of the MSFD and the Baltic Sea Action Plan. The indicator for underwater noise is likely to involve mapping of anthropogenic noise using soundscape maps, forming part of a GIS planning tool. This is initially showing the underwater noise generated by commercial vessels and the modelling of noise footprints of intermittent operations such as pile driving. This is one of the first stages of implementation of the MSFD.

2.2 BIAS Project

The Bias project has been established to bridge the gap between the indicators of the MSFD Descriptor 11 and the actual management of human induced underwater noise. Although it does not currently form in any way part of any available legislation, its results are thought to be highly valuable for the further development of D11.2. Hence the information related to this project is included here after the paragraph on the MSFD. The project is currently in progress and is aiming to establish and implement standards and tools for the management of underwater noise. It aims to demonstrate the national and regional advantages of a transnational approach by planning a cost effective and regionally coordinated approach to the management of underwater noise in the Baltic Sea. An objective of part of this project is to implement a user friendly GIS based planning tool and simplified calculations for the management of intermittent sound e.g. piling and underwater explosions (BIAS, 2013).

2.3 The International Law of the Sea

The International Law of the Sea states that pollution of the marine environment " means the introduction by man, directly or indirectly, of substances or energy into the marine environment, including estuaries, which results or is likely to result in such deleterious effects as harm to living resources and marine life...” (UNCLOS, 1982). Within this description energy has always been implicitly interpreted as inclusive of the effect of human induced underwater noise.

3 International Best Practise

3.1 OSPAR Convention

OSPAR coordinates international cooperation on the protection of the marine environment of the northeast Atlantic and includes 15 European countries, the European Commission and represents the European Union (EU). Member states have a responsibility to implement MSFD requirements through OSPAR. Guidelines and regulatory controls are already used in several OSPAR countries, including pile driving noise reduction (UK), a ban on pile driving during key reproductive periods for particular species (Netherlands) or the mandatory use of thresholds to limit man-made emissions with certain acoustic characteristics (Germany) (OSPAR, 2010).

Some noise generating activities including oil and gas developments and construction of offshore wind farms are regulated by the Environmental Impact Assessment Directive (85/337/EEC (as amended by 97/11/EC)). This Directive requires Member States to perform an Environmental Impact Assessment (EIA) if projects are likely to have significant effects on the environment (OSPAR, 2009).

Although noise mitigation guidance has been developed it is likely that the application of these measures will vary within the OSPAR area. Aside the EC EIA Directive (85/337/EEC) and Habitats Directives (92/43/EEC) there are very few other regulations specifically addressing noise in the marine environment. In addition it is currently difficult to provide an evaluation of the effectiveness and adequacy of the measures taken and to protect the marine environment against the effects from underwater noise (OSPAR, 2009). OSPAR highlights the need for further research to monitor the distribution of sound sources and the relevant marine species and the urgent need to standardise methods for assessing the impacts of sounds and to address the cumulative effects of different noise sources (OSPAR Quality Status Report, 2010).

3.2 ACCOBAMS

The agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and Contiguous Atlantic Area (ACCOBAMS) was signed by 23 countries bordering these waters. It should be noted that this is no legal obligation to enforce this agreement. It was adopted in 2002 with a number of relevant resolutions on noise suggested (Res. 2.16 on assessment and impact assessment of man-made noise (including the currently largely unknown chronic effects of increasing anthropogenic noise at a population level) urging a collaborative and coordinated temporal and geographic mapping of local ambient noise; Res. 3.10 on guidelines to address the impact of anthropogenic noise on marine mammals in the ACCOBAMS area (encouraging parties to develop quieter and environmentally safer acoustic techniques, proposing mitigation methods to avoid key marine mammal habitats, avoiding areas of high marine mammal population densities and Marine Protected Areas in light of cumulative, seasonal, and impacts from multiple sources); Res. 4.17 on guidelines to address the impact of anthropogenic noise on cetaceans in the ACCOBAMS area to propose mitigation methods for a variety of noisy activities; and Res. 5.13 on conservation of Cuvier's beaked whales in the Mediterranean to avoid mass strandings (recognising frequent exposure to intense underwater noise). These resolutions cover the most relevant issues related to noise in the ACCOBAMS area and suggest further actions.

3.3 ASCOBANS

The Agreement on the Conservation of Small Cetaceans in the Baltic, North East Atlantic, Irish and North Seas (ASCOBANS) has a specific requirement for all parties to address the effects of underwater noise to protect small cetaceans. It aims to promote close cooperation between countries to achieve this. It offers recommendations for the timing of seismic surveys, reduction of noise levels and monitoring for presence of marine mammals. Recommendations for best working practices are being developed including limiting work during periods of high density of marine mammals (ASCOBANS, 2009). However, there is currently no legal enforcement of these recommendations.

3.4 IMO MEPC

During its sixty-sixth session held 31 March -4 April 2014 in London, the International Maritime Organisation -Marine Environment Protection Committee (IMO MEPC) has adopted a draft MEPC circular on *Guidelines for the reduction of underwater noise from commercial shipping* (DE 57/25, annex 14). These guidelines are non-mandatory and suggest a detailed work programme which is listed below for ease of reference:

1) including a specific noise reduction target from the 2008 Hamburg International Workshop on Shipping Noise and Marine Mammals: to reduce the contribution of shipping to ambient noise levels in the 10-300Hz range by 3dB in 10 years and 10dB in 30 years, relative to current levels;
2) evaluating the contribution of underwater noise from vessels and other sources (landbased, drilling, ice breaking, etc.) so that mitigation can be directed at the largest contributor(s);
3) quantification of the relationship between individual ship noise and regional ambient noise level reductions;
4) continued progress in quantifying and understanding the adverse impact of noise on marine species;

5) setting operating guidelines for sensitive marine areas that have significant noise issues where specific operational and/or design measures may be needed to fundamentally reduce underwater noise from ships that operate there regularly, because of their impact on marine life;

6) identifying the types of areas and situations where waterborne noise is most disruptive for marine life (near-shore, during migration, ice breaking, etc.);

7) using standardized measurement protocols to develop noise profiles for each ship type under different operating conditions;

8) identifying the noisiest ships to gain a better understanding of the factors that elevate the noise levels of these ships;

9) establishing baseline ambient noise levels in ocean areas of key concern such as those with high levels of marine biodiversity where shipping activities are forecasted to rapidly increase; and

10) collect and provide information on sensitive areas, including well-known habitats or migratory pathways, to shipmasters and owners for the purpose of voyage planning.

The work programme indicates that the MEPC suggests that a decrease in overall underwater noise as emitted from ships is desirable, both for achieving more energy efficient propulsion systems as well as for reducing the potential impact noise may have on marine mammals.

It is beyond of scope of the review to judge if the work programme is fit for purpose, or if an overall decrease of underwater noise is sufficient for reaching GES or even desirable. However, it is worth noting that as the MEPC guidelines are non mandatory, they may therefore have little, if any effect at all in the short term for the purpose of reaching GES.

4 National Best Practise

4.1 United Kingdom

The Joint Nature Conservation Committee (JNCC) has guidelines for seismic surveys, the use of marine explosives and marine piling.

The seismic survey guidance (JNCC, 2010) aim is to reducing the risk of injury to negligible levels and reducing the risk of disturbance from seismic surveys. In the UKCS (United Kingdom Continental shelf) it is a requirement of the consent issued under regulation 4 of the Petroleum Activities that JNCC seismic guidelines are followed and any site survey specific guidance is incorporated into the legally binding condition of consent. The guidelines reflect the Conservation of Habitats and Species Regulations 2010 for England and Wales and the offshore Marine Conservation Regulations 2010 which apply to the UK Continental Shelf. The guidelines state that pre shoot survey should be conducted 30 minutes prior to commencement of airgun firing or 60 minutes in deep waters (›200m) due to the potential presence of deep diving species (such as sperm whales) known to dive for longer than 30 minutes. Soft start procedures should be followed from a low energy start for 20 minutes until full power is achieved. Passive Acoustic Monitoring (PAM) is recommended as a support tool for MMOs and as the mitigation technique in poor visibility.

The installation of marine driven piles without mitigation is likely to produce noise levels capable of causing injury and disturbance to marine mammals, having the potential to conflict with the legislative provisions of the Conservation of Habitats and Species Regulations 2010. The guidance for piling does not document measures to mitigate disturbance effects but has been developed to reduce to negligible levels the risk of injury or death to marine mammals in close proximity of piling operations. It has been incorporated into FEPA (now Marine Licence) Licence conditions for wind farm consent. Developers have to demonstrate that Best Available Technique (BAT) is being used. It seeks to balance the highest level of environmental protection against commercial affordability and practicality. Techniques such as hammer modifications, sleeving, muffling, the use of vibratory hammers and gravity based piling may all reduce noise levels from piling. However, developers may be able to demonstrate that certain installation methods are unsuitable as they do not amount to BAT (JNCC, 2010).

Seasonal considerations may be appropriate, e.g. "during periods of seal pupping when there is clear season demarcation in animal occurrence and seasonal restrictions would have practical application" (JNCC, 2010). MMOs should conduct a pre piling search for 30 minutes, observing a 500m mitigation zone from the pile diving. PAM systems can also be used as an MMO support tool. Prior to full power piling soft start procedures should also be utilised for 20 minutes with an incremental ramp up of power. Piling is prohibited in darkness or poor visibility when the sea state is not conducive to visual mitigation but if a developer feels this is unduly restrictive, the burden of proof lies with the developer to demonstrate that effective mitigation can be delivered. The guidance references that the use of ADDs have the potential to reduce the risk of causing injury to marine mammals. However, the evidence relating to the efficacy of acoustic deterrents such as pingers is currently limited and more research is needed to determine their applicability as suitable mitigation measures. If ADDs are used they should be used in accordance with recommended conditions that would prevent exposure of animals to disturbance that would constitute an offence under regulations 41 and 39 of the Habitats Regulations and the Offshore Marine Regulations. A wildlife licence under the Wildlife and Countryside Act 1981 may also be required to authorise a potential intentional disturbance (JNCC, 2010).

The JNCC guidance for the use of explosives is generic guidance that should be customised and incorporated into an Environmental Management Plan for a specific activity. The guidance recommends the use of MMOs and PAM in establishing mitigation zones around explosive detonations. 1km is the standard distance recommended which can be increased or decreased dependent on the size of the explosive and the proximity to marine mammals. If multiple explosive charges are used, smaller charges should be detonated first to maximise the 'soft start' or ramp up effect. This guidance is aimed at reducing the risk of injury to marine mammals to negligible levels (JNCC, 2010).

These guidance documents are incorporated into FEPA (now Marine Licence) licence conditions and are then legally enforceable part of the licence consent. These are long established guidance recommendations that have been established for almost 20 years and have undergone review and amendment. This demonstrates the continual improvements in technical advances and knowledge of best available techniques and changes in the legislative frameworks.

4.2 New Zealand

New Zealand does not currently have any regulations governing underwater noise exposure for marine fauna but a code of conduct has been drafted for minimising the acoustic disturbance to marine mammals from seismic survey operations and was published in 2012 (New Zealand Department of Conservation, 2012). The Code has been endorsed as industry best practice by the Petroleum Exploration and Production Association of New Zealand (PEPANZ). It has been developed by the Department of Conservation in collaboration with a range of domestic and international stakeholders. This best practice is not currently legally enforceable but it is likely that it will form the basis of future regulations, subject to a performance review in 2015.

The code is primarily concerned with the protection of marine mammals. However proponents are also encouraged to adopt whatever means are available to avoid or mitigate negative effects on other key species (such as turtles, penguins and seabirds) or key habitats identified in the planning stage as being potentially impacted by the operations.

A core component of the process is use of the lowest practicable power levels for acoustic surveys. It is recommended that marine seismic surveys are not undertaken in sensitive, ecologically important areas during key biological periods where the species of concern are breeding, calving, resting, feeding or migrating.

The Code considers three levels of seismic surveys given below:

1. Level 1 (Source> 427 in^3): minimum of two MMOs and two PAM operators present at all times: Pre-operation MMO and PAM survey of 30 minutes over mitigation zone; 20-40 minute soft-start; 1.5 km shut down zone for species of Concern calves; 1 km shut-down zone for Species of Concern without calves; delayed start if Other Marine Mammal within 200 m (primarily include large-scale geophysical investigations that would routinely be employed in oil and gas exploration activities. This level features large geophysical surveys routinely used by the Oil and Gas industry with dedicated marine seismic survey vessels, but may also apply to other studies using high-power acoustic sources).
2. Level 2 (source 151-426 in^3): minimum of two MMOs present at all times; PAM optional; pre-operation MMO survey of 30 minutes over mitigation zone; 20-40 min soft-start; 1 km shut-down zone for species of Concern with calves, 600 m shut-down zone for species of concern without calves; delayed start if Other marine mammal with 200 m.
3. Level 3 (source < 150 in^3, sparklers, pingers, boomers); no specific mitigation methods.

The Director General must be notified of Level 1 and 2 surveys at least three months in advance. The proponent must prepare a Marine Mammal Impact Assessment (MMIA), describing the proposed activities, identifying all potential effects on marine species and habitats and detailing an impact mitigation measures.

5 National Mandatory/Legislative Requirements

5.1 Germany

The German Federal Maritime and Hydrographic Agency (BSH) have set a sound level threshold value that must not be exceeded outside a 750 m radius around a pile. This is set as 190 dB re 1µPa (unweighted broadband peak to peak SPL) (Federal Agency for Nature Conservation (Bundesamt für Naturschutz, BfN), 2013). There is an exclusion zone for marine mammals 750 m around pile driving activity. The threshold level is based upon an exposure level to a single seismic impulse reported to induce an onset of a temporary threshold shift in harbour porpoise (Lucke et al. 2009). The value has been rounded down to allow for cumulative effects and inter species variability. The exclusion zone around pile driving has been established with the intension of avoiding a temporary threshold shift (TTS). There are additional considerations for temporal and spatial restrictions at times of high animal abundance. It should be noted that, although this sound level threshold value has been implemented, it has never been met until now and that, with current rates of installation much of the piling construction works will already have been completed before technology achieves this threshold.

5.2 Australia

The National Offshore Petroleum Safety and Environmental Management Authority (NOPSEMA) came into effect in January 2012. It is responsible for monitoring and enforcing compliance with the Offshore Petroleum and Greenhouse Gas Storage Act 2006 and (Environment) Regulations 2009 in Commonwealth waters. The requirement of the Regulations is for petroleum activities to be carried out in a manner consistent with principles of ecologically sustainable development and with an Environment Plan (EP) created and accepted by NOPSEMA before activities can commence. The regulations utilise a risk-based approach for managing environmental performance to reduce environmental impacts to as low as reasonably practicable (ALARP) in order for a petroleum activity to proceed. This can allow operators to employ innovative environmental protection measures that are tailored to specific circumstances. Ideally this will aid discussion and help develop good environmental best practice (NOPSEMA, 2012.) An EP put forward to NOPSEMA describes the natural physical and biological environment, including any environmental receptors that may be affected by the proposed operations and spatio-temporal sensitivities (e.g. breeding, spawning and migrating animals etc.) The intent of the document is to be used as a practical implementation and regulatory tool. Unlike many other jurisdictions the regulations do not describe a specific approach to reducing the environmental risk (e.g. acoustic exposure thresholds). Rather it considers proposals on a site by site basis with no single approach (or threshold) that suit all situations. This approach recognises that what is considered “reasonable practicable” will change over time as technology and expertise improves (Erbe, 2009; 2013).

5.3 United States (US)

In the US marine mammals are protected by the Endangered Species Act (ESA), and the Marine Mammal Protection Act (MMPA). The latter specifically protects marine mammals from anthropogenic noise. It is administered by the National Marine Fisheries Service (NMFS, a part of the US National Oceanic and Atmospheric Administration (NOAA)) and the Fish and Wildlife Service, but NMFS take the more active lead in managing the impact of underwater noise. Under MMPA amendment 1994 harassment is defined as any act of pursuit, torment or annoyance that has the potential to injure (Level A harassment) or to disturb (Level B harassment) a marine mammal or marine mammal stock in the wild. Level B harassment includes the disruption of behavioural patterns, which includes but is not limited to migration, breathing, sheltering, feeding, nursing, and breeding. Permission can be granted by NMFS for incidental ‘takings’ if the taking is believed to have a ‘negligible’ impact on animal population. However, this brings its difficulties of demonstrating the impact at a population level. Take is defined as harassment, hunting, capture killing or collection. In the US marine mammals are protected by the Endangered Species Act (ESA), and the Marine Mammal Protection Act (MMPA). The latter specifically protects marine mammals from anthropogenic noise. It is administered by the National Marine Fisheries Service (NMFS, a part of the US National Oceanic and Atmospheric Administration (NOAA)) and the Fish and Wildlife Service, but NMFS take the more active lead in managing the impact of underwater noise. Under MMPA amendment 1994 harassment is defined as any act of pursuit, torment or annoyance that has the potential to injure (Level A harassment) or to disturb (Level B harassment) a marine mammal or marine mammal stock in the wild. Level B harassment includes the disruption of behavioural patterns, which includes but is not limited to migration, breathing, sheltering, feeding, nursing, and breeding. Permission can be granted by NMFS for incidental ‘takings’ if the taking is believed to have a ‘negligible’ impact on animal population. However, this brings its difficulties of demonstrating the impact at a population level. Take is defined as harassment, hunting, capture killing or collection. (National Marine Fisheries Service (NMFS), 2008)

Policy Statement 2.1 under the Environmental Protection and Biodiversity Conservation (APBC) Act 1999 provides a framework designed to minimise the acoustic impacts to whales (baleen and large toothed whales) from marine seismic surveys. This includes avoiding sensitive breeding, calving and feeding areas. This utilises a 30 minute pre-operation observation period and the utilisation of soft start procedures. However there is no policy statements for smaller dolphins and porpoises and the only noise source directly stated in the policy statements is airguns. With these regulations the onus is on the operator to decide if a proposal is likely to have an impact on a matter of national environmental significance

In the US a range of criteria are used to assess the potential impact on marine mammals, fish and sea turtles. For marine mammals the NMFS criteria are used to assess the impact of impulsive and continuous sounds. For the effects of sonar and other active acoustic sources the United States Navy criteria have been developed for marine mammals and sea turtles. With respect to fish, the US currently adopts the interim injury criteria for piling noise as advised by the Fisheries Hydroacoustic Working Group (FHWG, 2008). New injury criteria for fish are expected from an Acoustical Society of American standards working group (Fay and Popper, 2006). There is currently a review[1] being undertaken of the NMFS policy (NMFS, 2000) in relation to marine mammals. This review has set out to use the best available science and the draft document indicates alternative threshold levels and noise exposure metrics and a refined approach for the assessment of potential impacts from noise on marine mammals are being considered (see NOAA, 2013)

Predicting how the loss of animals will affect a population is relatively well known. The challenge is the ability to assess if or how a marine mammal behaviour response (i.e. level B harassment in the US) in the short term results in a "biologically significant" or meaningful effect on individuals and their respective populations by potentially reducing their survival rate or annual recruitment (National Research Council, 2005).

It is highlighted by National Research Council (2000) that regulations must focus on significant disruption of behaviours critical to survival and reproduction. An action or activity becomes biologically significant to an individual animal when it affects the ability to the animal to grow, survive and reproduce. Thus these are the effects on individuals that can have population consequences.

Assessment of relevant population effects involves policy decision making as well as making scientific judgements. Although in the US there is an assessment (IHA) required under the MMPA on the level of “take” little is currently known how takes might reduce survival or annual recruitment.

1 [1] *Status of NOAA's Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammals can be viewed online: http://www.nmfs.noaa.gov/pr/acoustics/guidelines.htm*

5.4 Population Consequences of Acoustic Disturbance (PCAD)

In addition to specific national underwater noise regulations more generic approaches to assessing the impact of underwater noise on marine life have also begun development. One such approach which considers the potential population level consequences of underwater noise on marine life is the Population Consequences of Acoustic Disturbance (PCAD) model developed for marine mammals (National Research Council, 2005). The model considers a number of levels between the underwater sound and any related population effect. It should be noted, however, that assessing population effects caused by a disturbance is still in its infancy and compounded by the difficulty to discern effects of multiple factors on highly mobile and remote marine organisms.

The aim of the PCAD framework is a quantitative approach to help evaluate effects and the relationship between takes and possible changes to adult survival or animal recruitment. This indicates a positive step forward and a more rigorous and informed approach on the impact of behavioural response.

The initial developed of the PCAD model has begun to aid understanding and help predict the complexity in tracing acoustic stimuli to population effects. A key assumption to the modelling is that all individuals in a population respond to acoustic stimuli in the same manner. However, a variety of new statistical techniques are being developed, taking into account variations individual response.

The model is built on observation data. It is connected through transfer functions to develop an understanding of the population consequences of an acoustic disturbance. The transfer functions that are included within the model are shown in the figure given below (NRC, 2005).

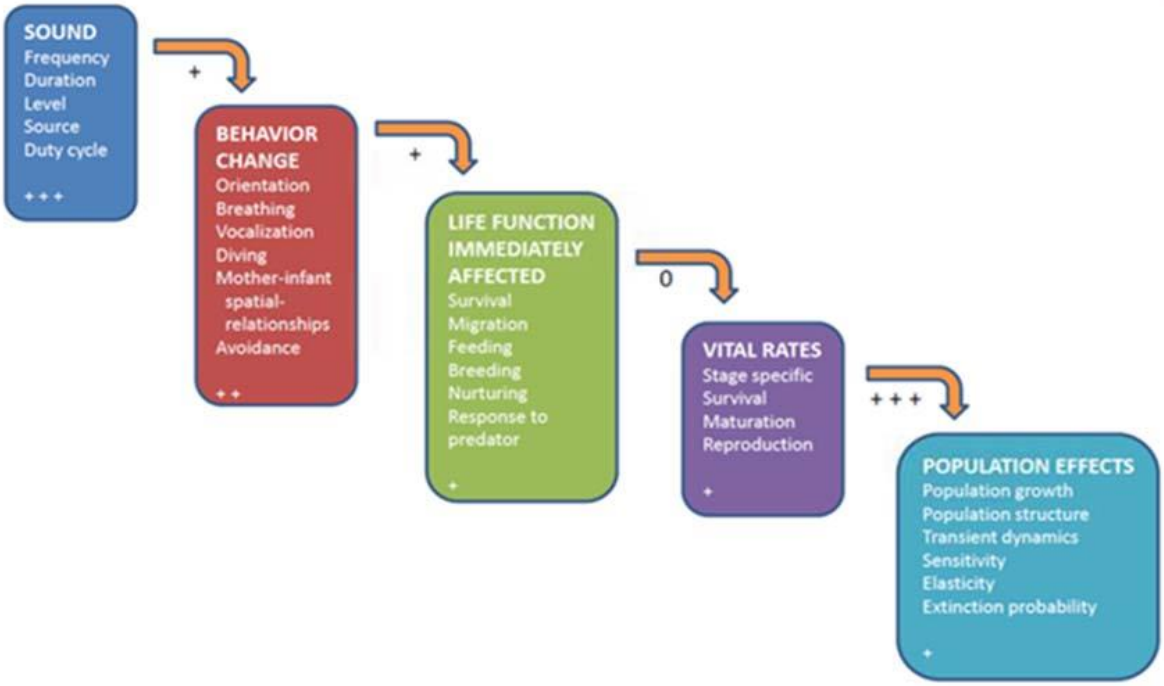

Figure 1 Stages of PCAD model development Source: National Research Council 2005

The US office of Naval Research has supported a PCAD working group to implement this model approach, set up in September 2009. In the model a distinction is made between income breeders (species that produce offspring using energy gained concurrently) and capital breeders (those that produce offspring using energy stores accumulated at an earlier time) (Houston et al, 2007). However, such models are in their infancy and require diverse robust data sets. It is currently considered too complex for implementation in a legislative arena.

6 Conclusions

Regulation and enforcement vary greatly from country to country with different bodies regulating noise in a variety of methods. Currently there are national and international best practice guidelines in place with a variety of different levels of legal enforcement. Some guidelines have been incorporated into legally enforceable legislation, where other agreements are not currently legally enforceable (e.g. ASCOBANS, ACCOBAMS). Some are currently working best practice recommendations that are not currently enforceable but are likely to form the basis of future law (e.g. New Zealand).

There is also recognition within current guidance that it is not static and that technological advances will improve the best available techniques, reducing the anthropogenic sound produced.

Up until the MSFD, European Directives (Environmental Impact Assessment, Strategic Environmental Assessment, Habitats and Species) can deal with underwater noise issues, however none deal with ecosystems, none work across national boundaries and none deal with sustainability.

The Marine Strategy Framework Directive has the goal to achieve GES (Good Environmental Status) for European seas, with a repeating six-year cycle of action.

For the descriptor for noise (a pressure) the development of criteria to describe GES has begun within the activities of TG Noise. Further, there is a need to develop metrics or indicators for such criteria, where GES would be a level or a point of that metric or indicator. Clearly, the implementation of the MSFD is the first pragmatic occasion for Europe to draft legislation that may effectively address management and that can be effectively enforced

7 References

ASCOBANS Secretariat, Adverse effects of Underwater Noise on Marine Mammals during offshore construction activities for renewable energy production, Resolution No.2, Bonn, Germany, 2009.

ACCOBAMS Resolution 2.16: Assessment and Impact Assessment of Man Made Noise Guidelines.

ACCOBAMS Resolution 3.10: Guidelines to Address the Impact of Anthropogenic Noise on Marine Mammals in the ACCOBAMS Area.

ACCOBAMS Resolution 4.17: Guidelines to address the impact of anthropogenic noise on cetaceans in the ACCOBAMS Area.

ACCOBAMS Resolution 5.13 Conservation of Cuviers Beaked Whales in the Mediterranean.

BIAS -Baltic Sea Information on the acoustic soundscape 2013. Available at http://biasproject.wordpress.com/ Accessed 26/03/2014

Erbe, C. "International Regulation of Underwater Noise", Acoustic Australia 12 (1) 2013.

Erbe, C. "Underwater noise from pile driving in Moreton Bay, Qld" Acoustics Australia 37(3) 97-92, 2009.

Fay, R.R. and Popper, A.N. ''Working group on the effects of sound on fish and turtles: An update''. *Journal of Acoustic Society of America*, 119, pp. 3284, 2006.

Federal Agency for Nature Conservation (Bundesamt für Naturschutz,BfN) Development of Noise Mitigation Measures in Offshore Wind Farm Construction , published July 2011, update February 2013.

Fisheries Hydroacoustic Working Group (FHWG), ''Memorandum -*Agreement in Principle for Interim Criteria for Injury to Fish from Pile Driving Activities'',* sent to NOAA, US Fish and Wildlife Service, Caltrans, California Dept. of Fish and Game, Oregon Dept of Transport and Washington State Department of Transport, 2008.

Hastings, M.C. "Clarification of the Meaning of Sound Pressure Levels and the Known Effects of Sound on Fish''. White Paper. August 2002.

Houston A.l, Stephans P.A, Boyd, I.L, Harding K.C, Mcnamara J.M. “Capital or income breeders? A theoretical model of female reproductive strategies.” Behavioural Ecology 18 (1), 2007.

International Maritime Organisation, International Maritime Organization Resolution *A.927* (22), 2001.

IMO MEPC 66/17, Noise From Commercial Shipping And Its Adverse Impacts On Marine Life. Outcome of DE 57. 15 November 2013, 10pp.

JNCC: JNCC guidelines for minimising the risk of injury and disturbance to marine mammals from seismic surveys. August 2010.

JNCC: Statutory nature conservation agency protocol for minimising the risk of injury to marine mammals from piling noise. August 2010.

JNCC: JNCC guidelines for minimising the risk of injury to marine mammals from using explosives. August 2010.

Lucke, K, Siebert, U, Lepper P.A, and Blanchet, M.A. “Temporal shift in the masked hearing thresholds in a harbour porpoise (Phocoena phocoena) after exposure to seismic airgun stimuli”, Journal of the *Acoustical Society of America* 125(6), 4060 -4070 (2009).

National Research Council, Marine Mammal Populations and Ocean Noise: Determining when noise causes biologically significant effects. Committee on Characterising Biologically Significant Marine Mammal Behaviour, National Academic Press, 2005.

National Research Council: Marine Mammals and low frequency sound: Progress since 1994: Washington DC: The National Academies Press, 2000.

National Offshore Petroleum Safety and Environmental Management Authority (NOPSEMA) Environmental Plan Preparation, Guidance Note N-04700-GL0931 Rev. 0, NOPSEMA,2012.

New Zealand Department of Conservation, *Code of conduct for minimising acoustic disturbance to marine mammals from seismic survey operations*, Department of Conservation, Wellington, New Zealand, 2012.

National Marine Fisheries Service (NMFS) ‘’Environmental Assessment on the effects of controlled exposure of sound on the behaviour of various species of marine mammals’’, Silver Spring, Maryland, USA. 2000.

NOAA, ''Draft Guidance for Assessing the effects of Anthropogenic Sound on Marine Mammals, Acoustic Threshold Levels for Onset of Permanent and Temporary Threshold Shifts''. pp 76, 2013.

OSPAR Commission -Assessment of the environmental impact of underwater noise. Biodiversity Series, 2009.

OSPAR Quality Status Report, 2010. Available at http://qsr2010.ospar.org/en/ch09_11.html Accessed: 26/03/2014

TSG Noise: Monitoring Guidance for Underwater Noise in European Seas -2nd Report of the Technical Subgroup on Underwater noise (TSG Noise). Part I – Executive Summary. Interim Guidance Report, May, 2013.

United Nations Division for Ocean Affairs and the Law of the Sea: United Nations Conventional on the Law of the Sea (UNCLOS) 1982.

Van der Graaf AJ, Ainslie MA, André M, Brensing K, Dalen J, Dekeling RPA, Robinson S,

Tasker ML, Thomsen F, Werner S (2012). European Marine Strategy Framework Directive

Good Environmental Status (MSFD GES): Report of the Technical Subgroup on Underwater Noise and other forms of energy.

Cefas contract report: C6082

ENV.D.2/FRA/2012/0025: Impacts of noise and use of propagation models to predict the recipient side of noise

Task 1: Compile existing information on impacts

Authors: Rebecca Faulkner, Fabrizio Borsani and Sarah Watts

Issue date: 30th May 2014

National Physical Laboratory

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Cefas Document Control

Title: ENV.D.2/FRA/2012/0025: Impacts of noise and use of propagation models to predict the recipient side of noise

Task 1: Compile existing information on impacts

Submitted to:	Paula Valcarce-Arenas (DG Environment)
Date submitted:	30th May 2014
Project Manager:	Daniel Wood
Report compiled by:	Rebecca Faulkner, J.Fabrizio Borsani and Sarah Watts
Quality control by:	Mandy Roberts, Daniel Wood
Approved by & date:	K. Baker
Version:	2.1

Version Control History			
Author	**Date**	**Comment**	**Version**
D. Wood	31 January 2014	Draft for reviewer comment	1
D. Wood	30 May 2014	Final version	2
K. Baker	30 Nov 2014	Authorship revised	2.1

ENV.D.2/FRA/2012/0025: Impacts of noise and use of propagation models to predict the recipient side of noise

Task 1: Compile existing information on impacts

The Impacts of Underwater Noise on Individuals, Populations and Ecosystems: A Literature Review, from 2006 Onwards

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Issue date: 30th May 2014

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Citation

Please cite as:

Faulkner, R., Borsani, J.F., Theobald, P., Pangerc, T., Watts, S., and S. Robinson. (2014). The Impacts of Underwater Noise on Individuals, Populations and Ecosystems: A Literature Review, from 2006 Onwards. Report for ENV.D.2/FRA/2012/0025: Impacts of noise and use of propagation models to predict the recipient side of noise, Task 1: Compile existing information on impacts. Pp 63.

1 Introduction

There has been very recent progress in science and guidance with respect to underwater sound (Monitoring Guidance for Underwater Noise in European Seas. 2nd Report of the Technical Subgroup on Underwater Noise (TSG Noise). November, 2013). Among others, the usage of the term of underwater "sound" and "noise" has been clarified. We refer here to the Monitoring Guidance for Underwater Noise in European Seas - Monitoring Guidance Specifications. 2nd Report of the Technical Subgroup on Underwater Noise (TSG Noise). November, 2013, Part II, pp. 5-6; where "noise" is used to describe any sound which can have an adverse effect on marine biota, other than for those terms of common usage such as "ambient noise" for example.

The world's oceans are permeated with natural sounds originating from a wide range of abiotic and biotic sources. Abiotic noise is mainly produced by physical processes, wind, waves, rain (Radford *et al.,* 2008), lightening, sediment transport, oceanic turbulence and seismic activity (earthquakes, volcanoes etc.). Ambient noise resulting from wind, wave and precipitation is a major contributor to deep ocean noise and dominates between around 500 Hz and 50 kHz (Richardson, 1995). Biotic sources of sound include marine fauna, such as marine mammals, fish, and some invertebrates that produce sound for a variety of purposes including foraging, communication and navigation (echolocation). The low absorption of propagating sound in seawater means that it can travel considerable distances (Urick, 1983). It is therefore not surprising that sound plays an important role in the lives of many forms of marine life.

A much more recent type of noise in the seas can be attributed to anthropogenic or man-made activities such as shipping, coastal development, exploitation of offshore resources (physical and environmental) and ocean exploration. Human use of the sea is growing and there is concern that the amount of anthropogenic noise that is being introduced into our oceans is increasing (Weilgart, 2007). For example, there is evidence to suggest that, in some parts of the world, there has been an increase in low-frequency ambient noise of at least 20 dB, from pre-industrial conditions to the present day (Hildebrand, 2009). Marine organisms that use sound as a sensory modality can be expected to have evolved to be successful in the natural ocean soundscape, but there is increasing concern that more recently introduced anthropogenic noise may have an impact on these marine organisms, their populations and ecosystems. Anthropogenic noise includes underwater explosions (for the construction or removal of installations such as offshore oil platforms), airguns (used by the oil and gas industry for seismic exploration), pile driving, vessel noise, fishing, dredging, sonar and operating wind farms (Normandeau Associates, Inc., 2012).

There are many complex questions related to establishing the effects of underwater noise on marine life, on the individual and on the population consequences (see review by Normandeau Associates, Inc., 2012). Among these are; (i) How does anthropogenic noise impact marine organisms? (ii) Are all sounds made by marine organisms important? (iii) What are the effects if biologically important signals are masked by anthropogenic noise? Many of these questions currently remain unanswered (McGregor *et al*., 2013). Further, for some animal groups such as invertebrates and birds, there is no knowledge on the effects of noise at all. However, knowledge of how and why some marine animals use sound as part of their daily lives is increasing. Numerous studies have been undertaken to investigate how marine animals are impacted by sound, particularly anthropogenic sounds. This report forms part of a wider EU project, '*Impacts of noise and use of propagation models to predict the recipient side of noise'.* It reviews the available literature on the impact of underwater noise on individuals, populations and ecosystems which has been published since 2006, in addition to identifying current knowledge gaps. It should be noted that there has been substantial work undertaken prior to 2006 both on underwater acoustics (Urick, 1983), ambient noise (Wenz, 1962) and the effects of noise on marine life (Richardson *et al*., 1995). Where appropriate, studies published prior to 2006 have been used to introduce concepts or demonstrate prior understanding.

2 Overview of Potential Effects of Anthropogenic Noise

Marine organisms may experience behavioural, physiological and physical effects when exposed to natural or anthropogenic sound. These effects can range in magnitude from no ‘observed’ impact to severe impact and depend on a number of factors which influence the loudness of the sound at the receptor. These sound factors include source level, sound duration, duty cycle, distance from the source, physical/environmental properties effecting propagation, and hearing sensitivity of the receptor. The same sound source may also have different impacts on individuals of the same species, depending on factors such as the age and sex of the animal, history of prior exposure to the sound type, animal activity and the season (Southall *et al.,* 2007; Ellison *et al.,* 2011).

For animals exposed to anthropogenic sound, potential effects are, commonly, broadly divided into:

- *acoustic masking*
- *behavioural disturbance/response*
- *hearing sensitivity loss (temporary threshold shift (TTS) and permanent threshold shift (PTS))*
- *non-auditory injury* (Erbe, 2012; Nowacek *et al.,* 2007; OSPAR Commission, 2009a; Southall *et al.,* 2007).

Noise may interfere with animal communication and hinder acoustic signal detection through masking. If the noise falls into the same critical hearing band as the signal being detected, echolocation, predator and prey sounds and environmental sounds may be masked.

Behavioural disturbances are changes in an animal’s activity in response to a sound, ranging from very subtle behavioural changes to strong avoidance reactions. Examples of behavioural disturbances include the abandonment of vital activity (i.e. feeding, nursing) or location, changes in swim speed or direction, or alteration of diving behaviour. It is important to note that if vital activities are repeatedly abandoned, this could lead to detrimental consequences for the organism(s) affected. If crucial behaviour like mating or spawning or nursing is repeatedly disrupted, it is possible that populations may be affected. Ellison *et al.* (2011) highlight that the extent to which an animal responds to a given anthropogenic sound can be influenced by that animal’s prior experience with the sound source. This is independent of the received sound level to which the animal was exposed.

Elevated noise exposure can result in hearing sensitivity loss, known as threshold shift. Temporary threshold shift (TTS) is when the hearing returns to normal after a quiet period and is considered auditory fatigue. If hearing does not return to normal, the effect is a permanent threshold shift (PTS) and is considered injury. Noise also has the potential to impact non-auditory systems and organs, such as damaging muscle tissue and swim-bladders (OSPAR Commission, 2009a) and enhancing nitrogen gas bubble growth in mammals (Southall *et al.,* 2007).

Exposure to noise may also result in other 'indirect' injuries, for example; a diving animal exposed to an elevated sound source may try to flee from the noise which involves rapid surfacing; this could cause decompression sickness and injury, possibly death (Erbe, 2012). Evidence of acute and chronic tissue damage (lesions) in stranded beaked whales was reported by Jepson *et al.* (2003) after a military sonar exercise. The lesions were caused by the formation of *in vivo* gas bubbles, resulting from rapid decompression. However, there is a lack of information on the chronic effects of noise on marine mammals (Erbe, 2012). Jepson *et al.* (2003) highlight that further research into the behavioural and physical effects on cetaceans exposed to sonar in particular, and the association of these effects to strandings and *in vivo* bubble growth is required.

It is widely acknowledged that the impact sustained by individuals holds the potential to translate into effects at a population level, and may therefore also hold potential for ecosystem wide effects (e.g. NRC, 2005). However, demonstrating such effects is challenging, and current studies, including the ones considered in this review, have primarily documented the observed effect on individuals resulting from sound exposure.

3 Impacts of Anthropogenic Noise on Marine Mammals

3.1 Marine Mammal Hearing

Marine mammals use sound to communicate during social interactions (Southall *et al.,* 2007) as well as to forage, navigate, detect predators and to facilitate reproduction (Weilgart, 2007). Echolocation is also used by some marine mammals to navigate through the water and to find prey. It has also been suggested that some cetaceans are able to obtain useful information by eavesdropping on the echolocation clicks and echoes produced by conspecifics (Gregg *et al.,* 2007).

Southall *et al.* (2007) grouped marine mammals into five distinct categories based on knowledge of functional hearing in these animals. It is estimated that the auditory bandwidth for: (i) low-frequency cetaceans (mysticetes) is 7 Hz to 22 kHz, (ii) mid-frequency cetaceans (majority of odontocetes; toothed whales) is from 150 Hz and 160 kHz, (iii) high-frequency cetaceans (porpoises, river dolphins and pygmy sperm whale) is 200 Hz to 180 kHz, (iv) pinnipeds (seals, walruses and sea lions) in water is from 75 Hz to 75 kHz and (v) pinnipeds in air is 75 Hz to 30 kHz.

The functional hearing groups of marine mammals are currently being reviewed by NOAA (National Oceanic and Atmospheric Administration). The categories / groupings will nominally stay the same, although NOAA has subdivided pinnipeds into their two families: Phocidae and Otariidae. There will also be some change to the auditory weighting functions. This is published in a 'draft' NOAA report (NOAA, 2013) and is based on the work by Finneran and Jenkins for the US Navy.

3.2. Marine Mammal Communication

All marine mammals studied to date are known to produce sounds in various important contexts (Southall *et al.,* 2007). Odontocetes (toothed whales) produce sounds across wide frequency bands (Southall *et al.,* 2007). Their social vocalizations, which are audible to humans, range from a few hundreds of Hz to several tens of kHz, whereas specialized clicks used in echolocation extend above 100 kHz. Low-frequency sounds (in the tens of Hz to the several kHz bands, with a few signals extending above 10 kHz) are produced by Mysticetes (baleen whales). It is thought that these sounds serve as a social function, such as maintaining contact and reproduction, but may also serve a function in spatial orientation (Southall *et al.,* 2007). As these long-wavelength sounds can be detected over hundreds of kilometres, they possibly allow contact over large distances (Rolland *et al.,* 2012). However, low-frequency noise from shipping can mask whale communication (Clark et al., 2009). The song of a humpback whale (*Megaptera novaeangliae*) is a well-known example of an animal that uses sound over long distances during the mating season. A series of vocalisations that collectively form a song are produced by male humpback whales. These songs can be heard over great distances, are complex in structure and are sung for long periods of time (Payne and McVay 1971).

Pinnipeds produce sounds both in water and air. Among these are grunts, chirps, whines, roars and pulsed sounds (Schusterman *et al.,* 2000, reviewed by Richardson *et al., 1995*). The majority of these sounds are associated with social behaviour and reproduction (Schusterman *et al.,* 2000) and are generally produced over a low and restricted bandwidth, from 100 Hz to several tens of kHz (Southall *et al.,* 2007).

3.3. Impacts of Noise on Marine Mammals

Much of the work prior to 2006 on the impacts of noise on marine mammals have been reviewed by Southall *et al*., (2007) and this section only seeks to provide an update of key publications in this area since 2006.

3.3.1. Impulsive Noise

3.3.1.1. Impact Pile Driving

Impact pile driving is undertaken during the installation of foundations for a large number of structures, including offshore wind turbines, oil and gas installations, pier developments and harbour works. Piles are driven into the seabed by means of a hydraulic hammer (Normandeau Associates, Inc., 2012). When the hammer strikes a pile, sound radiates into the air and a pulse, or transient stress wave, propagates down the length of the pile (Zampolli *et al*., 2013). Sound will also radiate into the water because the impact of the hammer strike will create waves in the pile wall, which combine with the surrounding fluid (water). Furthermore, the pulse propagating down the pile may combine to the substrate at the bottom, causing waves to propagate outward through the seabed sediment (Popper and Hastings, 2009).

Pile driving activities are of particular concern as they generate loud, impulsive sounds (Kastelein *et al.,* 2013) and have been shown to have a range of impacts on marine mammals, particularly harbour porpoises (*Phocoena phocoena*). Knowledge on the effect of anthropogenic sound on the behaviour of *P. phocoena* is increasing (Kastelein and Jennings, 2012) and numerous studies have been undertaken to assess the behavioural responses of these animals to pile-driving sounds (see Brant *et al*., 2009; Diederichs *et al.,* 2009). Of relevance is a study conducted by Tougaard *et al.* (2009) who investigated the behavioural reactions of harbour porpoises to pile driving during the construction of Horns Rev Offshore Wind Farm in the North Sea. Porpoise reactions were studied by use of passive acoustic loggers. High sound pressures were generated during piling, with a source level of 235 dB re 1 µPa at 1 m (peak-to-peak). A reduction in acoustic activity of porpoises was observed within the impact area, with porpoises reacting to pile driving operations at all three of the measuring stations. It was determined that the zone of responsiveness may have extended beyond 20km.

One can assume that a reduction in acoustic activity could be the result of animals vacating the vicinity. Or, on the other hand, acoustic reduction could occur if the animals remain in the vicinity but with an altered behaviour, thus emitting fewer echolocation clicks (Tougaard *et al.,* 2012). A controlled-exposure study was later conducted by Tougaard *et al.* (2012) in Denmark, in order to address whether animals vacate the area or remain but with changed behaviour. Pile driving sounds were played back from underwater speakers at reduced levels to *P. phocoena*. Results showed that when the sound was transmitted, the porpoises avoided a zone with a distance of ~200 m around the loudspeakers. On average, the received sound levels were 140 dB re 1 µPa (peak-to-peak) at a distance of 200 m from the loudspeakers. It was concluded that porpoises reacted in a similar way to real pile driving (by vacating the impact area), as this threshold level for behavioural reactions is consistent with the results from real pile driving events.

Brandt *et al.* (2012) found the acoustic activity of *Phocoena phocoena* was temporarily reduced during pile driving construction activities at two wind farms, Horns Rev II and Alpha Ventus, located in the North Sea. At Horns Rev II, effects were observed at a minimum distance of up to 17.8 km. Porpoise activity was reduced between 24 and 70 hours after pile driving at the closest distance studied (2.5 km). No effects were observed however at a mean distance of 21.7 km. The sound exposure level measured at 720m from the source was 176 dB re 1 µPa^2 s. Similarly at Alpha Ventus, effects were detected up to 9 km. Porpoise activity was reduced for 20-35 hours after pile driving in the near vicinity. No effect was observed between 16 and 20 km. A sound exposure level (based on measurements at greater distances) of between 167 and 170 dB re 1 µPa^2 s was estimated at 750 m. Furthermore, a strong avoidance response was documented (Dähne *et al.,* 2013) for harbour porpoises within 20 km of the pile driving source, during the construction of Alpha Ventus. Static acoustic monitoring showed reduced porpoise detection rates at distances up to 11 km from the sound source and an increase in detection rates at 25 km and 50 km from the source, suggesting that displaced porpoises moved out to these distances. Also of relevance is the work by Thompson *et al.* (2010) which involved the use of passive acoustic monitoring to assess whether cetaceans responded to pile-driving noise during the installation of two offshore wind turbines in 2006, as part of the Beatrice Demonstrator Project in NE Scotland. The sound source levels were predicted to be 225 dB re 1 µPa at 1 m. On the whole, the results suggested that although there may have been a short-term response by porpoises occurring within 1 – 2 km of the site, there were no long-term changes in the use of the area around the turbines.

A recent behavioural response study was conducted in a pool by Kastelein *et al.* (2013), where a harbour porpoise was exposed to playbacks of pile-driving sounds. It was found that the respiration rate of a harbour porpoise increased in response to the playbacks of pile-driving sounds. At higher levels, the porpoise also jumped out of the water more often. It was suggested that under low ambient noise conditions, porpoises, when exposed to broadband sound pressure levels of above ~142 dB re 1 µPa (zero-to-peak), may become agitated and flee from such locations. The main limitation of this study is that only a single individual was used in the investigation; one individual cannot be representative of a population. As previously mentioned, responses to acoustic sources vary between individuals, so this type of study should ideally be conducted with as many animals as possible.

It is important to note that the use of 'playback sound' is another limitation of studies using this method. For example, it is difficult to imagine that the playback of pile-driving in a tank truly reproduces amplitude and phase piling pulse characteristics. Thus in terms of future work, there is a need to undertake realistic *in-loco* observational studies, using the actual sources, with the field-observations correlated with the measured acoustic data. Taken individually, each of these studies are insufficient to conclusively derive behavioural effects among harbour porpoises as a result of pile-driving activities. Collective consideration of these studies however, is sufficient to demonstrate a causative link between high amplitude underwater noise and associated behavioural and physiological responses.

Investigations assessing the impacts of sound on other marine mammals include those findings by Borsani *et al*. (2008). Fin whales (*Balaenoptera physalus*) are regularly found in the Ligurian Sea. However, no visual sightings or simultaneous acoustic detections of these whales were made during a period of loud low-frequency noise production, consistent with that of a pile-driver. The nature of the sound caused fin whales to avoid the area in excess of 200 km. Fin whales were only detected again a few days after the noise source had ceased. It was weeks after the noise source had ceased before weak bioacoustic activity was resumed.

3.3.1.2. Seismic Surveys

Seismic surveys are used by the oil and gas industry to explore natural resources. Intense sound is deployed from air guns on a survey vessel either singly or in multiple arrays (Payne *et al.,* 2007). Usually, air guns are discharged roughly every 10 – 15 seconds (Løkkeborg *et al*., (2012) so thousands of shots may be produced over a 24 hour period (Payne *et al.,* 2007). Sound pulses with a very high peak sound pressure level are emitted, with source levels at ~250 dB re 1 µPa (Løkkeborg *et al*., (2012). Due to these impulsive sounds' high source levels and distant propagation as well as the widespread use of seismic surveying throughout the oceans, the impacts of seismic surveys on marine mammals is a major concern (Gedamke *et al*., 2011).

There is evidence to suggest that different species of cetaceans react in different ways to air gun exposure. For example, observations were undertaken during seismic surveys in UK waters to examine the effects on cetaceans, the results of which are reported by Stone and Tasker (2006). Small odontocetes showed a greater range of responses to the airguns than larger odontocetes or mysticetes and showed the strongest lateral spatial avoidance of airguns. Killer whales and mysticetes showed some localised spatial avoidance. While no significant effects were observed for sperm whales, long-finned pilot whales showed a change in orientation only, with more animals heading away from, and fewer heading towards the vessel during airgun shooting. The responses indicate that seismic surveys cause some level of disturbance of cetaceans; although it is not known whether these short-term effects were biologically significant. It is noted that the lack of an observed response in some species does not mean that the airguns did not have an effect on those species. Other potential effects including hearing damage, effects on vocalisations, auditory masking and long-term effects are largely unknown.

In fact, the noise-induced threshold shift (TS) levels for the harbour porpoise greatly differ from data on the beluga whale or bottlenose dolphin (Lucke *et al.,* 2009). Lucke *et al.* (2009) documented the first data on the potential impact of anthropogenic sounds on harbour porpoises. Previous assessments had been based on data from other odontocetes. The measurements of TTS were conducted on a harbour porpoise in response to single airgun stimuli. The predefined TTS criterion was exceeded at 4 kHz, at a received peak-to-peak sound pressure level of 199.7 dB re 1 μPa and a sound exposure level of 164.3 dB re 1 μPa^2 s. Furthermore, aversive behavioural reactions were observed at peak-to-peak sound pressure levels above 174 dB re 1 μPa and a sound exposure level of 145 dB re 1 μPa^2 s. It is unknown whether the differences in TTS levels between harbour porpoises and other marine mammal species tested to date are species-specific or representative of the functional hearing groups which are defined by Southall *et al*. (2007). In order to clarify this correlation, Lucke *et al.* (2009) highlight the need for more harbour porpoises and other high-frequency toothed whale species to be tested.

Recent findings by Thompson *et al.* (2013) demonstrated that short-term disturbance during a commercial two-dimensional seismic survey in the North Sea did not lead to the long-term displacement of harbour porpoises. There was evidence in the form of acoustic and visual data of group responses to the airgun noise, at received peak-to peak sound pressure levels of 165 – 172 dB re 1 μPa and sound exposure levels of 145 – 151 dB re 1 μPa^2 s, over ranges of 5 – 10 km. Within a few hours however, porpoises were detected again at the affected areas. Furthermore, over the ten day survey, a decline in the level of response was observed. It is noted that Thomsen *et al.* (2013) were unable to confirm whether it was the same individuals returning to the impacted sites. Although acoustic detections decreased considerably in the impacted area during the survey period in comparison with a control area, this effect was small in relation to natural variability and even during seismic surveying, porpoises continued to occupy impacted sites for approximately ten hours per day. A number of possible explanations are proposed by Thompson *et al.* (2013) for the observed porpoise responses (both in terms of aversive responses and the decline in response levels over the ten day period) to the seismic surveys. For example, the decline in response levels could be associated to habituation to the airgun noise. It is suggested that future efforts should focus on sub-lethal changes in foraging performance of animals occupying affected areas.

A number of studies have reported evidence of a reduction in call detection rates for some whale species during seismic activity. For example, Cerchio *et al.* (2011) report a decline in humpback whale singing activity off the coast of north Angola during seismic activity, suggesting that these animals either move to other areas during the survey or remain in the area but cease singing. The paper concludes that it is not possible to determine whether the decline in humpback whale singers would translate into detrimental impacts on individuals or at the population level. However, as songs are typically sung during the breeding season, it is likely that disruption of this behaviour could significantly impact male individuals and in turn, at the population level. Cerchio *et al.* (2011) recommend that further investigation into the effects of seismic exploration disturbance on baleen whales during the breeding season is required. Clark and Cagnon (2006) also revealed that singing humpback and fin whales in the North Atlantic stopped calling soon after seismic surveying commenced and continue to be silent throughout the survey period. The results indicate that most, if not all the singers did remain in the vicinity. Furthermore, Castellote *et al.* (2012) found that there was a significant decrease in the received levels and number of detections of 20-Hz song notes for male Fin whales (*Balaenoptera physalus*) within 72 hours after seismic activity had commenced. The results indicate that these animals moved away from the noise source and were barely detected again until two weeks after the seismic activity has ceased (see also Castellote *et al.,* 2010). The paper reports that during seismic activity, there was an increase in average background noise levels by 13 dB in the 10 – 585 Hz range and by 15 dB in the 15 – 28 Hz range. In contrast, blue whales (*Balaenoptera musculus*) exhibited an increase in frequency of call production in response to a low-medium power seismic sparker, deployed during geotechnical surveys in the Saint Lawrence Estuary, Canada (Di Iorio and Clark, 2009). The sparker had a source level of 193 dB re 1 µPa (peak-to-peak) (30 – 450 Hz). Calls were associated with feeding and social encounters. It is likely that this increase in call production represents a compensatory behaviour in response to elevated ambient noise levels resulting from the seismic activity. Increasing call rate results in a greater likelihood that the signals will be successfully received by conspecifics. Di Iorio and Clark (2009) highlight the important point that biologically important processes could be affected if an animal's ability to detect socially relevant signals is reduced. Reconsideration of the possible behavioural impacts of even low source level sounds from seismic activity on whales is suggested, especially for endangered species such as the blue whale (IUCN, 2008 as stated in Di Iorio and Clark, 2009) and fin whale (Castellote *et al.*, 2012). An explanation for the difference in response observed in this study, in comparison with Cerchio *et al.* (2011), Clark and Cagnon (2006) and Castellote *et al.* (2012), may be related to differences between song and social communication calls (Cerchio *et al.,* 2011).

Also of relevance, a simulation model was developed by Gedamke *et al.* (2010) which examined the impacts of individual variability and uncertainty on risk assessment of baleen whale TTS from seismic activity. As the results suggest, it is plausible that whales could be susceptible to TTS at distances several kilometres from seismic activity. It is recommended that for such models, the individual variation and uncertainty over TTS and PTS onset levels is included in future, to more accurately assign boundaries for risks associated with specific instances of sound introduction.

Although sea turtles are known to be sensitive to low-frequency sound, there is a lack of knowledge on the potential impacts of anthropogenic noise exposure on sea turtle biology or the extent of anthropogenic noise exposure in their natural habitats (Samuel *et al.,* 2005). These animals have previously been found to occur in waters where seismic exploration has taken place. For example, three species of sea turtle, the green sea turtle (*Chelonia mydas*), the loggerhead turtle (*Caretta caretta*) and the olive-ridley turtle (*Lepidochelys olivacea*) were recorded in the shallow waters of north-eastern Brazil during seismic activity in 2002 and 2003 (Parente *et al.,* 2006). A few investigations have been undertaken to assess the impacts of seismic surveys on sea turtles. Of relevance is a study by McCauley *et al.* (2000a, b) who carried out air gun trials on caged sea turtles. Findings revealed that the turtles noticeably increased their swimming activity in response to airgun noise levels louder than 166 dB re 1 µPa rms. Noise levels louder than 175 dB re 1 µPa rms caused erratic behaviour, possibly indicating that the turtles were agitated. It was also estimated that sea turtles displayed 'escape' or 'avoidance' behaviour at a range of 1 km from the noise source, and 'alarm' behaviour at a range of 2 km from the source.

3.3.1.3. Sonar

There are two types of sonar: passive and active sonar. Passive sonar is used to listen to and receive sounds. Active sonar is used to detect objects by examining echoes of sounds produced (Nowacek *et al.,* 2007). Sonar is widely used in the fishing industry, for example, fish-finding sonars and fishing net control sonars and by other vessels, such as multi-beam sonars, side-scan sonars and various sonars for mapping the seabed topography (Normandeau Associates, Inc., 2012). Military sonars range from low-frequency (<1000 Hz) to high frequency (>10 kHz) and often produce intense sounds, with source levels above 210 dB re 1 µPa at 1 m (Nowacek *et al.,* 2007).

Tyack *et al.* (2011) documented changes in the foraging behaviour and location of Blainville's beaked whales (*Mesoplodon densirostris*), before, during and after naval sonar exercise using newly developed acoustic monitoring methods and satellite tags in the Bahamas. Beaked whales were also exposed to simulated sonar playbacks and other control sounds. Findings revealed that the whales stopped echo locating during deep foraging dives and moved away from the sonar during both exposure conditions. The whales were detected approximately 16 km away from the sonar transmissions near the periphery of the range, during actual sonar exercise. Upon cessation of the sonar exercise, beaked whales gradually filled in the centre of the range over 2 – 3 days. Findings also revealed that in response to the sonar playback, beaked whales reacted at sound pressure levels below 142 dB re 1 µPa (it is not clear what metric this was). Echolocation ceased, followed by atypically long and slow ascents from their foraging dives. These results support a lower acoustic threshold of disturbance for beaked whales exposed to mid-frequency sounds, than is currently applied in the US. It is possible that other species of marine mammals may be less sensitive to sonar than beaked whales, but further experimentation is required to support this. Melcón *et al.* (2012) also found that blue whales were less likely to produce 'D' calls in the presence of mid-frequency active sonar. No diel pattern was observed in the animals' sensitivity to the sonar, but the reduction of calls was more pronounced when the animal was closer to the sound source.

3.3.2 Continuous Noise

3.3.2.1 Shipping

Marine vessels, especially large commercial ships, contribute significantly to anthropogenic sound sources in the marine environment. Large ships produce low-frequency noise below 1 kHz (Normandeau Associates, Inc., 2012). Ship noise has the potential to influence ambient noise over a large area (OSPAR Commission, 2009a). Furthermore, high-level transient sounds (peak-to-peak source levels of up to 200 dB re 1 µPa at 1 m) are generated during gear shifts that may be heard over great distances (Jensen *et al*., 2009). There are indications that the shipping contribution to ocean ambient noise has increased by as much as 12 dB over the past few decades, which co-insides with a considerable increase in the size and numbers of commercial vessels (Hildebrand, 2009). It should be noted that this inference is specific to deep ocean ambient noise however, and findings may not be directly applicable to shelf areas.

There is evidence to suggest that vessels could potentially have negative effects on marine mammals, including the auditory masking of mammal communication signals (see Clark *et al.,* 2009; Jensen *et al.,* 2009; Rolland *et al.,* 2012). Low-frequency noise generated by shipping overlaps the frequencies produced by some marine animals. For example, acoustic signals produced and perceived by baleen whales overlap with low-frequency noise (20 Hz – 200 Hz) from large ships (Rolland *et al.,* 2012).

Small ships travelling at 5 knots in shallow water may reduce the communication range of bottlenose dolphins (*Tursiops* sp.) by 26%, within 50 m. Likewise, vessels travelling at similar speed and range may reduce the communication range of short-finned pilot whales (*Globicephala macrorhynchus*) by 58% in quieter, deeper waters. These figures were derived from modelling undertaken by Jensen *et al.* (2009), who combined vessel noise quantifications with background noise and transmission loss measurements to assess the masking impact. Prior to modelling, digital acoustic recording tags were deployed on free-ranging pilot whales in 2003 and 2005 off the coast of Tenerife, to demonstrate variability of vessel noise levels experienced by these mammals. It is recommended that the implementation of vessel–quietening techniques along with whale watching guidelines for boats would significantly reduce any potential negative effects, i.e. masking. Whale watching guidelines include keeping a minimum distance of at least 50 m from the mammals, low speeds (less than 5 knots) and employing few, if any, gear shifts.

Marine mammals may compensate for increasing levels of background sea noise by changing the amplitude, duration, repetition rate and/or frequency of the signals they produce. Holt *et al.* (2008) found that free-ranging Killer whales (*Orcinus orca*) in Puget Sound near Seattle increased their call source level by 1 dB, for every 1 dB increase in background noise levels. North Atlantic right whales (*Eubalaena glacialis*) have also been known to produce calls with a higher average start frequency (in hertz) when exposed to low frequency vessel noise, possibly in response to masking (Parks *et al.,* 2008). It was suggested that shifting call frequency may be a common response in marine mammals to compensate for increased levels of background noise. Furthermore, recent findings by Melcón *et al.* (2012) revealed that blue whales (*Balaenoptera musculus)* produced more intense D calls in the presence of ships. Conversely, however, there is evidence that the measured spectral and temporal features of fin whale (*Balaenoptera physalus*) 20-Hz song notes decreased in response to high shipping noise levels (Castellote *et al*., 2012). Castellote *et al.* (2010) report that fin whales show a compensation mechanism for the masking effect of ship noise that appears to effectively increase vocal signals in areas of shipping. A decrease in the call frequency positions the fin whale signals in lower noise levels, since shipping noise quickly increases in the first 50 Hz, thus making it easier to detect. However, it is important to note that song functionality might be affected and energy costs will increase, which may lead to chronic effects if shipping noise is persistent within their habitats (Castellote *et al.* 2010). It has also been suggested by McDonald *et al.* (2009) that one of the reasons for a downward shift in frequency in the Eastern North Pacific blue whale song may be due to shipping noise.

Evidence that exposure to low-frequency vessel noise may be linked with chronic stress in whales was documented by Rolland *et al.* (2012). It was found that a reduction in shipping traffic resulted in a 6 dB decrease in underwater noise levels, with a considerable reduction below 150 Hz. Decreased levels of the stress-related faecal hormone metabolites (glucocorticoids) in North Atlantic right whales (*Eubalaena glacialis*) were associated with this noise reduction. It was suggested that exposure to low-frequency ship noise may have implications for baleen whales in the vicinity of heavy vessel traffic.

Although not directly noise related, findings by Christiansen *et al*. (2010) showed that modelled bottlenose dolphin (*Tursiops aduncus*) behaviour was significantly impacted by tourist boats (Zanzibar, Tanzania). Time spent foraging, socialising and resting decreased in the presence of tourist boats; the dolphins instead, spent more time travelling after the boat. Repeated disturbance from tourist boats during vital activities such as foraging and resting may have long-term negative effects on dolphin survival. Recently a significant seasonal displacement from noisy areas characterized by the intense leisure boating has been demonstrated in the bottlenose dolphin population (Rako *et al.,* 2013). Similarly, Pirotta *et al.* (2012) demonstrated that broadband vessel noise caused significant changes in the natural foraging behaviour of Bahamas Blainville's beaked whale (*Mesoplodon densirostris)*, up to a distance of 5.2 km away from the vessel. Christiansen *et al*. (2010) highlight the need to link the immediate or short-term effects to biologically significant long-term effects on populations, survival and reproduction.

Other findings have shown that changes in the diving and foraging behaviour of a Cuvier's beaked whale (*Ziphius cavirostris*) may be a response to intense motorised shipping noise (Aguilar de Soto *et al*., 2006). A beaked whale was tagged 25 km from the busy shipping ports of Genoa and Savona. One foraging dive, which coincided with a noisy vessel passage, had a noticeably shorter vocal phase and thus a lower foraging efficiency. It is suggested that while beaked whales may be habituated to moderate noise levels from shipping traffic, they may not be habituated to elevated noise levels from a ship in close proximity. A key limitation of this study is that findings are based on a single observation hence no firm conclusions can be drawn. Given the lack of behavioural data on Cuvier's beaked whale, this is a noteworthy result however. With vessel size and numbers increasing, it is important to assess whether this particular case reflects a general problem for beaked whales in particular and potential implications for this species in the future.

3.4. Marine Mammal Summary

Overall, there is an understanding that marine mammals respond negatively to some underwater sounds and are deterred over large distances by high amplitude low frequency sounds in particular. Pile-driving activities are of particular concern in this regard, due to the loud impulsive sounds that are generated. As previously mentioned, collective consideration of studies that have investigated the impacts of pile-driving on marine mammals demonstrate and suggest a causative link between high amplitude sounds and associated physiological and behavioural responses. In terms of the latter this includes vacating or avoiding the impact area (see Borsani *et al.,* 2008; Dähne *et al.,* 2013; Tougaard *et al*., 2012).

Low-frequency noise generated from vessels could also have negative effects on marine mammals, in particular the auditory masking of mammal communication signals. This is a concern especially for low-frequency specialists such as baleen whales, as the acoustic signals produced and perceived by these animals overlap with low-frequency noise (20 Hz – 200 Hz) from large ships (Rolland *et al,*. 2012). Aside from masking, there is evidence to suggest that exposure to low-frequency vessel noise may be linked with chronic stress in whales (see Rolland *et al.,* 2012). There is also evidence to suggest that behavioural changes may occur as a result of exposure, including changes in the time spent foraging or diving.

The need to link the immediate or short-term effect of underwater noise to biologically significant long term effects on populations, survival and reproduction is highlighted throughout these studies. Research to further explore such linkages is hence identified as a future priority in understanding and mitigating associated detrimental impacts in the future.

4 Impacts of Anthropogenic Noise on Fish

4.1 Fish Hearing

The hearing structures among fish are very diverse, hence the auditory capabilities across species differs greatly (Thomsen *et al.,* 2006). Many fish species hear in the range from below 50 Hz up to 500 – 1500 Hz. Some species are able to detect sounds over 3 kHz; a very small number of species can detect sounds above 100 kHz (Popper and Hastings, 2009).

Besides using the acoustic pressure component of a sound wave for sensing, some marine organisms, such as fish and some crustaceans are thought to be sensitive to the particle velocity component of the sound field (Popper and Hastings, 2009). The hearing physiology and capability of marine fauna is extremely diverse and Au and Hastings (2008) provide a comprehensive overview.

The terms *hearing generalist* and *hearing specialist* have been previously used to classify fish based on a species' hearing capability (Thomsen *et al.,* 2006). However, it should be noted that the use of this terminology is no longer supported. The term hearing generalists or 'non specialists' referred to fishes with the narrower bandwidth of hearing. Examples of these include cichlids, salmonids, and tunas (Popper and Hastings, 2009). The term hearing specialists referred to fishes with a broader hearing range and generally ones which possess specialized anatomical structures that enhanced hearing bandwidth and sensitivity (Popper and Hastings, 2009), i.e. some means of mechanical coupling between the inner ear and swim bladder (Thomsen *et al.,* 2006). Clupeiformes (herrings, shads, sardines and anchovies) and Otophysi (catfishes) are examples of these (Popper and Hastings, 2009). Fish with these specialised structures are more sensitive to sound pressure and can detect higher frequencies than those without (Smith, 2012). However, not all species with swim bladders are sensitive to sound pressure (Thomsen *et al.,* 2006). There is uncertainty regarding the particle motion and pressure sensitivity of species that possess a swim bladder but lack the specialized linkage between the swim bladder and the ears (Webb *et al.,* 2008).

Thus species of fish react very differently to sound. One such example is documented by Kastelein *et al*. (2008) who investigated the behavioural reaction threshold levels for eight fish species from the North Sea, to tones of 0.1 – 64 kHz. For sea bass, the 50% reaction threshold occurred for signals in the frequency range of 0.1 – 0.7 kHz; for pout 0.1 – 0.25 kHz; for horse mackerel 0.1 – 2 kHz and for Atlantic herring 4 kHz. No 50% reaction thresholds were reached for eel, cod and Pollack.

Fish have evolved two sensory mechanisms for detecting sound; the inner ear and the lateral line system. The lateral line system can be used to detect acoustic signals when very close to the sound source (Thomsen *et al.,* 2006). The inner ear contains solid calcareous stones called the otoliths, which are closely associated with a sensory epithelium containing mechanoreceptive hair cells. These otoliths are denser than the water and surrounding tissues. Thus in a sound wave, the otoliths will move at a different amplitude and phase than that of the epithelium (Popper and Schilt, 2008) causing displacement of the cilia on the hair cells (Thomsen *et al.,* 2006). For more detailed information on fish hearing, see Webb *et al.* (2008) and Wysocki (2006).

Many of the physiological systems in fishes are similar to those in marine mammals and underwater sound may also have the potential to impact the survival and/or health of fishes (Popper *et al.,* 2007). The hearing data for fish is limited however; data for only approximately 100 species (out of 29,000 or more existing species) is available (Popper and Hastings, 2009). Thus great caution must be applied when extrapolating hearing capabilities and determining the effects of sound between different species, particularly those species that are taxonomically distant (Popper and Hastings, 2009).

Elasmobranch fishes (sharks, skates and rays) will also be considered in this review. A wide range of experiments have been conducted to examine the hearing abilities of elasmobranchs. Only a few bony fishes with hearing specializations and swimbladders are able to detect sound pressure. All other fish, including elasmobranchs are only able to detect the particle motion component of sound (Casper and Mann, 2009). In comparison to many teleost fish, elasmobranchs appear to have a relatively narrow hearing range with relatively poor sensitivity (Casper *et al.,* 2012a). Hearing studies have shown that elasmobranchs detect sounds from below 50 Hz to above 500 Hz, even though they do not possess a swim bladder or other gas bubble associated with the ear (Normandeau Associates, Inc., 2012). Sound is detected by elasmobranchs using inner ear end organs (see Casper *et al.,* 2012a for further information).

4.2. Fish Communication

Many fish species produce sound, including some of the most commercially important and abundant fish such as haddock and Atlantic cod (Normandeau Associates Inc., 2012). Cod are known to produce deep “grunts” made by swim bladder contractions and “knocks” possible made by a single contraction of the sonic muscle (Worcester, 2006). These sounds are associated with different behavioural traits such as aggression, escaping and chasing. Male haddock produce a variety of sounds including “knocks” associated with mating behaviour (Worcester, 2006). However, due to a lack of detailed study, a lot of fish sounds are unknown (Hildebrand, 2009). Most of the sounds emitted by fish are pulsatile acoustic signals with major energies ranging from less than 100 Hz up to more than 1 kHz (Wysocki, 2006). Typically they show poor amplitude and frequency modulation (Amorim, 2006).

Fish have relatively limited acoustical repertoires; the diversity of sounds produced by fish depends upon differences in the underlying mechanisms of sound production (Amorim, 2006). Fish mainly produce sounds by; (1) hydrodynamic movement (quickly changing swimming speed and direction); (2) stridulation (rubbing skeletal components together); (3) swim bladder pulsations; (4) body and tendon vibrations and (5) air release (Worcester, 2006). Sounds produced by sonic muscles on the swim bladder are pulsed tonals; however sounds produced by stridulation are typically broadband pulses (Hildebrand, 2009). In general the dominant frequencies of sounds made by fish match their optimum hearing frequencies (Wysocki, 2006). Ontogenetic variability can also be found in fish sounds (Amorim, 2006).

Many fishes also engage in communal sound giving rise to choruses, such as croakers (family: Sciaenidae), toadfishes and midshipmen (family: Batrachoididae); when large numbers of animals call en masse, they may reach 35 dB above expected typical no-chorus background conditions (McCauley and Cato, 2000) and dominate the ambient noise in the sea. Sound production in fish is observed in a variety of contexts, ranging from courtship and agonistic interactions to competitive feeding. Acoustic communication may play an important role in active territorial defence, deterring intruders from territorial invasion, as well as in species recognition and in mate attraction and choice (Myrberg and Lugli, 2006). For example, Verzijden *et al.* (2010) provide experimental evidence that sounds affect mate preferences in female cichlids (*Pundamilia nyererei*).

4.3. Impacts of Noise on Fish

Much of the work prior to 2006 on the impacts of noise on fish has been reviewed by Hastings and Popper (2005) and this section only seeks to provide an update of key publications in this area since 2006.

4.3.1. Impulsive Noise

4.3.1.1. Impact Pile Driving

Pile-driving is also a concern for fish, particularly in shallow waters where a lot of marine and freshwater species live. Apart from explosives, pile driving is the only other anthropogenic sound source to be documented within scientific literature which has caused fish fatalities in the wild (Popper and Hastings, 2009). However, there have been few experiments that evaluate the physical effects of pile driving sound on fish in natural environments.

Some documented studies have found pile-driving activities to have little impact on fish. For example, Nedwell *et al.* (2006) investigated the effects of impact and vibro-piling on caged brown trout (*Salmo trutta*) at increasing distances from the piling, in Southampton Water on the south coast of England. Ten piles measuring 914 mm and 508 mm in diameter were driven using vibratory methods for approximately 20 minutes per pile. Three piles were driven to final depth via impact piling. No reactions were observed as a response to vibro-piling. No obvious damage to external tissue on any fish was observed. The source levels for impact piling were 193 dB *re* 1 µPa peak at 1 m for the 508 mm pile, and 201 dB re 1 µPa peak at 1 m for the 914 mm pile. No source levels were given for vibro-piling. There was a transmission loss for both sources of 0.13 dB per metre, but sound levels were not measured at the actual cages. One drawback of the experiment is that a behavioural flight response could not be demonstrated in this instance as fish were caged.

On the contrary, behavioural changes were observed in cod and sole when exposed to pile-driving playback noise, in a study undertaken by Mueller-Blenkle *et al.* (2010). The fish were held in two 40m net pens in a bay in West Scotland. Both species demonstrated a significant movement response to a playback of recorded pile-driving sound at relatively low received peak sound pressure levels (sole: 144 – 156 dB re 1µPa; cod: 140 – 161 dB re 1 µPa). A significant increase in swim speed was observed for sole during the playback noise, cod also but to a lesser extent. Cod however did show a significant freezing response at the start and end of playback. For both species, there were signs of directional movements away from the sound source. Furthermore, the results showed a decrease of response with multiple exposures, suggesting habituation of the fish to the pile-driving. Mueller-Blenkle *et al.* (2010) highlight the need to further investigate behavioural responses at vital times such as spawning and mating and also to further investigate habituation to such sounds.

Halvorsen *et al.* (2012a) found that juvenile Chinook salmon may start to show onset of physiological effects from pile driving sounds when the cumulative Sound Exposure Level (SEL_{cum}) exceeds about 210 dB re 1 µPa^2 s. In addition, the onset of physiological effects depends on the single strike level and the number of strikes. Thus, if there are to be more strikes, the single strike level should be lower to prevent reaching onset of physiological effects than if there are to be fewer strikes. Casper *et al.* (2012b) found no observed mortalities from the pile driving sound exposure; this paper supports the hypothesis that one or two *mild* injuries resulting from pile driving exposure are unlikely to affect the survival of the exposed animals, at least in a laboratory environment.

A more recent study undertaken by Casper *et al.* (2013) involved using a High Intensity Controlled Impedance Fluid Filled Wave Tube (HICI-FT) to determine the effects of pile driving exposure on two size groups of hybrid striped bass (*Morone chrysops* and *Morone saxatilis*). Playback sounds that accurately reproduced the acoustic characteristics and sound levels of previously recorded pile-driving sounds were used. All fish survived exposure to the pile driving playback sounds in the HICI-FT. The results demonstrated that the larger sized bass (average size 17.2 g) had more total injuries, including more severe injuries in comparison with the smaller sized fish (average size 1.3 g). Although within ten days of exposure, fish in each size group had recovered from most injuries. An important point is highlighted by Casper *et al.* (2013) however, in that fish recovery was within laboratory settings, without real life stressors such as searching for food or predation. Thus, the results may not be a true reflection of what happens to fishes in the wild.

Furthermore, the results from this study support previous findings that fishes which possess physoclistous[1] (closed) swim bladders are more susceptible to injury from pile-driving compared with fishes that possess physostomous[1] (open) swim bladders (Casper *et al.,* 2013). For example, Halvorsen *et al.* (2012b) investigated the response to pile-driving in three fish species; lake sturgeon (*Acipenser fulvescens*) which possess an open (physostomous) swim bladder, Nile tilapia (*Oreochromis niloticus*), which possess a closed (physoclistous) swim bladder and the hogchoker (*Trinectes maculatus*), a flatfish without a swim bladder. A range of injuries were observed in the Nile tilapia and lake sturgeon, but no visible injuries were apparent in any of the exposed hogchokers. Findings revealed that Nile tilapia (with an open (physostomous) swim bladder) had the highest total injuries and most severe injuries per fish, at the loudest sound exposure levels. The number and severity of injuries were more similar between the lake sturgeon and tilapia at lower exposure levels. Thus, the presence and type of swim bladder may correlate with injury at higher sound exposure levels. Injuries occur due to the rapid motion of the walls of the swim bladder as it

[1] The swim bladder of physoclistous fishes, (bass, rockfish, perch) has a gas gland that enables as exchange by diffusion between the swim bladder and blood. The swim bladder of physostomous fishes (sturgeons, salmonids) is connected to the gut via a pneumatic duct. This enables the fish to gulp air from the water surface or expel air to adjust the volume of air within the swim bladder (Halvorsen *et al.* 2012).

repeatedly contacts nearby tissues (Halvorsen *et al.,* 2012b). In addition, the results also demonstrate that sound levels eliciting physical injury are in keeping with those found for all other species studied and well above current interim criteria (187 dB re 1 μPa2·s SEL_{cum} for fishes above 2 g and 183 dB re 1 μPa2·s SEL_{cum} for fishes below 2 g) in common use.

Research on acoustic stress induced by air gun showed that blast did cause biochemical responses in European seabass (*Dicentrarchus labrax*). The variation in cortisol, glucose, lactate, AMP, ADP, ATP and cAMP concentrations in different tissue were primary and secondary responses to the noise. The biochemical parameters had returned to physiological values within 72 h after the acoustical stress exposure (Santulli *et al.,* 1999).

4.3.1.2. Seismic Surveys

Worcester (2006) provides a review of studies that have investigated the effect of seismic surveys on fish prior to 2006. It was found that only a limited number of studies had been conducted on the impacts of airgun impulses on adult and juvenile fish. The review concluded that seismic surveys are considered unlikely to result in immediate mortality of fish, although physiological impairments and sub-lethal physical damage may occur in close vicinity (e.g. within 10s of metres) of an airgun source. Furthermore, exposure to such noise sources could result in delayed mortality or chronic effects. A number of data gaps were identified by Worcester (2006); these are highlighted in section 8.1.2.

The effect of air gun exposure on caged species of coral reef fish was investigated by Boeger *et al.* (2006). Experiments were carried out (State of Bahia, Brazil) using an array of 8 synchronised air guns, producing 196 dB re 1 µPa at 1 m (it is not clear what metric this was). No obvious external damage was observed as a result of exposure and there were no fatalities. Most airgun blasts resulted in a startle response; a temporary increase in swim speed and/or a change in swim direction were observed, before the fish returned to normal swim speed shortly after. Results may also indicate habituation to the blasts as repeated exposure led to less obvious startle responses. As with other studies however, a behavioural flight response could not be demonstrated as the fish were kept in cages. Furthermore, no information is given on the sound level or sound spectra received by the fish.

Engas *et al.* (1996) on the other hand, showed that seismic shooting with air guns severely affected fish distribution of cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*), their local abundance and catch rates in the entire investigation area of 40 x 40 nautical miles. The results are thus most likely explained by the hypothesis that fish are scared by the sound generated by the air guns and migrate out of the area. The results are also in keeping with findings by Løkkeborg (1991) who studied the effects of seismic surveys on longline catches of cod (*Gadus morhua*). Within the survey area, a catch reduction of 55 – 80% was observed. Moreover, the results indicated a 5-mile spatial extent of reduced longline catches. Also of relevance, Skalski *et al.* (1992) found a decline in the longline catch rates of rockfish (*Sebastes spp*.) during seismic surveying. Peak pressures above 186 dB re 1 µPa were produced by a single air gun with a source level of 223 dB re 1 µPa.

A number of recent studies have further investigated the extent to which certain fish species are affected by seismic surveys, either by vacating the area or changing their behaviour, thus affecting the fisheries. Løkkeborg *et al*. (2012) for example, found that gillnet catches of Greenland halibut (*Reinhardtius hippoglossoides*) and golden redfish (*Sebastes marinus*) increased during seismic shooting, whereas long-line catches of *R. hippoglossoides* fell during the shooting. Furthermore, a decline in gillnet catches for saithe (*Pollachius virens*) was observed both during and after seismic shooting. It was assumed that *P. virens* may have vacated the area whereas *R. hippoglossoides* and *S. marinus* raised their level of swimming activity, thus making them more susceptible to be taken by gillnets.

Fewtrell and McCauley (2012) revealed that fish (trevally and pink snapper) responded to an increase in air gun noise levels by swimming faster in more tightly cohesive groups and moving to the bottom of the water column. At sound exposure levels exceeding 147 – 151 dB re 1 μPa^2 s, significant increases in alarm responses were observed among the fish. As the fish in this experiment were caged however, the results do not provide conclusive evidence for the responses of how unrestrained fish in the wild may react following exposure to similar air gun noise. However, there is consistency between the behavioural responses observed as a result of air gun exposure, in this particular study and in other investigations (Fewtrell and McCauley, 2012). Thus, it is possible to some degree, to predict the behavioural responses of fish subject to such a noise source. This paper highlights the need for further research into the effects of seismic surveys on marine fish, in order to design effective mitigation techniques that (i) benefit the surrounding aquatic life and (ii) does not compromise the economic value of seismic exploration (Fewtrell and McCauley, 2012).

A wealth of information on the effects of seismic surveying on fish has also been provided by McCauley *et al.* (2000a, b). An 'alarm' response was observed for captive fish, which involved increased swimming speed and tightened school structure with a downward movement, at an estimated distance of 2–5 km from the source. Fish congregated at the bottom centre of the enclosures during periods of high air-gun exposure > 156 – 161 dB re 1 µPa (rms). Moreover, modelling of fish hearing predicts that a fish ear would begin a rapid increase in displacement parameters, at ranges of less than 2 km from the source. Although there was no evidence of increased stress for fish exposed to short range air-gun signals, there was signs of some damage to hearing structures.

One of the best known studies to date, in which damage to fish ears was caused as a result of exposure to anthropogenic sound, was undertaken by McCauley *et al.* (2003). Widespread damage to the sensory epithelia of fishes' ears (caged pink snapper *Paragus auratus*) was observed after air-gun exposure. The air gun had a source level of 222.6 dB re 1 µPa at 1 m (peak-to-peak) or 203.6 dB re 1 µPa at 1 m (RMS). Electron microscopy analysis revealed dense patches of holes on the epithelium surface and "blistering" or "blebbing" on the epithelium surface coincided with the position of hair cells. Even 58 days after exposure to the air-gun, there was no indication that damaged sensory cells had been replaced or repaired and considerable regeneration occurred only well after the 58 day period. This is one example where extensive damage from high intensity sound occurred after a relatively short period of exposure. Such findings highlight the potential threats to animals from exposure to high amplitude anthropogenic sound sources even over relatively short periods.

These findings contradict those by Boeger *et al.* (2006); however there are various limitations that must be noted when considering the results. Firstly, the fish were caged and could not escape the air-gun blasts. If possible, the fish would have escaped the noise source, which is proposed by video monitoring of fish behaviour. Secondly, the effects of noise exposure on the survival of fish are unknown. A number of fish show disorientated and abnormal swimming behaviour when exposed to such noise sources. Hence ear damage might also have vestibular impact. Furthermore, pink snappers were the only species used for the investigation and it is likely that these fish are more or less sensitive to extreme noise sources, in comparison to other species (McCauley *et al.,* 2003).

As a result of exposure to high intensity sounds, the fitness of fish may be reduced by hearing damage and this in turn may possibly affect the ability of fish to communicate, find prey, and sense their acoustic surroundings. Furthermore, fish with reduced fitness are more likely to be susceptible to predators (McCauley *et al.,* 2003). Although some of the available literature is contradictory, considerable damage has been observed to the ears of fish when exposed to air-gun blasts and it is suggested by the results that care needs to be taken when applying very extreme sounds in fish inhabited surroundings. Further investigations are however, required to understand more about the effects on fish behaviour and fitness, the repair processes and the physiological and mechanical processes that lead to damage. Finally, many other marine organisms could possibly be affected if exposed to high-intensity noise sources, since the vital end organs of all vertebrates hearing systems are formed from hair cells (McCauley *et al.,* 2003).

4.3.1.3. Sonar

The effects of exposure to high intensity, low frequency sonar on rainbow trout (*Oncorhynchus mykiss*) were investigated by Popper *et al.* (2007). A sound pressure level of 193 dB re 1 µPa (RMS) did not result in damage to the ears of the rainbow trout. Among the most significant findings was a 20 dB auditory threshold shift at 400 Hz. However as variation occurred among different groups of trout, findings are suggestive of a developmental or genetic influence.

Doksæter *et al.* (2009) investigated the behavioural effect of mid-frequency sonar on free ranging over-wintering herring (*Clupea harengus*). The herring were exposed to two different frequency ranges (1-2 kHz and 6-7 kHz). No significant escape reactions were detected in response to the sonar transmissions. These findings led to the conclusion that the operation of sonar systems at the tested frequencies and source levels (above 1 kHz and 209 dB re 1 µPa at 1 m (RMS)) will not have any large scale detrimental impact on overwintering herring populations or on the commercial herring fishery. However, Doksæter *et al.* (2009) highlight the need for further studies to demonstrate how herring may react to military sonars in different life history stages, as herring are known to change their behaviour in relation to their physiological, functional and motivational states.

4.3.2. Continuous Noise

4.3.2.1. Shipping

As previously established, noise from boats and shipping is the major chronic source of low-frequency noise in coastal waters. There is evidence to suggest that vessel noise can also impact fish as well as marine mammals. In particular playback of field recordings under laboratory conditions, at natural spectral content and level, confirmed experimentally that (i) the noise generated by ferry-boat (source level of approx. 143 dB re µPa at 1 m) can significantly diminish hearing ability in the Lusitanian toadfish, *Halobatrachus didactylus* (Vasconcelos *et al.,* 2007) and (ii) the noise produced by a cabin-cruiser type of boat (132 dB re µPa, with a maximum instantaneous SPL of 138 dB re µPa) can significantly increase detection threshold levels for conspecific sounds in both the Mediterranean damselfish (*Chromis chromis*) and brown meagre drums (*Sciaena umbra*) (Codarin *et al.,* 2009). Wysocki *et al.* (2006) also showed that cortisol levels in four fish species increased when the fish were exposed to playbacks of variable ship noise (Leq average 153 dB re µPa, 30 min), but not when exposed to continuous Gaussian noise of similar intensities.

As highlighted earlier, even with the best recording conditions and measurement and playback equipment, one cannot expect to reproduce the sound generated from a ship or impact pile-driver for example. Furthermore, sound from speakers lacks the particle velocity component of the sound field. On the other hand, it is important to note that whilst playbacks cannot necessarily reproduce the acoustic conditions to which an animal might be exposed, they do provide a valuable means of providing control under conditions which can be monitored. They are also useful for finding out initial information about a species sensitivity to sound.

Vessel noise has also been proved to affect fish behaviour. A behavioural response was observed in the bluefin tuna (*Thunnus thynnus*) when exposed to boat noise in Sicily (Sarà *et al.,* 2007). The tuna generally displayed calm behaviour in the absence of boat noise, swimming slowly and horizontally. The school maintained movement in the same direction but with no consistent shape. In the presence of vessel noise, tuna increased their vertical movements in the water column and displayed uncoordinated swimming behaviour. The findings suggest that noise from local shipping traffic produces a deviation from normal activity in this species. Such findings may be of relevance as any disruption to tuna schooling behaviour could influence their ability to effectively undertake migration to spawning and feeding grounds. The auditory capabilities of tuna were not the primary focus of these investigations however and it was not possible to determine from the results whether bluefin tuna can hear more complex sounds and high frequency bands. Thus it is recommended that further studies are needed, specifically designed to investigate the hearing abilities of this migratory species (Sarà *et al.,* 2007).

The playback of a field-recorded diesel engine boat noise, at same spectral content and levels, show that the ability of fish to maintain its territory was significantly diminished in the red mouthed goby (*Gobius cruentatus*) while exposed to such a noise (Sebastianutto *et al.,* 2011). Similarly, Bruintjes and Radford (2013) found that playback noise of a passing boat run in a laboratory negatively affects two key behaviours in *Neolamprologus pulcher*, a territorial and cooperatively breeding cichlid fish: nest digging and defence against predators. *In situ* experiments made in a Northern Mediterranean Marine Protected Area (MPA) proved that the playback of boat noises did affect the amount of time *Gobius cruentatus* and *Chromis chromis* spent in their nests and inside their shelter respectively (Picciulin *et al.,* 2010). In addition, Picciulin *et al.* (2012) showed that in the same MPA, the mean pulse rate of *Sciaena umbra* increased over multiple boat passages in the experimental condition but not in the control condition, excluding that the observed effect was due to a natural rise in fish vocalizations, suggesting a form of vocal compensation. Evaluating the nautical traffic in a Southern Mediterranean Marine Protected Area and simultaneously the feeding behaviour of *C. chromis*, Bracciali *et al.* (2012) also found a significant modification of the daily foraging habits of *C. chromis* due to boat noise, which was slightly buffered by no-take zones established within the MPA.

On the other hand, interestingly, Røstad *et al.* (2006) found that fish were attracted to vessels. This was true for vessels that were anchored, freely drifting or kept stationary by dynamic satellite positioning (which is considered noisy). Different species assemblages of fish were found to rapidly accumulate beneath vessels with different noise levels, during both the day and night, in various habitats. The mechanisms causing the attraction of fish to vessels are unclear and it was concluded that these findings suggest more complex relationships between fish, vessels and noise than previously anticipated. Also of interest, Sand e*t al*. (2008) comment on a previous publication by Ona *et al.* (2007) which compares the avoidance reactions by herring to a silent "stealth" survey vessel and a traditional (non-quiet) research vessel. Surprisingly, findings revealed that avoidance reactions were stronger and more prolonged towards the "stealth" vessel. A possible explanation for this is due to the fact that the otolith organs in the inner ears of fish are very sensitive to infrasonic particle acceleration. Thus, the herring may have responded to the near-field infrasonic particle motion which is generated by the moving hull of the ship. Sand *et al.* (2008) point out that the focus of vessel noise analysis has been on propagating sound and measuring sound pressure, rather than on the near-field particle motion. They recommend that possible effects of near-field particle motions associated with the local flow field generated by a moving vessel should be considered. The directionality of avoidance responses particularly should be compared and correlated to the directionality of such flow fields.

4.4. Impacts of Noise on Fish Larvae

Knowledge on the sound levels at which lethal and sub-lethal effects occur is very much limited for fish eggs and larvae. Recently, the lethal effects of sound exposure from pile-driving in common sole larvae (*Solea solea*) were investigated by Bolle *et al.* (2012). The highest cumulative sound exposure level that the larvae were subject to was 206 dB re 1 μPa^2 s. No significant differences in mortality between control and exposure groups were observed at sound exposure levels above the US interim criteria for injury (non-auditory tissue damage) to fish from pile-driving. It was suggested that although these findings cannot be extrapolated to fish larvae in general, they are an indication that the current criteria may need to be revised. However, it is important to note that body tissues or hearing may have been damaged as a result of the sound exposures, but the focus of the study was on the lethal effects only of sound exposure. Further research is needed on lethal and also sub-lethal effects in fish larvae, ranging from behavioural responses to injuries. This is important because if the behaviour or physiology of larvae is affected, this could lead to starvation and predation risks (Bolle *et al.,* 2012).

More recently, by using a choice chamber experiment with settlement-stage coral reef fish larvae of the species *Apogon doryssa*, Holles *et al.* (2013) show that anthropogenic noise has a disruptive effect on the response of fish larvae to natural reef sound, with implications for settlement and population dynamics in coral reef habitats disturbed by boat traffic.

4.5. Impacts of Noise on Elasmobranchs

There are no studies to date concerning how exposure to anthropogenic sounds might affect elasmobranchs (sharks, skates and rays). However, it will be very important to understand the effects of anthropogenic sounds on at least a few of these species, since these fishes are a vital part of the ecosystem throughout the world's oceans (Normandeau Associates, Inc., 2012). It is thought that sounds at high levels from pile driving could cause a temporary threshold shift for elasmobranchs in close vicinity to the source (Casper *et al.,* 2012a). However, as a result of the impulsive energy created when the hammer strikes the pile, it is more likely that barotrauma would be the main source of damage (Casper *et al.,* 2012a). Barotrauma, in fish, is physiological damage to non-auditory tissue as a result of pressure changes (Carlson, 2012). Furthermore, the intense vibrations within the sediment from piling could also be damaging to skates and rays. This is because many of these fishes' organs are in close proximity to the ventral body surface, thus providing little protection from vibrations (Casper *et al.,* 2012a). It is unlikely that hearing damage (TTS) would occur as a result of exposure to noise typically produced by vessels and operating wind farm turbines. However it is possible that biologically relevant signals will be masked (Casper *et al.,* 2012a).

4.6. Fish Summary

Definitive conclusions cannot be drawn from existing literature as not enough is known about the effects of anthropogenic sound exposure on fish (Popper and Hastings, 2009). One main reason for this is because it is very difficult and expensive to study behaviour in the field and results are usually difficult to interpret (Normandeau Associates, Inc., 2012). However, it is apparent that sound can play an important part in the lives of many fishes. Thus, a rise in anthropogenic underwater noise levels may have negative consequences for individuals as well as populations (Slabbekoorn *et al.* 2010).

It is worth noting that efforts are being made in the USA to produce new guidance for the effects of pile driving on fish, as indicated by Popper, A. R. at the Workshop on International Harmonisation of Approaches to Define Underwater Noise Exposure Criteria

(http://an2013.org/workshop_on_harmonisation.html).

5 Impacts of Anthropogenic Noise on Marine Invertebrates

5.1 Marine Invertebrate Hearing

Research on the significance of hearing for invertebrates is limited, including whether they use sound to communicate, capture prey or avoid predation. Little is known about the impacts of anthropogenic sounds on invertebrates. It is unclear whether man-made noise can cause masking in invertebrates, or whether such sounds would impact behaviour or cause physiological effects (Normandeau Associates, Inc., 2012).

Despite the limited data, there is some evidence that a range of invertebrates are sensitive to low frequency sounds (Normandeau Associates, Inc., 2012). Mooney *et al.* (2010), (2012) suggest that cephalopods appear to be sensitive to the low frequency particle-motion component of the sound field and not the pressure. A recent study by Mooney *et al.* (2010) used auditory evoked potentials (AEPs) with electrodes placed near the statocysts of the longfin squid (*Loligo pealeii*) in order to obtain electrical responses. Statocysts are the structures responsible for the animals' sense of balance and position (see Andrè *et al.,* 2011). Responses were obtained at frequencies between 30 and 500 Hz, with lowest thresholds between 100 and 200 Hz. It was suggested that squid most likely detect acoustic particle motion stimuli from predators and prey in addition to low-frequency environmental sound signatures that might aid their navigation. Furthermore, the responses suggested that squid detect sound similarly to most fish species. Squid detect the particle motion component of a sound field through the statocyst, which acts as an accelerometer (Mooney *et al.,* 2010).

Wilson *et al.* (2007) found that *Loligo pealeii* did not show any detectable anti-predator behaviour in response to the playback of intense ultrasonic echolocation clicks from toothed whales which are a known squid predator. The playback mimicked sounds made by toothed whales as they approach and capture prey. The clicks did not acoustically debilitate this species of cephalopod, indicating that *L. pealeii* are unable to detect the ultrasonic pressure component of a sound signal. The received peak-to-peak sound pressure levels were 199 – 226 dB re 1 µPa which is very high.

However, a study undertaken by Hu *et al.* (2009) demonstrated that two cephalopod species, the oval squid (*S. lessoniana)* and the octopus (*O. vulgaris)* were able to detect sounds ranging from 400 Hz to 1500 Hz and from 400 Hz to 1000 Hz, respectively. It was concluded that these cephalopods are possibly only sensitive to the motion of water particle displaced by sound frequencies up to 1000 Hz – 1500 Hz, given that the frequencies detected in both species were in the range of other animals that lack gas filled chambers. These results differ greatly with the findings by Mooney *et al.* (2010) and Wilson *et al.* (2007) described above.

Among the few studies addressing behavioural responses of cephalopods to sound, Samson *et al.* (2013) assessed the behavioural responses of cuttlefish (*Sepia officinalis*) to sounds in the frequency range from 80 Hz to1000 Hz and intensities of 110 – 165 dB re 1 µPa. For sounds between 100 Hz and 300 Hz, at intensities above 140 dB re 1 µPa, inking and jetting responses of juveniles were observed. At all frequencies and intensities, slight fin movements and skin patterning changes were observed. The study also observed potential behavioural adaptation and habituation to repeated sound stimuli when a decrease in response intensity was observed, particularly in juveniles. Earlier findings by Kaifu (2007) revealed that the behavioural response of the small benthic octopus (*Octopus ocellatus*) was modified by the presence of underwater noise. Overall, *O. ocellatus* responded to 120 dB (rms) sound stimuli at frequencies of 50 Hz – 150 Hz, with lengthened respiratory activities. There was no observed response for frequencies between 200 Hz and 1000 Hz. However, it is noted that the behavioural responses of this animal to sound may depend on individuals and/or other factors (e.g. stresses caused by handling). For example, individuals responded in slightly different ways to the sound; some having a longer respiratory suppression than others. Furthermore, one individual did not show a clear response to the sound (i.e. no clear respiratory disturbance was observed).

The prawn (*Palaemon serratus*) is responsive to low-frequency sounds in the range of 100 Hz to 3000 Hz, similar in range to the hearing in generalist fish (Lovell *et al.,* 2005). The mechanism of sound reception and hearing capabilities of this marine invertebrate using a mixture of electron microscopic, electrophysiological and anatomical approaches was studied by Lovell *et al.* (2005). The Auditory Brainstem Response (ABR) recording technique was also used. Findings revealed that *P.serratus* 'have an array of sensory hairs projecting from the floor of the statocyst into a mass of sand granules embedded in a gelatinous substance'. This statocyst is sensitive to the motion of water particles displaced by low-frequency sounds. The study concludes that there is a need to include invertebrates, particularly crustaceans in future impact studies on underwater noise, as the long-term effects of intense low-frequency sounds on the shrimp hearing ability and ecology is unknown.

Studies indicate that pelagic crustacean larvae have the ability to detect certain underwater sounds which play an important role in the orientation and settlement of the larvae (Montgomery *et al.,* 2006; Radford *et al.,* 2007 and Stanley *et al.,* 2010); see section 6.4 for further information.

5.2. Marine Invertebrate Communication

In comparison to the widespread literature available on acoustic communication in other marine fauna, such as cetaceans, few studies have investigated acoustic communication among marine invertebrates, especially benthic crustaceans (Staaterman *et al.,* 2011). Numerous invertebrates are known to produce sound, particularly those with hard body parts. Sounds emitted by species that do not possess clearly defined vocal organs may be incidental (Normandeau Associates, Inc., 2012). However some species emit sounds using sound-producing mechanisms such as the spiny lobster (Bouwma & Herrnkind, 2009) that may have significant communication purposes.

Findings by Bouwma & Herrnkind (2009) suggest that Caribbean spiny lobsters (*Panulirus argus)* produce sound (known as stridulation) as a defence mechanism. Lobsters were shown to stridulate during staged encounters with octopus (*Octopus briareus)* when grasped, captured and restrained by the octopus. Furthermore, in comparison with muted lobsters, stridulating lobsters were much more effective at escaping from attacking octopuses and remained un-captured for a longer duration. These findings suggest that stridulating is a crucial component of escaping and may improve survival rates. Furthermore, *Panulirus interruptus* the California spiny lobster produces pulsatile rasps when interacting with potential predators (Patek *et al*., 2009); sound is generated using frictional structures found at the base of each antenna.

A recent experiment was conducted by Buscaino *et al.* (2011) to better understand sounds emitted by European spiny lobsters (*Palinurus elephas*). The acoustic signals produced by these lobsters were examined under different conditions, i.e. in the presence and absence of a predator. All signals emitted by the lobsters consisted of a 'pulsatile rasp or screech'. The lobster produced ultrasound screeches (20–55 kHz) when it was alone, but produced both ultrasound and audible signals (rasps in the 2–75 kHz range, with a peak frequency of 15 kHz) when a predator was present. In the presence of a predator, the lobsters emitted considerably more signals. It was also found that single lobsters produced a higher number of ultrasonic screeches in comparison with lobsters in groups. Thus such signals may allow lobsters to maintain contact with conspecifics.

The California mantis shrimp (*Hemisquilla californiensis*) are known to emit low frequency rumbling sounds through muscle vibrations (Staaterman *et al.,* 2011). Numerous individuals emit these 'rumbles' in unison, suggesting that such sounds serve a critical function in their ecology, such as mating and defending territories. This supports the work of Patek and Caldwell (2006) who found that the mantis shrimp produces a low 'rumbling' sound (20-60 Hz frequency range) through carapace vibrations, when interacting with potential intruders and predators. These sounds could serve as a territorial or anti-predator / defensive warning.

Staaterman *et al.* (2012) later found that the sounds produced by *H. californiensis* are extremely variable; the 'rumbles' produced by individuals differed in number of rumbles per bout and dominant frequency. Recordings were taken off the Californian coast during the mating season when males compete for burrow space and attempt to attract a mate. *H. californiensis* were observed to spend a large amount of time throughout the day producing sound. This highlights the potentially important contribution of the rumbling to this animals' behavioural ecology. Rumbles were loud and produced in rhythmic sequences when *H. californiensis* was guarding its burrow, compared with very few rumbles or lower frequency rumbles when the burrow was closed for protection. Hence these rumbles may serve as a function in attracting a potential mate and/or establishing territories. It is noted that this particular study area was subject to frequent vessel noise and it was unclear whether complete acoustic masking was taking place or whether the shrimp ceased rumbling, during periods of intense ship noise.

Furthermore, snapping shrimp (*Alpheus heterochaelis*) are known to defend themselves with sound, or use sound to kill or stun its prey. A distinctive loud snapping sound is produced by a very rapid closure of the shrimps' large snapper claw, which may reach half of its body length (Versluis *et al.,* 2000). A high-velocity water jet is emitted from the claw during the rapid claw closure, creating a cavitation bubble. The sound is solely generated from the collapse of this cavitation bubble. The force is so powerful it can deter predators (Scowcroft *et al.,* 2012). Interestingly, in order to advertise their cleaning services to reef fish, cleaner shrimp clap a pair of their claws together. The more clapping it does, the hungrier the shrimp is (Scowcroft *et al.,* 2012).

5.3. Impacts of Noise on Marine Invertebrates – Adults

Special attention has been paid to seismic surveys and the impacts on invertebrates over the past few years (Payne *et al.,* 2007). No direct evidence of acute or mid-term mortality was found by Parry and Gason (2006), when the statistical coincidence between seismic surveys and changes in commercial rock lobster (*Panulirus cygnus*) catch rates in western Victoria between 1978 and 2004 were assessed. However it was expected that impacts would be minimal as most seismic surveys occurred in deep water. Payne *et al.* (2007) also pointed out that a mortality rate in the range of 50% would have been required before direct seismic impact could have been resolved from other factors.

Payne *et al.* (2007), when examining the effects of seismic sounds upon American lobsters (*Homarus americanus*), found no effect of low (~202 dB re 1 µPa) or high (~227 dB re 1 µPa) peak-to-peak sound levels of airgun exposure in relation to delayed mortality or damage to mechanosensory systems, assessed by turnover rates. Furthermore, there was no evidence for loss of legs or other appendages. However, sub-lethal effects of exposure were observed with regard to serum biochemistry and feeding. These effects were being observed weeks to months after exposure. Changes in the hepatopancreas of animas exposed four months previously were also observed. Studies have also been undertaken in order to assess the physiological effects of seismic exploration on snow crabs on the Canadian east coast. No short or long term effects of seismic exposure in young or adult crabs or on eggs were observed (Boudreau *et al.,* 2009).

More recent findings suggest that invertebrates could possibly be susceptible to the detrimental impacts of anthropogenic noise (Wale *et al.,* 2013). Interestingly, Andrè *et al.* (2011) present the first morphological and ultrastructural evidence of acoustic trauma in four cephalopod species, subjected to low-frequency controlled-exposure experiments. Permanent and substantial alterations of the sensory hair cells of the statocysts occurred as a result of exposure to low-frequency sound. It was concluded that since the relatively short exposure and low levels applied in this study could induce severe acoustic trauma in cephalopods, the effects of similar noise sources on such species in natural conditions over longer time periods may be significant. Fewtrell and McCauley (2012), who also investigated the effect of air gun noise on squid (*Sepioteuthis australis)*, found that sound exposure noise levels greater than 147 dB re 1 µPa^2 s are required to induce avoidance behaviour in this species. Their findings also suggest that prior exposure to air gun noise and a gradual increase in air gun signal intensity reduces the severity of the alarm responses in *S. australis*. In an earlier paper by McCauley *et al.* (2000b), it is stated that captive squid would demonstrate a significant behavioural response at approximately 2 – 5 km from an approaching seismic source.

A few studies have demonstrated that vessel noise playback may affect the behaviour and physiology of some species of marine invertebrates. For example, Wale *et al.* (2013) found that the physiology of shore crabs (*Carcinus maenas*) was affected by both single and repeated exposure to ship-noise playback (sound pressure level of 148–155 dB re 1 µPa (RMS)). Individuals exposed to the ship noise consumed 67% more oxygen than those exposed to ambient-noise playback (sound pressure level 108–111 dB re 1 µPa (RMS)), indicating potentially greater stress and a higher metabolic rate. Heavier individuals showed a stronger response than lighter individuals when exposed to single ship-noise playback. Furthermore, repeated exposure to ship-noise playback produced no change in physiological response, however repeated exposure to ambient-noise playback led to increased oxygen consumption. It is thought that the crabs either became tolerant to the ship noise or that they showed a maximal response on first exposure to the ship noise.

Furthermore, a playback experiment was designed by Chan *et al.* (2010) to test the effect of vessel noise on predation risk assessment. They found that Caribbean hermit crabs (*Coenobita clypeatus*), in response to boat motor playback, allowed a simulated predator to approach closer before they hid. These findings suggest that anthropogenic sounds may distract prey and make them more vulnerable to predation. It also suggests that quite subtle responses to noise exposure by an individual may affect its survival (Normandeau Associates, Inc., 2012).

5.4. Impacts of Noise on Marine Invertebrates – Eggs and Larvae

The planktonic larval stages of many invertebrates undergo development in offshore waters, away from coastal settlement sites. The migration back to these coastal settlement sites is a vital period in larval development (Radford *et al.,* 2008). There is evidence to suggest that pelagic post-larval crustaceans use underwater sound as an orientation cue for settlement onto reefs (Montgomery *et al.,* 2006). Radford *et al.* (2007) found that the post-larvae of five New Zealand common crab species (*P*. *chabrus*, *N. ursus*, *C. lavauxi*, *Pagurus* spp. and *H. edwardsii*) were able to localize and respond to artificial reef noise. The results suggest that acoustic orientation behaviour firstly, may be widespread among species of coastal crab and secondly, could be of great ecological importance in influencing the settlement processes of such species.

A later study by Stanley *et al.* (2010) demonstrated how ambient underwater sound can affect the physiological development rate of tropical and temperate crab larvae. The effect of exposure to underwater reef sound on the settlement behaviour and time to metamorphosis (TTM) was observed in the megalopae of tropical crabs (species of the Grapsidae family) and temperate crabs (*Hemigrapsus sexdentatus*, *Cyclograpsus lavauxi*, and *Macrophthalmus hirtipes*). When exposed to the reef noise, settlement behaviour was observed earlier and there was a considerable decrease in TTM (by 34-60%) in the megalopae of all species, in comparison with silent (control) conditions. Thus ambient underwater sound may be an important settlement cue for many species of crab and may play a significant role in the recruitment to crab populations (Stanley *et al.,* 2010; 2012).

Whilst some species settle onto reefs, a diverse community of free-swimming organisms (a large number of which are crustaceans) live in waters surrounding these reefs. It is likely these species would benefit from avoiding the many predators resident on reefs (Simpson *et al.,* 2011). Simpson *et al.* (2011) investigated whether tropical organisms either living in the water column throughout their lives (pelagic taxa) or those that are hidden in sediment during the day but present in the water column at night (nocturnally emergent taxa) were deferred by reef noise. Findings showed that pelagic or nocturnally emergent organisms present in the vicinity of reefs, but which do not settle on them, actively avoid reef noise. Findings also showed that the larvae of species which inhabit reefs as adults were attracted to the playback of reef noise, which are consistent with the findings from Radford *et al.* (2007) and Stanley *et al*. (2010; 2012).

When considering human-generated noise in addition to natural ambient sounds in the marine environment, Stanley *et al*. (2012) conclude that anthropogenic noise, particularly continuous noise, may interfere with settlement and recruitment process of species that use ambient noise to locate and settle into suitable habitats. This could lead to reduced or premature settlement. Anthropogenic noise has the potential to act as an orientation and settlement cue given that such noise is occurring at biologically relevant frequencies. On the other hand, anthropogenic noise may interfere with the ability of larvae to seek out suitable habitats by masking the detection of ambient noise cues, such as reef sound (Montgomery *et al.,* 2006). Or, non-settling species may be less able to detect and avoid reef environments that could potentially be dangerous (Simpson *et al.,* 2011).

Although little is known about the effect of noise on early developmental stages of marine life, recently Aguillar de Soto *et al.* (2013) proved that scallop larvae exposed to playbacks of seismic pulses showed significant developmental delays and 46% developed body abnormalities; similar effects were observed in all independent samples exposed to noise while no malformations were found in the control groups.

5.5. Marine Invertebrate Summary

To some extent, there are conflicting findings within the available scientific literature on invertebrate hearing. Evidence suggests that invertebrates are likely to be sensitive to low frequency sounds (below 100 Hz) (Normandeau Associates, Inc., 2012). Cephalopods in particular, appear to be sensitive to the low frequency particle-motion component of the sound field and not pressure (Mooney *et al.,* 2010, 2012). However Hu *et al.* (2009) demonstrated that cephalopods are capable of detecting high frequency sounds up to 1500 Hz. A possible explanation for the difference in findings has been put forward by Mooney *et al.* (2010) who state that only the pressure component of the sound field was measured by Hu et *al*. (2009). It is possible that a large pressure release at the water surface, where the squid were held, caused very large but un-quantified particle velocities. The squid may have responded to this rather than directly to the frequencies reported (Mooney *et al.,* 2010). It appears many invertebrate species are sensitive to low frequency particle accelerations generated by sources nearby. However, very little data currently exists on invertebrate hearing and a lot of uncertainties remain on this subject, such as whether these animals respond to sounds at a distance from the source (Normandeau Associates, Inc., 2012).

On the whole, in the absence of field observations to reveal the context in which sounds are produced by invertebrates, we can only speculate as to their function (Patek and Caldwell, 2006). The findings by Bouwma & Herrnkind (2009); Buscaino *et al.* (2011) and Staaterman *et al.* (2011) suggests that sounds and signals play an important part in communication between individuals and that conspecifics are able to detect them (Normandeau Associates, Inc., 2012). Evidence suggests that some sounds are used as an anti-predator/defence mechanism or a territorial warning. Anthropogenic noise could potentially mask these important sounds and interfere with their detection (Normandeau Associates, Inc., 2012). For example, vessel noise may impact the acoustic ecology of the California Mantis Shrimp (see section 4.2) by masking the 'rumble' sounds made by this species (Staaterman *et al.,* 2012). Evidence also suggests that cephalopods may be susceptible to more severe impacts of noise (see Andrè *et al.,* 2011) and this warrants the need for further investigations on potentially vulnerable invertebrates.

It is clear that ambient noise such as reef sound may play an important role in the orientation and settlement of pelagic crab larvae (Montgomery *et al.,* 2006; Radford *et al.,* 2007; Stanley *et al.,* 2010, 2012). It remains to be determined whether anthropogenic noise interferes with recruitment processes by disrupting orientation and settlement cues, through the masking of important signals.

There is a general need for further investigation to assess the impacts of anthropogenic noise on invertebrates. Recent findings (Andrè *et al.,* 2011 and Wale *et al*., 2013) indicate that anthropogenic noise could potentially have physiological impacts on invertebrates and future studies are necessary to support and build upon these findings.

6 Effects at the Population Level

Within the available scientific literature, the reported effects of noise on marine life are concerned with reactions of individuals or groups, not facilitating a direct translation to assessing a population and ecosystem level impact. However, the notion that reductions in individuals' fitness (i.e. ability to survive and reproduce) following exposure to underwater sound could translate to population level effects is well documented (NRC, 2005; Richardson *et al*., 1995; Southall *et al*., 2007; Popper and Hastings, 2009). The apparent lack of data relating to documented population wide effects resulting from noise exposure is at least in part due to the challenges associated with studying mobile marine organisms *in situ*, the limited ability to discern the effect of noise from other impacts and the relatively recent emergence of underwater noise as a potential factor that may adversely impact marine life. The growing interest in the effects on anthropogenic noise on the populations of sensitive marine organisms is manifested in the existing literature (OSPAR Commission, 2009a), and for marine mammals at least, an approach has been devised that aims to assess the effect of acoustic disturbance on population viability. Underlying this approach is the Population Consequence of Acoustic Disturbance model (PCAD, NRC, 2005) that constitutes a number of steps between the sound and any related population effect. It is fair to say that such population level studies of the effects of underwater noise have focussed predominantly on marine mammals, with less emphasis on the population level consequences for fish and invertebrates. There is, however, understanding that migratory fish species may be deterred from reaching their preferred spawning or breeding sites (Normandeau Associates, Inc., 2012), and that species relying on active acoustics could have diminished ability to acoustically find food or establish any necessary contact with conspecifics, such as for the purpose of mating or social cohesion, for example (Mueller-Blenkle *et al.*, 2010; whale example).

7 Discussion

After reviewing widespread literature, primarily from the past eight years, it is evident that anthropogenic noise has been recognised as having the potential to impact marine life in numerous ways. Such impacts include the masking of biologically important signals, behavioural responses, temporary or permanent shift in hearing threshold and mortality. It is also evident from the above review, that there are gaps in our understanding of the impacts of anthropogenic noise on marine life, which are detailed in section 7.1 below.

7.1. Knowledge Gaps and Recommendations for Future Research

It is evident that there is a need to link immediate or short-term effects of noise exposure to biologically significant long-term effects on reproduction, survival and populations (Christiansen *et al.,* 2010). This is true for all marine animals. For example, there is a need to further investigate behavioural responses at critical times such as mating and spawning (Erbe, 2012; Mueller-Blenkle *et al.,* 2010). Alas it is important from a conservation perspective to assess whether anthropogenic sound has a significant effect on populations (OSPAR Commission, 2009b).

Future research on habituation to anthropogenic sounds is also required (Mueller-Blenkle *et al.,* 2010), in order to answer a key question 'to what extent are animals capable of adapting to noise?' (Science Communication Unit, 2012).

Currently, the effects of cumulative exposure to anthropogenic sounds and the manner in which repeated exposure gets accumulated by an animal are unknown. Mitigation measures and regulation mainly address acute exposure from a single event / operation and direct damage (Erbe, 2012). Key questions as highlighted in the EU Future Brief 2013 are (i) what are the cumulative effects of less frequent, loud impulsive noise and low-level continuous noise? (ii) does it matter if animals remain in noisy areas or leave but later return?

It is also important to assess the impacts of noise in relation, or addition to other stresses in order to assess cumulative impacts (OSPAR Commission, 2009b). Marine animals which are already extremely stressed may be pushed into population decline due to the additional threat of living in a noisy environment. This may have subsequent effects on marine communities and biodiversity (Science Communication Unit, 2012).

It is recommended in the OSPAR Commission (2009b) report that in order to reduce the potential impacts of underwater noise on marine life, greater efforts should be made to develop and apply effective mitigation measures. For example, seasonal and geographical restrictions may be applied to sound-producing activities to avoid areas and times where/when sensitive animals are normally engaged in vital activities such as foraging, breeding, spawning and mating.

7.1.1. Recommendations for Marine Mammals

There is an understanding that marine mammals are negatively impacted by specific anthropogenic sounds and are deterred over large distances by high amplitude sounds in particular. However, there is not enough information currently available to fully understand the extent of impact(s) arising from a given sound in view of its specific characteristics (frequency, amplitude and temporal characteristics).

There is no doubt we need understanding of the response of marine mammals to real sounds, in the environment where the impact is expected to happen. If we take the wind farm example, the only studies which have really looked at this are the Brandt and Tougaard studies which are limited in their applicability to other sites due to the lack of acoustic measurements where the PODS/observations were made.

It is particularly difficult to translate knowledge and findings from controlled investigations to real open water situations. For example, a dolphin in a tank may respond to the tone of a given frequency, of given duration at a given sound pressure level. However, in a real life open water situation, the dolphin may be exposed to a sound which is not a tone with the same characteristics and might be very different in nature. There is very limited understanding about population level consequences arising from noise, especially those resulting from masking, but understanding in-situ responses is a step forward in tackling this issue.

Hence, there is a great need to obtain information and gain understanding on how a given species responds in its own environment to different sound levels, in different contexts (e.g. migrating, feeding, and breeding) resulting from real sound sources, be these piles, seismic airguns or vessel noise. Having considered the sources of greatest concern within this report it would be beneficial to develop a strategic approach to addressing these knowledge gaps. Without this information, it will be difficult to fully understand the direct population level consequences.

Whilst playback experiments can serve as a beneficial mechanism for conducting controlled studies and determining preliminary information about species sensitivity to sound, they may not necessarily be the best way forward in terms of establishing criteria or an understanding of the true impact of noise sources upon marine mammals. Difficulties arise in part from limitations in accurately replicating sound waves with the same amplitude and phase characteristics as the real sources, while sound reflection from tank walls and difficulties in reproducing representative ambient sound-scapes introduce further margin for error.

One major knowledge gap concerning marine mammals is that very limited information on the chronic effects of anthropogenic underwater noise exists.

A detailed list of research recommendations is provided by Southall *et al*., (2007) in order to enhance future marine mammal noise exposure (see Annex I).

Also important to note, only the acute effects of noise on marine mammal hearing and behaviour have been addressed in impact assessments (Ellison et al., 2011). Adverse effects of chronic noise at the individual or population level, or at habitat or ecosystem level, have not been included in management decisions. Following on from Southall *et al.* (2007), Ellison *et al.* (2011) propose that a more comprehensive assessment method is required to take into account the fact that several factors can affect the probability of a behavioural response to chronic and acute noise, other than the received sound level. These contextual factors include animal activity, the nature of the sound, spatial relations between sound source and receiver and history of prior exposure to the sound. The proposal consists of three approaches including; (i) measurement and evaluation of context-based behavioural responses of marine mammals to various sound sources; (ii) new sound-exposure metrics that highlight relative sound levels (in addition to absolute sound levels) and (iii) the consideration of the effects of acute and chronic noise exposure.

7.1.2. Recommendations for Fish

Likewise for fish, there is also a need to obtain information and gain understanding on how a given species responds in its own environment to different sound levels, in different contexts, resulting from real sound sources. Ultimately, it is important to know if fish are deterred from particularly noisy events, such that they are prevented from migrating and spawning for example. Such information is similarly useful in developing mitigation techniques to actively deter fish from low head hydropower plants and nuclear cooling facility intakes.

It is apparent that a greater understanding on the hearing sensitivities of fish is required. Not enough is known about the impacts of anthropogenic sound exposure upon fish to draw definitive conclusions from existing literature (Popper and Hastings, 2009). However, there is some evidence that high intensity sounds can cause damage to fish ears (McCauley *et al.,* 2003). Further investigation is required in order to understand more about the physiological and mechanical processes that lead to damage and also the repair processes.

Moving forward, there is a need for field-based experiments to compliment previous evidence of demonstrable impacts, enhancing the focus on ecologically relevant behaviour and including consideration of the particle motion component of sounds. Moreover, studies need to examine the effect of repeated and/or chronic noise exposure, as this represents the more ecologically realistic scenario in most circumstances.

Future in-situ observational experiments (using a true sound source) on fish would need to be well correlated with measurements of particle velocity and acoustic pressure in the water column as well as sea-bed vibration for demersal species.

With regard to fish eggs and larvae, information on sound levels at which lethal and sub-lethal effects occur is very much limited. Bolle *et al.* (2012) recommends that future research is needed on lethal and sub-lethal effects, including behavioural effects and injury.

7.1.3. Recommendations for Marine Invertebrates

Knowledge of the hearing capabilities of marine invertebrates is at a very early stage in comparison with that of marine mammals and even fish. As previously established, data on marine invertebrate hearing is very limited and few studies have investigated acoustic communication among invertebrates, especially benthic crustaceans (Staaterman *et al.,* 2011). Thus undertaking controlled tank experiments to determine the sensitivity of different species to underwater sound would go some way to addressing this issue.

On the whole, little is known about the impacts of anthropogenic underwater sound exposure on these animals (Normandeau Associates, Inc., 2012). Thus, in order to address a key question 'how are less well studied species affected by underwater noise? (EU Future Brief, 2013) invertebrates, particularly crustaceans, should be included in future impact studies (Lovell *et al.,* 2005). There is indication that anthropogenic noise could potentially have physiological impacts on invertebrates (see Wale *et al.,* 2013) but further studies are necessary to support and build upon these findings. A lot of uncertainty remains as to whether marine invertebrates respond to sounds at a distance from the source (Normandeau Associates, Inc., 2012). It is still largely unknown whether anthropogenic noise interferes with recruitment processes by disrupting orientation and settlement cues, through the masking of important signals; this requires further investigation.

8 References

Aguilar de Soto, N., Johnson, M., Madsen, P.T., Tyack, P.L., Bocconcelli, A. and Borsani, J.F. (2006) Does intense ship noise disrupt foraging in deep-diving cuvier's beaked whales (*Ziphius cavirostris*). Marine Mammal Science. 22(3): 690-699.

Aguilar de Soto, N., Delorme, N., Atkins, J., Howard, S., Williams, J. and Johnson, M. (2013) Anthropogenic noise causes body malformations and delays development in marine larvae. SCIENTIFIC REPORTS | 3 : 2831 | DOI: 10.1038/srep02831

http://www.nature.com/srep/2013/131003/srep02831/full/srep02831.html#ref13

Amorim, M.C.P. (2006) Diversity of sound production in fish. In: Communication in fishes. Vol. 1 F. Ladich, S. P. Collin, P. Moller & B.G. Kapoor (eds.). Science Publishers, Enfield. pp. 71-104.

André, M., Solé, M., Lenoir, M., Durfort, M., Quero, C., Mas, A., Lombarte, A., van der Schaar, M., López-Bejar, M., Morell, M., Zaugg, S. and Houégnigan, L. 2011. Low-frequency sounds induce acoustic trauma in cephalopods. *Frontiers in Ecology and the Environment* **9**: 489–493. http://dx.doi.org/10.1890/100124

Au, W.W.L. and Hastings, M.C. (2008) *Principles of Marine Bioacoustics.* DOI: 10.1007/978-0-387-78365-9-1, Springer Science+Business Media, LLC 2008.

Boeger, W.A., Pie, M.R., Ostrensky, A., Cardoso, M.F. (2006) The effect of exposure to seismic prospecting on coral reef fishes. Brazilian Journal of Oceanography. 54(4). 235-239.

Bolle L.J., de Jong, C.A.F., Bierman, S.M., van Beek, P.J.G., van Keeken, O.A., et al. (2012) Common Sole Larvae Survive High Levels of Pile-Driving Sound in Controlled Exposure Experiments. PLoS ONE 7(3): e33052. doi:10.1371/journal.pone.0033052.

Borsani, J.F., Clark, C.W., Nani, B. and Scarpiniti, M. (2008) Fin Whales Avoid Loud Rythmic Low-Frequency Sounds in the Ligurian Sea. *Bioacoustics. The International Journal of Animal Sound and its Recording,* Vol. 17, pp. 151 – 193.

Boudreau, M., Courtenay, S.C. and Lee, K. (2009) Proceedings of a workshop held 23 January 2007 at the Gulf Fisheries Center. Potential Impacts of Seismic Energy on Snow Crab: An Update to the September 2004 Review. Can. Tech. Rep. Fish. Aquat. Sci. 2836: vii + 31 p.

Bouwma, P.E. and Herrnkind, W.F. (2009) Sound production in Caribbean spiny lobster *Panulirus argus* and its role in escape during predatory attack by *Octopus briareus*. New Zealand Journal of Marine and Freshwater Research, 43:1, 3-13, DOI: 10.1080/00288330909509977.

Bracciali, C., Campobello, D., Giacoma, C. and Gianluca, S. (2012) Effects of nautical traffic and noise on foraging patterns of Mediterranean damselfish *(Chromis chromis)*. PloS ONE 7: e40582.

Brandt, M.J., Diederichs, A. and Nehls, G. (2009) Harbour porpoise responses to pile driving at the Horns Rev II offshore wind farm in the Danish North Sea. Final Report to DONG Energy, BioConsult SH, Husum, Germany.

Brandt, M.J., Diederichs, A., Betke, K. and Nehls, G. (2012) Effects of Offshore Pile Driving on Harbour Porpoises (Phocoena phocoena). In: Popper, A.N. and A.D. Hawkins, eds. The effects of noise on aquatic life. New York: Springer Science + Business Media, LLC. Pp. 281-284.

Bruintjes, R. & Radford, A.N. (2013) Context-dependent impacts of anthropogenic noise on individual and social behaviour in a cooperatively breeding fish. Animal Behaviour 85: 1343-1349.

Buscaino, G., Filicoiotto, F., Gristina, M., Bellante, A., Buffa, G., Di Stefano, V., Maccarrone, V., Tranchida, G., Buscaino. C. and Mazzola, S. (2011) Acoustic behaviour of the European spiny lobster *Palinurus elephas*. Mar Ecol-Prog Ser 441:177-18.

Carlson, T.J. (2012) Barotrauma in fish and barotrauma metrics. In: Popper, A.N. and A.D. Hawkins, eds. The effects of noise on aquatic life. New York: Springer Science + Business Media, LLC. Pp. 229-234.

Casper, B.M. and Mann, D.A. (2009) Field hearing measurements of the Atlantic sharpnose shark (*Rhizoprionodon terraenovae*). Journal of Fish Biology 75:2768-2776.

Casper, B.M., Halvorsen, M.B. and Popper, A.N. (2012a) Are sharks even bothered by a noisy environment? In: Popper, A.N. and A.D. Hawkins, eds. The effects of noise on aquatic life. New York: Springer Science + Business Media, LLC. Pp. 93-98.

Casper, B. M., Popper, A. N., Matthews, F., Carlson, T. J., and Halvorsen, M. B. (2012b) Recovery of barotrauma injuries in Chinook salmon, *Oncorhynchus tshawytscha* from exposure to pile driving sound. PLoS ONE, 7(6): e39593. doi:10.1371/journal.pone.0039593.

Casper, B.M., Halvorsen, M.B., Matthews, F., Carlson, T.J. and Popper, A.N. (2013) Recovery of Barotrauma Injuries Resulting from Exposure to Pile Driving Sound in Two Sizes of Hybrid Striped Bass. PLoS ONE 8(9): e73844. doi:10.1371/journal.pone.0073844.

Castellote, M., Clark, C.W. and Lammers, M.O. (2010) Potential negative effects in the reproduction and survival on fin whales (*Balaenoptera physalus*) by shipping and airgun noise. Int. Whal. Comm. Working Pap. SC/62/E3. 12 p.

Castellote, M., Clark, C.W. and Lammers, M.O. (2012) Acoustic and behavioural changes by fin whales (*Balaenoptera physalus*) in response to shipping and airgun noise. *Biological Conservation* 147, pp 115 – 122.

Cerchio, S., Strindberg, S., Collins, T., Bennett, C. and Rosenbaum, H. (2011) Humpback whale singing activity off northern Angola: an indication of the migratory cycle, breeding habitat and impact of seismic surveys on singer number. p. 56 *In*: Abstr. 19th Bienn. Conf. Biol. Mar. Mamm., Tampa, FL, 27 Nov.– 2 Dec. 2011. 344 p.

Chan, A., Giralso-Perez, P., Smith, S. and Blumstein, D.T. (2010) Anthropogenic noise affects risk assessment and attention: the distracted prey hypothesis. Biol. Lett. 6, 458–461. doi:10.1098/rsbl.2009.1081.

Christiansen, F., Lusseau, D., Stensland, E. and Berggren, P. (2010) Effects of tourist boats on the behaviour of Indo-Pacific bottlenose dolphins off the south coast of Zanzibar. Endangered Species Research. 11. 91-99.

Clark, C.W. and Gagnon, G.C. (2006) Considering the temporal and spatial scales of noise exposures from seismic surveys on baleen whales. Intern. Whal. Commis. Working Pap. SC/58/E9. 9 p.

Clark, C.W., Ellison, W.T., Southall. B.L., Hatch, L., Van Parijs, S.M., Frankel, A. and Ponirakis, D. (2009) Acoustic masking in marine ecosystems: intuitions, analysis, and implication. Marine Ecology Press Series. Vol. 395: 201 – 222.

Codarin, A., Wysocki, L.E., Ladich, F. and Picciulin, M. (2009) Effects of ambient and boat noise on hearing and communication in three fish species living in a marine protected area (Miramare, Italy). Mar. Pollut. Bull. doi:10.1016/j.marpolbul.2009.07.011.

Dähne, M., Gilles, A., Lucke, K., Peschko, V., Adles, S., Krügel, K., Sundermeyer, J. and Siebert, U. (2013) Effects of pile-driving on harbour porpoises (Phocoena phocoena) at the first offshore windfarm in Germany. Environ. Res. Lett. 8, 1-16.

Di Iorio, L. and Clark, C.W. (2009) Exposure to seismic survey alters blue whale acoustic communication. Biol. Lett. (2010) 6, 51–54; published ahead of print September 23, 2009. doi:10.1098/rsbl.2009.0651.

Diederichs, A., Brandt, M.J. and Nehls, G. (2009) Effects of construction of the transformer platform on harbour porpoises at the offshore test field "alpha ventus." Report to Stiftung Offshore-Windenergie, BioConsult SG, Husum, Germany.

Doksæter, L., Godø, O. R., Handegard, N. O., Lam, F-P. A., Donovan, C. and Miller, P. J. O. (2009) Behavioral responses of herring (Clupea harengus) to 1–2 and 6 – 7 kHz sonar signals and killer whale feeding sounds. J. Acoust. Soc. Am.125, (1), pp. 554–564.

Ellison, W.T., Southall, B.L., Clark, C.W. and Frankel, A.S. (2011) A New Context-Based Approach to Assess Marine Mammal Behavioral Responses to Anthropogenic Sounds. *Conservation Biology,* Volume 26, No. 1, pp. 21–28.

Engas, A., Lokkeborg, S., Ona, E. and Soldal, A.V. (1996) Effects of seismic shooting on local abundance and catch rates of cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*). Canadian Journal of Fisheries and Aquatic Sciences, 53, 2238e2249.

Erbe, C. (2012) "Effects of Underwater Noise on Marine Mammals". *Advances in Experimental Medicine and Biology* 730: 17-22.

Fewtrell, J. L. and McCauley, R. D. (2012) Impact of air gun noise on the behaviour of marine fish and squid. Marine Pollution Bulletin, 64, pp. 984–993.

Gedamke, J., Gales, N. and Frydam, S. (2011) Assessing risk of baleen whale hearing loss from seismic surveys: The effect of uncertainty and individual variation. J Acoust. Soc. Am., 129 (1), pp. 496–506.

Gregg, J.D., Dudzinski, K.M. and Smith, H.V. (2007) Do Dolphins Eavesdrop on the Echolocation Signals of Conspecifics? *International Journal of Comparative Psychology,* 2007, **20**, 65-88.

Halvorsen, M. B., Casper, B. M., Woodley, C. M., Carlson, T. J. and Popper, A. N. (2012a) Threshold for onset of injury in Chinook salmon from exposure to impulsive pile driving sounds. PLoS ONE, 7(6) e38968. doi:10.1371/journal.pone.0038968.

Halvorsen, M.B., Casper, B.M., Matthews, F., Carlson, T.J. and Popper, A.N. (2012b) Effects of exposure to pile-driving sounds on the lake sturgeon, Nile tilapia and hogchoker. Proc. R. Soc. B (2012) 279, 4705–4714 doi:10.1098/rspb.2012.1544.

Hastings, M. C. and Popper, A. N. (2005) *Effect of Sound on Fish*. Report to California Department of Transportation, Contract No. 43A0139.

Hildebrand, J.A. (2009) Anthropogenic and natural sources of ambient noise in the ocean. *Marine Ecology Progress Series* 395:5–20.

Holles, S., Simpson, S.D., Radford, A. N., Berten, L. and Lecchini, D. (2013) Boat noise disrupts orientation behaviour in a coral reef fish. Marine Ecology Progress Series 485: 295–300.

Holt, M.M., Noren, D.P., Veirs, V., Emmons, C.K. and Veirs, S. (2008) Speaking up: Killer whales (*Orcinus orca)* Increase their call amplitude in response to vessel noise. J. Acoust. Soc. Am. **125** _1_, January 2009.

Hu, M., Yan, H.Y., Chung, W.S., Shiao, J.C. and Hwang, P.P. (2009) Acoustical evoked potentials in two cephalopods inferred using the auditory brainstem response (ABR) approach. Comparative Biochemistry and Physiology A 153:278-283.

Jensen, F.H., Bejeder, L., Wahlberg, M., Aguilar Soto, N., Johnson, M. and Madsen, P.T. (2009) Vessel noise effects on delphinid communication. Marine Ecology Progress Series. 395. 161-175.

IUCN (2008) International Union for Conservation of Nature Red List. See http://www.iucnredlist.org/details/2477.

Jepson, P.D., Arbelo, M., Deaville, R., Patterson, I.A.P., Castro, P., Baker, J.R., Degollada, E., Ross, H.M., Herráez, P., Pocknell, A.M., Rodríguez, F., Howie, F.E., Espinosa, A., Reid, R.J., Jaber, J.R., Martin, V., Cunningham, A.A. and Fernández, A. (2003) Gas-bubble lesions in stranded cetaceans. NATURE|VOL 425 | 9 OCTOBER 2003 |www.nature.com/nature.

Kaifu, K. (2007) Behavioural Responses to Underwater Sound in the Small Benthic Octopus *Octopus ocellatus.* J. Marine Acoust. Soc. Jpn. Vol. 34 No. 4. Oct. 2007 pp 266 - 273

Kastelein, R.A., van der Heul, S., Verboom, W.C., Jennings, N., van der Veen, J. and de Haan, D. (2008) Startle response of captive North Sea fish species to underwater tones between 0.1 and 64 kHz. Marine Environmental Research **65** (2008) 369–377.

Kastelein, R. and Jennings, N. (2012) Impacts of Anthropogenic Sounds on Phocoena phocoena (Harbour Porpoise). In: Popper, A.N. and A.D. Hawkins, eds. The effects of noise on aquatic life. New York: Springer Science + Business Media, LLC. Pp. 311-315.

Kastelein, R.A., van Heerden, D., Gransier, R. and Hoek, L. (2013) Behavioral responses of a harbor porpoise (Phocoena phocoena) to playbacks of broadband pile driving sounds. Marine Environmental Research 92: 206 – 2 14.

Løkkeborg, S. (1991) Effects of a geophysical survey on catching success in longline fishing. ICES C.M 1991/B, 40, 9.

Løkkeborg, S., Ona, E., Vold, A. and Salthaug, A. (2012) Effects of sounds from seismic air-guns on fish behaviour and catch rates..Advances in Experimental Medicine and Biology 730: 415-419.

Lovell, J.M., Findlay, M.M., Moate, R.M., Yan, H.Y. (2005) The hearing abilities of prawn Palaemon serratus. Comparative Biochemistry and Physiology, Part A. 140. 89-100.

Lucke, K., Siebert, U., Lepper, P.A. and Blanchet, M. (2009) Temporary shift in masked hearing thresholds in a harbour porpoise (*Phocoena phocoena*) after exposure to seismic airgun stimuli. The Journal of the Acoustical Society of America. 125 (6) pp 4060 – 4070.

McCauley, R.D. and Cato, D.H. (2000) Patterns of fish calling in a nearshore environment in the Great Barrier Reef. Philosophical Transactions of the Royal Society of London Series B-Biological Sciences 355: 1289–1293.

McCauley, R.D., Fewtrell, J., Duncan, A.J., Jenner, C., Jenner, M-N., Penrose, J.D., Prince, R.I.T., Adhitya, A., Murdoch, J. and McCabe, K. (2000a) Marine seismic surveys: a study of environmental implications. APPEA Journal, 40:692-708.

McCauley, R.D., Fewtrell, J., Duncan, A. J., Jenner, C., Jenner, M-N., Penrose, J. D., Prince, R. I. T., Adhitya, A., Murdoch, J. and McCabe, K. (2000b) Marine seismic surveys: Analysis and propagation of air-gun signals; and effects of air-gun exposure on humpback whales, sea turtles, fishes and squid. Project CMST 163, Report R99-15, Centre for Marine Science and Technology, Curtin University of Technology.

McCauley, R.D., Fewtrell, J., Popper, A.N. (2003) High intensity anthropogenic sound damages fish ears. Journal of the Acoustical Society of America. 113(1). 638-642.

McDonald, M.A., Hildebrand, J.A. and Mesnik, S. (2009) Worldwide decline in tonal frequencies of blue whale songs. Endang Species Res. 9, 13–21.

McGregor, P.K., Horn, A.G., Leonard, M.L. and Thomsen, F. (2013) Anthropogenic Noise and Conservation. Animal Communication and Noise SE – 14. pp 409-444. Springer Berlin Heidelberg. 10.1007/978-3-642-41494-7_14 http://dx.doi.org/10.1007/978-3-642-41494-7_14.

Melcón, M.L., Cummins, A.J., Kerosky, S.M., Roche, L.K., Wiggins, S.M. and Hildebrand, J.A. (2012) Blue Whales Respond to Anthropogenic Noise. PLoS ONE 7(2): e32681. Doi:10.1371/journal.phone.0032681.

Monitoring Guidance for Underwater Noise in European Seas – Part I Executive Summary. 2nd Report of the Technical Subgroup on Underwater Noise (TSG Noise). November, 2013.

Monitoring Guidance for Underwater Noise in European Seas – PART II Monitoring Guidance Specifications. 2nd Report of the Technical Subgroup on Underwater Noise (TSG Noise). November, 2013.

Monitoring Guidance for Underwater Noise in European Seas – Part III Background Information and Annexes. Guidance Report. 2nd Report of the Technical Subgroup on Underwater Noise (TSG Noise). November, 2013.

Montgomery, J.C., Jeffs, A., Simpson, S.D., Meekan, M. and Tindle, C. (2006) Sound as an orientation cue for the pelagic larvae of reef fish and decapod crustaceans. Adv Mar Biol 51:143–199.

Mooney, T.A., Hanlon, R.T., Christensen-Dalsgaard, J., Madsen, P.T., Ketten, D.R. and Nachtigall, P.E. (2010) Sound detection by the longfin squid (*Loligo pealeii*) studied with auditory evoked potentials: Sensitivity to low-frequency particle motion and not pressure. Journal of Experimental Biology 213:3748-3759.

Mooney, T.A., Hanlon, R., Maden, P.T., Christensen-Dalsgaard, J., Ketten, D.R and Nachtigall, P.E. (2012) Potential for Sound Sensitivity in Cephalopods. *Advances in Experimental Medicine and Biology* 730: 125-128.

Mueller-Blenkle, C., McGregor, P.K., Gill, A.B., Andersson, M.H., Metcalfe, J., Bendall, V., Sigray, P., Wood, D.T. and Thomsen, F. (2010) Effects of Pile-driving Noise on the Behaviour of Marine Fish. COWRIE Ref: Fish 06-08, Technical Report 31st March 2010.

Myrberg, A.A. and Lugli, M. (2006). Reproductive Behavior and Acoustical Interactions In: Communication in fishes. Vol. 1 F. Ladich, S. P. Collin, P. Moller & B.G. Kapoor (eds.). Science Publishers, Enfield. pp. 71-104.

NOAA. (2013) Draft Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammals. Acoustic Threshold Levels for Onset of Permanent and Temporary Threshold Shifts. Draft: 23 December 2013.

Nedwell, J. R., Turnpenny, A. W. H., Lovell, J. M. and Edwards, B. (2006) An investigation into the effects of underwater piling noise on salmonids. *Journal of the Acoustical Society of America* **120,** 2550–2554.

Normandeau Associates, Inc. (2012) Effects of Noise on Fish, Fisheries, and Invertebrates in the U.S. Atlantic and Arctic from Energy Industry Sound-Generating Activities. A Literature Synthesis for the U.S. Dept. of the Interior, Bureau of Ocean Energy Management. Contract # M11PC00031. 153 pp.

Nowacek, D.P., Thorne, L.H., Johnston, D.W. and Tyack, P.L. (2007) Responses of cetaceans to anthropogenic noise. *Mammal Review,* Volume **37**, No. 2, 81-115.

NRC. (2005) *Marine mammal populations and ocean noise: Determining when noise causes biologically significant effects.* Washington, DC: The National Academies Press. 126 pp.

Ona, E., Godø, O. R., Handegard, N. O., Hjellvik, V., Patel, R. and Pedersen, G. (2007) "Silent vessels are not quiet". J. Acoust. Soc. Am. **121** (4): EL145-EL150. DOI: 10.1121/1.2710741.

OSPAR Commission. (2009a) Overview of the impacts of anthropogenic underwater sound in the marine environment.

OSPAR Commission. (2009b) Assessment of the environmental impact of underwater noise. Biodiversity Series.

Parente, C. L., Lontra, J.D. and AraÚjo, M.E. (2006). Occurrence of sea turtles during seismic surveys in Northeastern Brazil. Biota Neotropica [online] 2006, 6 (Sin mes) : [Date of reference: 24 / marzo / 2014] Available in:<http://www.redalyc.org/articulo.oa?id=199114285004> ISSN 1676-0611.

Parks, S.E., Clark, C.W. and Tyack, P.L. (2008) Long and short term changes in right whale acoustic behaviour in increased low-frequency noise. *Bioacoustics. The International Journal of Animal Sound and its Recording,* Vol. 17, pp. 179 – 180.

Parry, G.D. and Gason, A. (2006) The effect of seismic surveys on catch rates of rock lobsters in western Victoria, Australia. Fish Res 79: 272-284.

Patek, S.N. and R. L. Caldwell. (2006) The stomatopod rumble: sound production in *Hemisquilla californiensis*. *Marine and Freshwater Behaviour and Physiology* 39(2): 99-111.

Patek, S.N., Ship, L.E. and Staaterman, E.R. (2009) The acoustics and acoustic behavior of the California spiny lobster (*Panulirus interruptus*). Journal of the Acoustical Society of America 125:3434-3443.

Payne, R.S. and McVay, S. (1971) Songs of Humpback Whales. Science. Volume 173 pp 587-597.

Payne J.F., Andrews, C.A., Fancey, L.L., Cook, A.L. and Christian, J.R. (2007) Pilot study on the effects of seismic air gun noise on lobster (*Homarus americanus*). Canadian Technical Report of Fisheries and Aquatic Sciences No.2712:v + 4.

Picciulin, M., Sebastianutto, L., Codarin, A., Farina, A. and Ferrero, E. A. (2010) *In situ* behavioural responses to boat noise exposure of *Gobius cruentatus* (Gmelin, 1789; fam.Gobiidae) and *Chromis chromis* (Linnaeus, 1758; fam. Pomacentridae) living in a Marine Protected Area. *Journal of Experimental Marine Biology and Ecology* 386(1-2): 125-132.

Picciulin, M., Sebastianutto, L., Codarin A., Calcagno G. and Ferrero, E.A. (2012) Brown meagre vocalization rate increases during repetitive boat noise exposures: A possible case of vocal compensation. The Journal of the Acoustical Society of America 132(5):3118-24.

Pirotta, E., Milor, R., Quick, N., Moretti, D., Di Marzo, N., Tyack, P., Boyd, I. and Hastie, G. (2012) Vessel noise affects beaked whale behaviour: Results of a dedicated acoustic response study. Plos One. 7(8), e42535.

Popper, A.N., Halvorsen, M.B., Kane, A., Miller, D.L., Smith, M.E., Song, J., Stein, P. and Wysocki, L.E. (2007) The effects of high-intensity, low-frequency active sonar on rainbow trout. J. Acoust. Soc. Am. Vol **122** No. 1. pp 623 – 635.

Popper, A.H. and Hastings, M.C. (2009) Review Paper. The effects of anthropogenic sources of sound on fishes. *Journal of Fish Biology* (2009) **75**, 455–489.

Popper, A.N. and Schilt, C.R. (2008) Hearing and Acoustic Behaviour: Basic and Applied Considerations. In: Webb, J.F., Popper, A.N. and Fay, R.R. 2008. Fish Bioacoustics. Springer Handbook of Auditory Research. pp 17- 48.

Radford, C.A., Jeffs, A.G and Montgomery, J.C. (2007) Directional swimming behavior of five species of crab postlarvae in response to reef sound. Bull Mar Sci 80:369–378.

Radford, C.A., Jeffs, A.G., Tindle, C.T. and Montgomery, J.C. (2008) Temporal patterns in ambient noise of biological origin from a shallow water temperate reef. Oecologia 156:921-929.

Rako N., Fortuna C.M., Holcer D., Mackelworth P., Nimak-Wood M., Plesic G., Sebatianutto L., Vibilic I., Wiemann A. and Picciulin M. (2013) Leisure boating noise as a trigger for the displacement of the bottlenose dolphins of the Cres–Lošinj archipelago (northern Adriatic Sea, Croatia). Bulletin Marine Pollution 68 (1-2):77-84

Richardson, W. J., Malme, C.I., Green, C. R.jr. and Thomson, D.H. (1995) *Marine Mammals and Noise*. Academic Press, San Diego, CA 576 pp.

Rolland, R.M., Parks, S.E., Hunt, K.E., Castellote, M., Corkeron, P.J., Nowacek, D.P., Wasser, S.K. and Kraus, S.D. (2012) Evidence that ship noise increases stress in right whales. Proc. R. Soc. B **279:** 2363–2368

Røstad, A., Kaartvedt, S., Klevjer, T. A. and Melle, W. (2006) Fish are attracted to vessels. ICES Journal of Marine Science, 63 pp. 1431-1437.

Samson, J.E., Mooney, T.A., Gussekloo, S.W.S. and Hanlon, R.T. (2013) Behavioral responses to sound stimuli in cuttlefish (*Sepia officinalis*). W*oods Hole Oceanographic Institution and Wageningen University ; Woods Hole Oceanographic Institution; Wageningen University; Marine Biological Laboratory, Woods Hole, MA* jsamson@whoi.edu.

Samuel, Y., Morreale, S.J., Clark, C.W., Greene, C.H. and Richmond, M.E. (2005) Underwater, low-frequency noise in a coastal sea turtle habitat. J. Acoust. Soc. Am. 117 (3), Pt. 1, March 2005 0001-4966/2005/117(3)/1465/8/$22.50 pp 1465–1472.

Sand, O., Karlsen, H.E. and F.R. Knudsen. (2008) Comment on "Silent research vessels are not quiet" [J. Acoust. Soc. Am. 121, EL145-EL1501 (L). Journal of the Acoustical Society of America, 123 (4)**:** 1831–1833.

Santulli, A., Modica, A., Messina, C., Ceffa, L., Curatolo, A., Rivas, G., Fabis, G. and D'amelio, V. (1999) Biochemical Responses of European Sea Bass (*Dicentrarchus labrax L.*) to the Stress Induced by Offshore Experimental Seismic Prospecting. Marine Pollution Bulletin Vol. 38, No. 12, pp. 1105 - 1114, 1999.

Sarà, G., Dean, J.M., Amato, D.D., Buscaino, G., Oliveri, A., Gebovese, S., Ferro, S., Buffa, G., Martire, M.L. and Mazzola, S. (2007) Effects of boat noise on the behaviour of Bluefin tuna Thunnus thynnus in the Mediterranean Sea. Marine Ecology Progress Series. 331. 243-253.

Schusterman, R.J., Kastak, D., Levenson, D.H., Reichmuth, C.J. and Southall, B.L. (2000). Why pinnipeds don't echolcate. J. Acoust. Soc. Am. **107** (4), April 2000.

Science Communication Unit, University of the West of England, Bristol (2012). *Science for Environment Policy Future Brief: Underwater Noise*. Report produced for the European Commission DG Environment, June 2013. Available at: http://ec.europa.eu/science-environment-policy.

Scowcroft, G., Vigness-Raposa, K., Knowlton, C. and Morin, H. (2012) Discovery of Sound in the Sea. University of Rhode Island.

Sebastianutto L., Picciulin M., Costantini M. and Ferrero, E.A. (2011) How boat noise affects an ecologically crucial behaviour: the case of territoriality in *Gobius cruentatus* (Gobiidae). Environmental Biology of Fishes, 92(2), 207-215.

Simpson, S.D., Radford, A.N., Tickle, E.J., Meekan, M.G. and Jeffs, A.G. (2011) Adaptive Avoidance of Reef Noise. PLoS ONE 6(2): e16625. doi:10.1371/journal.pone.0016625.

Skalski, J.R., Pearson, W.H. and Malme, C.I. (1992) Effects of sounds from a geophysical device on catch per unit effort in a hook and line fishery for rockfish (*Sebastes spp*.). Canadian Journal of Fisheries and Aquatic Sciences. 49(7), 1357 – 65.

Slabbekoorn, H., Bouton, N., van Opzeeland, I., Coers, A., ten Cate, C. and Popper, A.N. (2010) A noisy spring: the impact of globally rising underwater sound levels on fish. Trends in Ecology and Evolution **25** pp 419 – 427.

Smith, M.E. (2012) Predicting Hearing Loss in Fish. In: Popper, A.N. and A.D. Hawkins, eds. The effects of noise on aquatic life. New York: Springer Science + Business Media, LLC. Pp. 259-262.

Southall, B.L., Bowles, A.E., Ellison, W.T., Finneran, J.J., Gentry, R.L., Greene, C.R. Jr., Kastak, D., Ketten, D.R., Miller, J.H., Nachtigall, P.E., Richardson, W.J., Thomas, J.A. and Tyack, P.L. (2007) Marine mammal noise exposure criteria: Initial scientific recommendations. Aquatic Mammals 33:411-521.

Staaterman, E.R., Clark, C.W., Gallagher, A.J., deVries, M.S., Claverie, T. and Patek, S.N. (2011) Rumbling in the benthos: acoustic ecology of the California mantis shrimp *Hemisquilla californiensis*. Aquat Biol 13:97-105.

Staaterman, E.R., C.W. Clark, A.J. Gallagher, T. Claverie, M.S. deVries, and S.N. Patek. (2012) Acoustic ecology of the California mantis shrimp (*Hemisquilla californiensis*). In: Popper, A.N. and A.D. Hawkins, eds. The effects of noise on aquatic life. New York: Springer Science + Business Media, LLC. Pp. 165-168.

Stanley, J.A., Radford, C.A. and Jeffs, A.G. (2010) Induction of settlement in crab megalopea by ambient underwater reef sound. Behav Ecol 21:113-120.

Stanley, J.A., Radford, C.A. and Jeffs, A.G. (2012) Effects of underwater noise on larval settlement. Adv Exp Med Biol 730:371-374.

Stone, C.J. and Tasker, M.L. (2006) The effects of seismic airguns on cetaceans in UK waters. Journal of Cetacean Research and Management 8(3):255– 263.

Thompson, P.M., Brookes, K.L., Graham, I.M., Barton, T.R., Needham, K., Bradbury, G., Merchant, N.D. (2013) Short-term disturbance by a commercial two-dimensional seismic survey does not lead to long-term displacement of harbour porpoises. *Proc. R. Soc. B*, 280, 20132001 http://dx.doi.org/10.1098/rspb.2013.2001.

Thomsen, F., Lüdemann, K., Kafemann, R. and Piper, W. (2006) Effects of offshore wind farm noise on marine mammals and fish, biola, Hamburg, Germany on behalf of COWRIE Ltd.

Thompson, P.M., Lusseau, D., Barton, T., Simmons, D., Rusin, J. and Bailey, H. (2010) Assessing the responses of coastal cetaceans to the construction of offshore wind turbines. Mar. Pollut. Bull., 60, 8, pp. 1200-1208. doi:10.1016/j.marpolbul.2010.03.030.

Tougaard, J., Carstensen, J. and Teilmann, J. (2009) *Pile driving zone of responsiveness extends beyond 20 km for harbour porpoises (Phocoena phocoena* (L.)) (L). J. Acoust. Soc. Am., 126, pp. 11-14.

Tougaard, J., Kyhn, L.A., Amundin, M., Wennerberg, D. and Bordin, C. (2012) "Behavioural Reactions of Harbour Porpoises to Pile-Driving Noise". *Advances in Experimental Medicine and Biology* 730: 277-280.

Tyack, P.L., Zimmer, W.M.X., Moretti, D., Southall, B.L., Claridge, D.E. et al. (2011) Beaked Whales Respond to Simulated and Actual Navy Sonar. PLoS ONE 6(3):e17009.doi:10.1371/journal.pone.0017009

Urick, R.J. (1983) Principles of underwater sound. New York: McGraw-Hill Book Company.

Vasconcelos, R.O., Amorim, M.C.P., Ladich, F. (2007) Effects of ship noise on the detectability of communication signals in the Lusitanian toadfish. J. Exp. Biol. 210, 2104–2112.

Versluis, M., Schmitz, B., von der Heydt, A. and Lohse, D. (2000) How Snapping Shrimp Snap: Through Cavitating Bubbles. *Science*, New Series, Vol. 289, No. 5487. pp. 2114-2117.

Verzijden, M.N., van Heusden, J., Bouton, N., Witte, F., ten Cate, C. and Slabbekoorn, H. (2010) Sounds of male Lake Victoria cichlids vary within and between species and affect female mate preferences. Behav. Ecol. 21, 548–555.

Wale, M.A., Simpson, S.D. and Radford, A.N. (2013) Size dependent physiological responses of shore crabs to single and repeated playback of ship noise. Biol Lett 9:20121194.

Webb, J.F., Popper, A.N. and Fay, R.R. (2008) Fish Bioacoustics. Springer Handbook of Auditory Research.

Weilgart, L.S. (2007) A Brief Review of Known Effects of Noise on Marine Mammals. International Journal of Comparative Psychology, UCLA Department of Psychology, UC Los Angeles **20**, 159-168.

Wenz, G.M. (1962) Acoustic ambient noise in the ocean: Spectra and sources. Journal of the Acoustical Society of America 34:1936-1956.

Wilson, M., Hanlon, R.T., Tyack, P.L. and Madsen, P.T. (2007) Intense ultrasonic clicks from echolocating toothed whales do not elicit anti-predator responses or debilitate the squid *Loligo pealeii*. Biol. Lett 3:225-227. Doi:10.1098/rsbl.2007.0005.

Worcester, T. (2006) Effects of Seismic Energy on Fish: A Literature Review. Canadian Science Advisory Secretariat, Research Document 2006/092 (http://www.dfo-mpo.gc.ca/csas/).

Wysocki, L.E. (2006) Diversity of sound production in fish. In: Communication in fishes. Vol. 1 F. Ladich, S. P. Collin, P. Moller & B.G. Kapoor (eds.). Science Publishers, Enfield. pp. 71-104.

Wysocki, L. E., Dittami, J. P. and Ladich, F. (2006) Ship noise and cortisol secretion in European freshwater fishes. Biological Conservation, 128, 501-508.

Zampolli, M., Nijhof, M. J. J., de Jong, C. A. F., Ainslie, M. A., Jansen, E. H. W. and Quesson, B. A. J. (2013) Validation of finite element computations for the quantitative prediction of underwater noise from impact pile driving, *J. Acoust. Soc. Am*. 133 (1), pp 72–81.

9 Annex I

Table 1 From Southall et al. (2007). Research recommendations.

Research topic	General description	Critical information needs
Acoustic measurements of relevant sound sources	Detailed measurements needed of source levels, frequency content, and radiated sound fields around intense and/or chronic noise sources.	Comprehensive, calibrated measurements of the properties of human-generated sound sources, including frequency dependent propagation and received characteristics in different environments.
Ambient noise measurements	Systematic measurements of underwater ambient noise are needed to quantify how human activities are affecting the acoustic environment.	Comprehensive, calibrated measurements of ambient noise, including spectral, temporal, and directional aspects, in different oceanic environments; ambient noise "budgets" indicating relative contribution of natural and anthropogenic sources and trends over time.
"Absolute" hearing measurements	Audiometric data are needed to determine functional bandwidth, species and individual differences, dynamic hearing ranges, and detection thresholds for realistic biological stimuli.	Carefully controlled behavioural and electrophysiological measurements of hearing sensitivity vs. frequency for more individuals and species, particularly for high-priority species, such as beaked whales and mysticetes. Also, detection thresholds for complex biological signals.
Auditory scene analysis	Measurements to determine the sophisticated perceptual and processing capabilities of marine mammals that enable them to detect and localize sources in complex, 3-D environments.	Measurements of stream segregation, spatial perception, multidimensional source localization, frequency discrimination, temporal resolution, and feedback mechanisms between sound production and hearing systems.
Marine mammal behavioural responses to sound exposure	Measurements of behavioural reactions to various sound types are needed, including all relevant acoustic, contextual, and response variables.	Carefully constructed observational and exposure experiments that consider not only RL but also source range, motion, signal-to-noise ratio, and detailed information on receivers, including baseline behaviour, prior experience with the sound, and responses during exposure.
Effects of sound exposure on marine mammal hearing: masking, TTS, and PTS	Continued effort is needed on the simultaneous and residual physiological effects of noise exposure on marine mammal hearing.	Masked hearing thresholds for simple stimuli in more species and individuals, as well as complex biological signals and realistic maskers; allowance for directional effects; comparative data on TTS-onset and growth in a greater number of species and individuals for nonpulse and pulsed anthropogenic sources; recovery functions after exposures and between repeated exposures.
Effects of sound exposure on marine mammal non-auditory systems	Physiological measurements are needed for both acute and chronic sound exposure conditions to investigate effects on non-auditory systems.	Various baseline and exposure-condition measurements, including nitrogen saturation levels; bubble nuclei; the formation of haemorrhages, emboli, and/or lesions; stress hormones; and cardiovascular responses to acute and chronic noise exposure.
Particularly sensitive species: beaked whales	Baseline and exposure data on these poorly understood taxa to assess their apparent sensitivity to certain anthropogenic sound sources.	Various studies, including measurements and modelling related to (1) hearing sensitivity, (2) diving and vocalization parameters, (3) tissue properties, (4) gas/fat emboli formation and significance, (5) advanced detection capabilities for localizing and tracking them, and (6) behavioural

	reactions to various anthropogenic and natural sound sources.

Cefas project report C6082

ENV.D.2/FRA/2012/0025: Impacts of noise and use of propagation models to predict the recipient side of noise

Task 2 Workshop Report

Author: J. Fabrizio Borsani

Issue date: October 2014

Cefas Document Control

Title: ENV.D.2/FRA/2012/0025: Impacts of noise and use of propagation models to predict the recipient side of noise

Final Report

Submitted to:	Lydia Martin-Roumegas
Date submitted:	31 Oct 2014
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Quality control by:	Kelly Baker
Approved by & date:	John Bacon
Version:	1

Version Control History			
Author	**Date**	**Comment**	**Version**
JF Borsani	30th May 2014	Draft for participant comment	0.1
JF Borsani	27 October 2014	Draft status removed following TG Noise 2014 meeting	1

ENV.D.2/FRA/2012/0025: Impacts of noise and use of propagation models to predict the recipient side of noise

Workshop Report

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1 Introduction

A workshop with the title **'Propose methodologies and guidelines on how to evaluate impacts of noise on marine biota'** was held in Brussels on 10-11 April 2014 within the contract "*Impacts of noise and use of propagation models to predict the recipient side of noise*" (DG ENV 1109.05/659011/SER/C.2). The workshop co-chairs were Dr. M. Tasker (JNCC) and J.F. Borsani (CEFAS).

The aims of the workshop were:

a) Discuss and propose a roadmap towards defining Good Environmental Status (GES) for underwater noise,

b) Identify knowledge gaps and define research needs to address the impacts of underwater noise on marine biota and,

c) Provide guidance for important features and considerations that a proposal related to the effects of underwater noise should have when submitted to the EC for funding.

37 delegates from Industry, Academia, NGOs and DG Environment attended and provided their own perspective to the objectives of the workshop. Five international experts provided insight respectively into the fields of effects of noise on invertebrates, fish, marine mammals; into the PCAD (Population Consequences of Acoustic Disturbance) framework as well as into noise modelling and mapping.

Thereafter one full day was dedicated to discuss the topics in break-out groups each of which had the task to provide its perspective on each topic. The results of the discussions were merged and then presented and discussed in plenary. The outcome of the discussions by objective is provided in the following.

1.1 Purpose of this report

This report is intended to be an internal document to a) report on the different views and aspects on the workshop objectives as expressed by the delegates, and, b) to inform Task 3 of the project.

Task 3 is described as: "Propose a roadmap to wards defining sound limits for GES". In particular:

a) Prepare a roadmap towards a sufficient assessment of impacts of underwater sound for all marine biota and at all levels (individual, population, ecosystem) in order to define operational targets or GES criteria (i.e. limits for impulsive and ambient underwater sound). Each element of the roadmap (i.e. proposed new research) should be specific and accompanied by an estimation of cost and a recommendation of the relevant framework for its accomplishment.

b) Prepare input for a possible revision for the Commission Decision on Descriptor 11.

2 Workshop Objectives

The three main objectives of the workshop were:

1. **Discuss and propose a roadmap towards defining Good Environmental Status (GES) for underwater noise.**

Work on MSFD descriptor 11 on emissions of energy has so far focussed on developing indicators of the spatial and temporal patterns from emissions of two forms of anthropogenic underwater sound. So far no links have been made to the consequential change in status of the marine environment and its biological components. In some jurisdictions, criteria for defining sounds that have adverse effects on biota have been developed, but none have been developed that would provide a status indicator for the ecosystem as a whole, or for assessing the cumulative effects of sound. Work to develop standards to measure underwater sound is still underway.

(1.1) Review progress towards a consensus for standards to measure and describe underwater sound.

(1.2) Review progress in integrating the results of 'field' Controlled Exposure Experiments (CEE) and other sources of information with models describing population and/or ecological effects.

(1.3) Consider the usefulness of thresholds for describing Good Environmental Status.

(1.4) Draft a roadmap (or roadmaps) towards defining GES.

2. **Identify knowledge gaps and define research needs to address the impacts of underwater noise on marine biota.**

Funds may exist within the European Union to support research that enables the attainment of GES. Considerable research is in progress (or in later stages of planning) elsewhere. The workshop should aim to inform the European Commission of its views on priority research areas.

(2.1) Prioritize gaps and define research needs to address the achievement of GES, taking account of existing or planned projects.

3. **Provide guidance for important features and considerations that a proposal related to the effects of underwater noise should have when submitted to the EC for funding. This objective will take a lesser priority at the workshop.**

It is likely that any proposals relating to underwater noise that are submitted for funding will be assessed partly by non-specialists. There are important features that will be common to most proposals for projects on underwater sound (e.g. calibration, use of standards, testing of models). Guidance will be of use to both those that submit and those that review the proposals.

3 Workshop

3.1 Presentations

Five presentations were given at the start of the workshop by experts in their respective fields:

1. Professor Michel André, UPC. “Filling knowledge gaps with invertebrates.”
2. Dr. Michele Halvorsen, SCA Ocean Sciences Inc. “Acoustic Effects on Fish and Data Gaps.”
3. Dr. Christine Erbe, Curtin University, Perth. “Noise impacts on marine mammals—what do we know?”
4. Professor John Harwood, PDAD, University of St Andrews. “Forecasting the population-level consequence of acoustic disturbance for marine mammals.”
5. Dr. Kevin Heaney, OASIS. “Acoustic Forecasting: Capabilities and Environmental Sensitivities.”

4 Summary of Workshop Conclusions

The workshop attendees were divided into three break-out groups, following the presentations, to discuss each of the three objectives in turn. The summary of the priorities identified by each group are reported in the following merged by objective as reported by each group.

The results of the workshop will be used to inform Task 3 “Propose a roadmap to wards defining sound limits for GES”.

4.1 Objective 1:

Discuss and propose a roadmap towards defining Good Environmental Status (GES) for underwater noise.

(1.1) Review progress towards a consensus for standards to measure and describe underwater sound.

(1.2) Review progress in integrating the results of ‘field’ Controlled Exposure Experiments (CEE) and other sources of information with models describing population and/or ecological effects.

(1.3) Consider the usefulness of thresholds for describing Good Environmental Status.

(1.4) Draft a roadmap (or roadmaps) towards defining GES.

1.1: Documenting standards

- Itinerary of EU standards (from current relevant EU project outputs) (Standards actually available are listed in Tables 1 and 2)
- Consideration of major international project outputs to help identify / predict and refine potential EU standards within areas of limited data knowledge.
- Re-define terminology for better clarification more widely throughout EU (continuity of terms).
- Important to standardise ambient sound and modelling techniques.
- Combined (measurements & modelling), approach to monitoring standards required
- What is it we need to measure?
- How to implement it? (e.g. seismic surveying / risk registers)
- Standardised monitoring requirements
- Defining the source of noise

- Record of mitigation measures (widespread mitigation measures will have impacts upon measurement standardisation e.g. level of pile driving small fine-scale issue in comparison to oceanographic seismic surveys)
- MSFD should have an “alert system” e.g. register numerous accounts of events spatially, but not specific small-scale localised noise concerns.

Table 1 and 2: Inventory of national and international measurement and terminology standards relevant to underwater sound (EU Noise Impact Workshop, Brussels)

Authors: M A Ainslie, S P Robinson

Version: 0.3, date: 11 April 2014

Table 2: Existing standards

	Terminology and reference value	Reference values and frequency bands	Measurements and measurement systems
National standards (DIN, BSI, ANSI, GOST R)	ANSI S3.20-1995 Bioacoustical terminology ANSI/ASA S1.1-2013 Acoustical terminology DIN 1320 Acoustics – Terminology (1997, in German) R50.2.037-2004 Underwater acoustic measurements – terms and definitions (in Russian)	ANSI S1.8-1989 Reference Quantities	ANSI/ASA S12.64-2009/Part 1, 2009. Quantities and Procedures for Description and Measurement of Underwater Sound from Ships - Part 1: General Requirements, American National Standard Institute, USA, 2009 ANSI/ASA S1.20-2012, Procedures for Calibration of Underwater Electroacoustic Transducers, American National Standard Institute, USA, 2012.
International standards (ISO, IEC, ICGM)	ISO 80000-3:2006 Space and Time (level, decibel) ISO 80000-8: 2007. Quantities and units - part 8: Acoustics,	ISO 1683:2008 Acoustics – Preferred reference values (sound in air, plus structural vibrations) IEC 61260 (EN 61260), Electroacoustics - Octave-band and fractional-octave-band filters,	ISO/PAS 17208-1:2012 Acoustics - Quantities and procedures for description and measurement of underwater sound from ships. Part 1: General requirements for measurements in deep water, International Organization for Standardization, Geneva, 2012.

	International Organization for Standardization, Geneva, 2007. ISO/TR 25417:2007. Acoustics - Definitions of basic quantities and terms. International Organization for Standardization (ISO), Geneva, 2007. IEC 60050:1994, International Electrotechnical Vocabulary, part 801: Acoustics and Electroacoustics, (section 801-32 covers terms for underwater acoustics), International Electrotechnical Commission (IEC), Geneva, 1994.	International Electrotechnical Commission, Geneva, Switzerland, 1996.	ISO1996-1: 2006, Acoustics - Description, measurement and assessment of environmental noise - Part 1: Basic quantities and assessment procedures. International Organization for Standardization, Geneva, 2006. IEC60565: 2006 Underwater acoustics-Hydrophones - Calibration in the frequency range 0.01 Hz to 1 MHz, IEC 60565 - 2006 (EN 60565: 2007, BS60565:2007), International Electrotechnical Commission, Geneva, 2006. IEC 60500: Underwater acoustics - Hydrophones - Properties of hydrophones in the frequency range 1 Hz to 500 kHz (currently at CDV stage, revision of IEC60500:1974 IEC Standard Hydrophone) JCGM 100:2008, Evaluation of measurement data - Guide to the Expression of Uncertainty in Measurement (GUM), joint publication by BIPM, IEC, IFCC, ILAC, ISO, IUPAC, IUPAP and OIML, 2008. Available from www.bipm.org JCGM 200:2012, International vocabulary of metrology - Basic and general concepts and associated terms (VIM) 3rd edition, joint publication by BIPM, IEC, IFCC, ILAC, ISO, IUPAC, IUPAP and OIML, 2012. Available from www.bipm.org The

			International System of Units (SI), Bureau International des Poids et Mesures (BIPM), Paris (brochure available from www.bipm.org).

Table 2: Work in progress by the Standards Institutes to update standards listed in the Table 1

	Terminology and reference value	**Reference values and frequency bands**	**Measurements and measurement systems**
National standards (DIN, BSI, ANSI, GOST R)	ANSI S3/WG 73 (review of S3.20-1995 Bioacoustical Terminology)		
International standards (ISO, IEC, ICGM)	ISO/CD 18405 Underwater Acoustics - Terminology	ISO/DIS 1683 (includes reference values for water) ISO/DIS 1683:2013 Acoustics – Preferred reference values … (DIS)	ISO/DIS 16654.3 Ships and marine technology — Measurement and reporting of underwater sound radiated from merchant ships — Survey measurement in deep-water ISO/DIS 17208 Underwater acoustics — Quantities and procedures for description and measurement of underwater sound from ships — Part 1: Requirements for deep water measurements used for comparison purposes WG3

notes

#1 ISO standards are not consistent with IEC standards (eg the ISO definitions of "sound pressure" and "sound pressure level" are different from the IEC definitions of these terms)

#2 ISO standards are not all consistent with one another (eg ISO 80000-1:2009 contains a normative Appendix that deprecates terminology introduced in ISO 80000-3:20060; progress towards the ISO underwater acoustics terminology standard presently under development by ISO/TC 43/SC 3/WG 2, is hindered by this inconsistency. Development of this terminology standard would be facilitated if this inconsistency in ISO 80000 were removed. The ISO 80000 series is presently under review. Participation by one or members of ISO/TC 43/SC 3/WG 2 would facilitate progress towards a terminology standard. Of particular importance are the definitions of “level” and “decibel” in ISO 80000:3-2006.

1.2 : Integrating results of field experiments and other sources.

- How to translate effects of field experiments to chronic effects of individuals at population level?
- Lack of data here so "expert judgement" models required. Exception to the rule is beaked whales in relation to being able to predict lost foraging opportunities (through absence of number of daily routine foraging dives), however this is a special case and rare!
- Data on fish is poor – need to use models to predict effects by different regions, areas, habitats, fishing pressure, noise exposure, behaviour state, feeding, breeding ambient sound etc.
- Time budgets / foraging behaviour / energy use
- Results that don't come from field experiments can be used to validate models (e.g. lab experiments, Michelle Halvorsen studies / juvenile fish lab research.
- Don't necessarily need field experiments for many fish species if plentiful controlled lab baseline studies undertaken (not relevant for larger fish species and marine mammals though to larger extent where field trials are critical).
- Noise exposure experiments involving mesocosm work required and a good baseline (starting point for further more open sea research. Can identify short term behaviour in such experiments and set standards to allow progression of more complex open sea studies.
- Tony Hawkins – field based wild behaviour in lock experiments (naturally enclosed environments for monitoring noise and behaviour – potentially highly valuable)

1.3: Consider usefulness of thresholds.

- Need to first of all identify the metric!
- Thresholds can give a probability of error using best possible data available.
- Useful example: Step function used for beaked whales (John Harwood's research)
- Threshold dependent on many variables e.g. habitat
- Sound maps overlaid with critical areas / hotspot areas
- Environmental sensitivity maps could prove more useful
- Dose responses are highly useful, thresholds less so. A shifting dose response can have an even greater effect.
- Precautionary statements for MSFD, may be required if you cannot set thresholds e.g. defining what are the most important measurements based on specific ecosystem

- Using “Expert Judgement” model you could predict standards by region to set standard precautionary thresholds and identify gaps.
- Could include shipping lanes / traffic and choose between specified indicator species (most sensitive, most abundant etc)
- A combined ecosystem approach to thresholds could prove useful.
- For regulation management you need “action based thresholds”
- Thresholds are necessary but not desirable.
- Set thresholds would be unlikely to be relevant over a wide geographical area. Maybe better by sub-regions?
- From a regulatory management view thresholds are useful, but from a biological perspective there are a lot of issues (e.g. geographical, ecosystem differences), that result in such thresholds being floored.

1.4: Road Map:

1) Ways of measuring ambient sound
2) EU register of noise sources (this should already be in place by each member state)
3) Implement register for EU sources of noise
4) Standardisation of:
    - Environmental impact
    - GES
    - Development of standardising
    - Current and future Knowledge outputs (modelling & measuring)
5) Knowledge of potential adverse effects (as a traffic light system). Use species which are easy to monitor (e.g. within a constrained spatial area / localised), Priority effects/priority species, what are the receivers?
    - Define / standardisation of effect
    - Measurement of adverse effect (lab and or field experiments), dose response assessment for overall risk.
    - Modelling; noise maps/masking maps, define GES in terms of an acceptable level
    - Thresholds – define the level of masking that is acceptable, i.e. masking maps for sensitive species. What level of masking is critical?
    - First stage would be to map the noise (ambient and impulsive). Second stage would be to map the species.

- Masking maps for specific species (i.e. fish). For example, first step would be to monitor ambient noise. The second step would be to model communication space of spawning. Look at the statistical data. Percentile view of ambient noise. Estimate the communication range for the lower percentile and then the higher percentiles (have a different map for different percentiles). Key question – over what communication ranges do males attract females?

6) GES = implementation of many factors (e.g. recruitment of fish – larvae to adult life history phases), i.e. we need to consider other pressures not just noise alone.
7) Experiments required to monitor adverse chronic effects
   - Long-term ambient noise levels
   - Larvae – to adult behaviour responses
   - Quantify baseline measurements prior to determining chronic exposure effects
   - Population based studies required
   - “expert judgement” modelling alternative approach
   - Social – economic requirement (fishing activity)

Summary:

- Set up register that gives you a baseline of noise
- Followed by measurement of trends for ambient noise
- There will still be a huge variance within any initial baseline measurements (e.g. seasonal etc), so useful to model / predict potential variances (time & space modelling)
- Distribution measurement array

Description of what is actually happening in the environment (sub region), in question:

- Acoustic surveying
- Activity register
- Shipping traffic
- Data already collected for region
- Oceanographic mapping
- Nutrients / dose responses
- Eutrophication – defining limits
- MSFD descriptors to manage the problem within reasonable bounds

- Measure and monitor individual pressures; need to have a goal (end product) of the roadmap i.e. the percentage of habitat loss.
- Defining potential pressure indicators for potential GES

Must first document what monitoring has been already undertaken, this will then help to identify trends, potential foodweb dynamics: it is important to look at whole ecosystem effect not just at individual species level.

Must use a combined approach e.g. understanding of regional foodweb dynamics, then impose/add pressures e.g. noise, masking, oceanography, chemistry etc.

What are the impacted effects on a species as a result of the 'pressures' to the regional foodweb / ecosystem.

Availability of resources to the species in question hugely important factor – e.g. animal might cope with exposure / chronic effects if food resource is abundant within region: however if it is restrained then the chronic effect is likely to increase resulting behaviour shifts.

4.2 Objective 2:

Identify knowledge gaps and define research needs to address the impacts of underwater noise on marine biota, in relation to:

1. **Low and mid-frequency impulsive noise:**

It was suggested that a selection of the most relevant (indicator) and representative species needs to be made, based on conservation status and/or sensitivity. For shallow/inshore waters, focus may be on cetaceans (e.g. harbour porpoise), and selected species of fish that may be sensitive and/or commercially important (e.g. herring, cod; partial overlap with D3-populations of commercial fish). For deep/offshore waters, focus could be on beaked whales, baleen whales and fish. Further, it was suggested that one species could be selected out of the following groups: high (i.e. porpoises), mid and low frequency cetaceans (i.e. baleen whales), pinnipeds and fish (more than one). Further research is needed for clupeid fishes (herring) as they are sensitive to sound and therefore these are a good indicator group. No concrete proposal for indicator species was made.

There is a requirement for an improved risk assessment framework. Present impact assessment may contain exposure assessments and to some extent there is information on direct/individual responses, but the implications for populations or ecosystems is still unclear. The group noted the progress made in projects like PCoD. For the selected species, relation between direct responses at the individual level and population / ecosystem effects needs to become clear. It was suggested that studies on energetics as important fitness parameter for different species could be useful.

Per region there are differences of distributions of species. The group noted that there is a bias, most attention now is on species in NW-Europe, for many of these species there is information on responses to noise exposure, but there should be more attention to describe pressure/impact relations parameters of Mediterranean species (fish, baleen whales). How do we help all major Mediterranean countries with management decisions? It was noted that there are often communication difficulties. Also important to consider countries outside Europe.

- Behavioural disturbance was identified as a priority issue, as this may have ecosystem effects.
- Potentially, there may be auditory effects for some (important) species like harbour porpoise that should not be neglected.
- The group noted that effects to fish like acoustic trauma may happen at lower levels than mostly assumed, at lower level than TTS. Still, injury effect with fish are probably of lower concern at ecosystem scale because of the high levels needed to induce these effects.
- Habitat modelling and acoustic modelling need to come together. It was noted that there are knowledge gaps for deep-water animals.
- Biota groups of table 1 that are of lesser concern are fish larvae, turtles (indications of high levels needed to induce effects). For birds no information is available due to the lack of studies addressing effects on diving birds.
- The effects on invertebrates are not well known, for some this could be a priority because they are commercially important species (partial overlap with D3- populations of commercial fish), notably crustaceans and scallops.
- More work on masking is needed. For example, what are the population effects as a result of masking? Knowledge in general on population effects is needed.
- Need to look at the impacts of low and mid-frequency impulsive noise on vocal fish in terms of reproduction for key species. For example, the fitness of an animal could be affected.

2. Continuous low frequency ambient noise:

- Main effect that raises concern related to elevated (i.e. increased by anthropogenic activities) ambient noise levels is masking (interference with communication, echolocation, navigation, predator/prey relations, interaction with social behaviour, e.g. schooling); in theory masking can be calculated to some extent but whether communication ranges are effectively reduced is still not clear.

- The long term chronic effects (i.e. stress, coronary heart disease) and physiological impacts of chronic noise exposure are unknown for marine biota.
- At what level does TTS and PTS occur? What level does the noise exposure have to be when there is no recovery?
- Shipping lanes leading to displacement/habitat loss may be an important effect in some regions.
- For masking, both direct effects on individuals and population effects are largely unknown.
- Effects of ambient noise like reproduction of vocal fish, reducing fitness should be addressed.
- Groups of sensitive species were discussed: clupeid fish like herring, vocal fish, potentially some dolphins and low frequency species like baleen whales. Species for which effects are not well known and therefore of concern may be invertebrates, some may be commercially important (crustaceans; partial overlap with D3- populations of commercial fish), and there are indications of potential effects at low level with cephalopods.
- As with impulsive noise, there is no need to study all species, but based on conservation status and/or sensitivity a selection of species can be made. For shallow/inshore waters that may be fish, potentially some dolphins species. For deep/offshore waters focus could be on baleen whales and fish. Invertebrates should also be a priority because they are of commercial value.
- It was highlighted that continuous ambient noise is important for fish larvae and shellfish larvae.
- The TSG Noise report (monitoring guidance) addressed averaging methods, describing pro's/cons of different methods. At present, it still unclear what the most biologically relevant measures are, this should be addressed in the ambient noise monitoring programmes being set up by EU Member States.

3. General research topics:

- For specific species (invertebrates, fish) and situations (bottom species, piling) not the pressure but the particle motion seems to be the relevant factor. This is not commonly addressed, and these parameters are often not monitored or determined.
- Transfer data from test tanks/laboratory studies to the field/wild may be specific research topic, since this may aid in more rapid development of knowledge. Research in a laboratory setting has a number of advantages, the context is better controlled and relation between specific parameters and effects can be identified. In many situations, use of test tanks may be cost-effective, or it may provide guidance for field studies. For physiological parameters results can be considered to be representative for the field situations. However, application

of the results of behavioural studies is desirable but needs to be validated. It was agreed that a combination between tank and field experiments is needed.

4. <u>Other issues:</u>

- The group noted that addressing mitigation could be a priority research topic, but this was not the scope of this meeting and not further addressed.
- The group noted that other indicators of noise than the two indicators of the CD 2010 might be needed. Since this is identified in the work plan of TG Noise this was not further discussed.

Prioritizing Research Gaps

1. Determine population effects of low- and mid-frequency impulsive noise on marine life in order to establish targets (might be used already for 2018/2021 MSFD cycle)
    a. Relation of direct responses and population effect for indicator species like porpoises and fish
    b. Improved knowledge of response of deepwater species (e.g. baleen whales and beaked whales)
    c. Develop knowledge on effects of noise on selected species of invertebrates
        c.i. Commercially important species like crustaceans
        c.ii. Potentially sensitive species like cephalopods (others)

2. Effects of elevated ambient noise levels on marine life, in order to establish targets for future MSFD cycles.
    a. Develop knowledge on masking effects of elevated ambient noise levels
        a.i. Baleen whale communication
        a.ii. Other receptors

    b. Develop knowledge on effects of elevated ambient noise levels on fish communication
    c. Mindfully measure both particle motion / acoustic pressure during any experiments for future research to create greater long-term understanding.
    d. Establish the relation between reduced communication and fitness in order to determine population effects

e. Broad ecosystem scale approach needed so acoustic pressure a more useful tool of measurement for GES levels (highlight particle motion as a knowledge gap at the fine-scale).

3. Determine which additional parameters (other than currently used pressure parameters) are needed to characterise sound sufficiently
   a. Effects of particle motion on sensitive species (fish, invertebrates)

4. Develop methodology to enable improved use of results of laboratory studies, enabling improved use of behaviour studies in test facilities

Research Gaps as considered from an animal group perspective

Marine mammals:

Biggest Gap for Marine Mammals: Chronic effects of noise exposure – needs to be defined e.g. stress etc. and how best to measure it in the wild (e.g. identification of a suite of biomarkers required, but not easy to determine, e.g. cortisol levels). Anything that doesn't cause death is essentially a chronic behaviour effect to marine mammals.

Two different things: Chronic effect (harder to measure) and chronic exposure (easier to measure).

Dose response relationships to measure physiological effects e.g. stress health, respirometry, dive behaviour.

Cortisol – remote monitoring, knowledge gap that isn't likely to be achievable.

Priority of Behaviour response values for marine mammals required:

- Relationship between behaviour responses and (chronic or acute) effects and resulting effects in the environment
- Putting the behaviour into context of an event (e.g. feeding, breeding etc)
- Is there a relationship between average exposure to noise and population effects (at the behavioural level)

Significantly more information on marine mammals than compared to fish so need to re-define the colour of the table (e.g. fish in red due to severe lack of data but marine mammals more orange)

Fish:

Priority of evidence gaps for fish: More behavioural and masking studies in the semi-constrained (mesocosm trials) and open sea (wild trials)?

- Using tagging experimental studies to track broad spatial patterns of distribution to model up to population level.
- Accelerometer tracking to track immediate behaviour responses to sound (Speak to Vicky)
- Population / food web level – behaviour and population level effects (need to combine interactions).
- Current literature often not directly applicable in terms of regions, habitats, field controlled exposures, lack of information – evidence gaps.
- More field based but also lab based experiments – required to create greater understanding of dose response levels on fish in relation to behaviour effects.

Fish Larvae (Pelagic larvae)

Fish larvae are a research priority since it is not clear if potential impacts (such as growth response rates, mortality) have an effect at the population level.

Measurement between sound exposure and fitness an essential requirement for all marine biota.

Identify predictions of small fish protection measures from noise disturbance

Sea Turtles (highest conservation status – so important concern)

Sea turtle – subtle behaviour responses to seismic noise.

More secondary responses in relation to invertebrate prey responses.

Crustaceans (evidence needed for behaviour responses)

Priority is behaviour – (need to understand the hearing / detection rate within behaviour research)

Sea Birds:-

Priority – behaviour changes in foraging responses.

Examine noise by Identification of relevant indicator species for monitoring GES.

What is the value of indicator species – most abundant / most vulnerable / most responsive / ranking.

4.3 Objective 3:

Provide guidance for important features and considerations that a proposal related to the effects of underwater noise should have when submitted to the EC for funding. This objective will take a lesser priority at the workshop.

The following is intended to serve two purposes:

i) For non specialists to check proposals

ii) For proposal author to understand what it should contain (e.g. calibration section)

The workshop participants identified the following items as important features and considerations which would need to be addressed in any proposals related to underwater noise effects. It should be noted that not all items need to be met by each proposal.

1) Calibration: Frequency spectrum over frequencies of relevance and interests. Traceable standards and procedures or auditable calibration for hydrophones
2) Transmission conditions:
   - Bathymetry
   - geo-acoustics
   - oceanography
   - sea surface conditions
   - local weather conditions
3) Dose relationships – use received levels rather than modelled levels wherever possible
4) Source characteristics - outline probability of bias, issues using modelled data. Understanding any bias in results through using models.
5) Standard of units and terms (calibration, measurements and terminology)
6) Targeted needed research for implementation – (needs clarifying here)
7) Behaviour – studies in context (e.g. for feeding, population rate)
8) Description of how contextual information will be gathered (e.g. ensuring there is no observer effect)
9) Proposal – have you recognised observer effect? How will it be quantified and assessed.

10) Modelling – standards (what are the assumptions or approximation of the model, benchmarking of the model; what is there approach to source levels for the models).
11) 2D & 3D measurements – measuring the perceived whole oceanography / physical environment. Ensure measurement at a range of depths throughout environment.
12) “Masking” – very few studies (signal processing constraints)
13) Displacement used as a proxy – vertical, horizontal – and combined with a state (e.g. ceased feeding behaviour)
14) Impact of “Self noise” around your system (set up), ensure calibration and tested control measures to understand your set up prior to measuring / recording noise.
15) Knowledge of the natural ambient noise is key prior to starting projects
16) Mitigation measures – need to define what you are mitigating against.
17) Indicator of shipping mitigation
18) Studies on the source – knowledge of source characteristics –
19) Refraction considerations for sound characteristics – relate to mitigation measures.
20) Finding out what part of noise spectrum causes the effect to marine biota
21) Environmental uncertainty (to defining modelling)
22) Approach has to be treated scientifically to clarify levels of probability / uncertainty / bias to the range of levels measured (e.g. for source, environmental state, effect, model error).
23) Standard QA of results and reporting.
24) Publicly available datasets – to allow open analysis of results for future work.
25) Problems of modelling using non-peer-review techniques – needs to be evidence based / QA’d.
26) Fish experiments – need to show evidence based understanding for measurements required to accurately perform fish behaviour studies (e.g. the requirement to include “near field measurements” & quantify “particle loss”).
27) The proposal should highlight its socioeconomic value, stakeholder engagement, impact on policy, impact on achieving GES.
28) In relation to biology, ethics, repeatability, context should be clearly defined.

4.4 Conclusions:

The above list of items for each objective was discussed in plenary. Comments contributed by delegates were considered in each list. Additional comments are listed below:

- Particle motion is an important research topic. It may not be vital for short term (maybe not for the first MSFD cycle) but possibly in the future this will be something to consider.
- It is important to consider ecosystem level effects and food web dynamics – linkages within the food web.
- Crustaceans that are not key commercially important species should also be considered as these species support the food web.
- Particle motion and mitigation are two main discussion topics.
- Uncertainty is important to know! (Expert Judgement).
- What constitutes best practise? – Standards.
- Need to consider limitations of a particular study – i.e. prior exposure of the animal to noise source.
- Extrapolation of results is important – what does the experiment tell you in the real world?
- It was suggested that a way forward may be to hire an expert group to review proposals so reviewers with expertise are evaluating work.
- It was also highlighted that a list of what should be included in a proposal should be project specific. Maybe undertake a risk assessment approach, for example, all studies undertaking seismic work have to include X, Y and Z (suggested table format). A separate table could then be included which lists certain criteria that ALL proposal should contain (tick box format) – table and parameters could be sent to the applicant, allowing them to tick what their proposal will contain.

5 Annex 1 – Workshop Introduction document

Propose methodologies and guidelines on how to evaluate impacts of noise on marine biota

10-11 April 2014, Avenue de Beaulieu 5, 1160 Brussels, (B)

1) Terms of reference
2) Objectives
3) Agenda
4) Workshop layout
5) Conclusions from legislation and literature review
6) List of Attendees and skills for workshop purposes

Cefas

NPL National Physical Laboratory

TNO innovation for life

1) Terms of reference

To organize a workshop for relevant experts (e.g. from industry, geologists, biologists, NGO's, engineers, physicists etc) to:

"Propose methodologies and guidelines on how to evaluate impacts of noise on marine biota, especially to fill in the knowledge gaps identified in the first part of this project."

<u>The first part of the project consisted of:</u>

a) Review existing relevant literature and results from research projects of the last 8 years.
b) Review initiatives and related legislation to mitigate impacts of underwater sound on marine biota in European and non-European (e.g. USA, Australia, Canada) countries.
c) Make an inventory of impacts by animal group (marine mammals, fish etc), related to sound characteristics (impulsive/ambient, sound level, frequency etc) and proposed upper limits for no or insignificant impact (if available). This should include primary effects (i.e. directly from sound wave propagation) and secondary effects, such as cavitation and shockwave formation, that originate from sound waves and can have important consequences.
d) Identify gaps in the current knowledge of impacts and create an inventory of specific additional research needed

2) Objectives

Objective 1: Discuss and propose a roadmap towards defining Good Environmental Status (GES) for underwater noise.

Work on MSFD descriptor 11 on emissions of energy has so far focussed on developing indicators of the spatial and temporal patterns from emissions of two forms of anthropogenic underwater sound. So far no links have been made to the consequential change in status of the marine environment and its biological components. In some jurisdictions, criteria for defining sounds that have adverse effects on biota have been developed, but none have been developed that would provide a status indicator for the ecosystem as a whole, or for assessing the cumulative effects of sound. Work to develop standards to measure underwater sound is still underway.

(1.1) Review progress towards a consensus for standards to measure and describe underwater sound.

(1.2) Review progress in integrating the results of 'field' Controlled Exposure Experiments (CEE) and other sources of information with models describing population and/or ecological effects.

(1.3) Consider the usefulness of thresholds for describing Good Environmental Status.

(1.4) Draft a roadmap (or roadmaps) towards defining GES.

Objective 2: Identify knowledge gaps and define research needs to address the impacts of underwater noise on marine biota.

Funds may exist within the European Union to support research that enables the attainment of GES. Considerable research is in progress (or in later stages of planning) elsewhere. The workshop should aim to inform the European Commission of its views on priority research areas.

(2.1) Prioritize gaps and define research needs to address the achievement of GES, taking account of existing or planned projects.

Objective 3: Provide guidance for important features and considerations that a proposal related to the effects of underwater noise should have when submitted to the EC for funding. This objective will take a lesser priority at the workshop.

It is likely that any proposals relating to underwater noise that are submitted for funding will be assessed partly by non-specialists. There are important features that will be common to most proposals for projects on underwater sound (e.g. calibration, use of standards, testing of models). Guidance will be of use to both those that submit and those that review the proposals.

3) Agenda

<u>10th April: (Day 1)</u>

Morning 1: 09:00 – 09:15: Registration

09:15 – 09:45: Introduction to the Workshop (M.Tasker)

09:45 – 10:15: "Filling knowledge gaps with invertebrates" (M.André)

10:15 – 10:45: "Acoustic effects on fish and data gaps" (M.Halvorsen)

10:45 – 11:15: "Noise impacts on marine mammals—what do we know? What do we need to know?" (C.Erbe)

11:15 – 11:30: *Coffee break*

11:30 – 12:00: "Forecasting the population-level consequences of acoustic disturbance for marine mammals" (J. Harwood)

12:00 – 12:30: "Acoustic Forecasting: Capabilities and Environmental Sensitivities" (K.Heaney)

12:30 – 13:30: *Lunch break*

Afternoon 1: 13:30 – 15:00: Break-out groups

15:00 – 15:15: *Coffee break*

15:15 – 16:30: Break-out groups

16:30 – 18:00: Plenary wrap-up

<u>11th April: (Day 2)</u>

Morning 2: 09:00 – 10:30: Break-out groups

10:30 – 10:45: *Coffee break*

10:45 – 12:30: Break-out groups

12:30 – 13:30: *Lunch break*

Afternoon 2: 13:30 – 15:45: Drafting report

15:45 – 16:00: *Coffee break*

(Plenary) 16:00 – 17:00: Adopting report

17:00 – 17:30: Close meeting

4) Workshop layout

The workshop is co-chaired by J.Fabrizio Borsani (Cefas) and Mark Tasker (JNCC).

It is a 2-day workshop with approximately 30 international experts. Five invited speakers will address specific topics, and two half days will be used to address workshop tasks in break-out groups and the final half day will be devoted to finalizing and adopting a workshop report in a plenary session.

Invited speakers:

Professor Michel André (UPC) michel.andre@upc.edu

"Filling knowledge gaps with invertebrates"

Professor at the Technical University of Catalonia (UPC)

Director of the Laboratory of Applied Bioacoustics (LAB)

Michel André is an Engineer in Biotechnologies graduated from the Institut National des Sciences Appliquées, INSA, Toulouse, France. He holds a Master degree in Biochemistry and Animal Physiology from the Université Paul Sabatier de Toulouse, France. His PhD Dissertation that he defended at the Universidad de Las Palmas de Gran Canaria was on sperm whale acoustics and noise pollution. He was a research assistant at the San Francisco State University, California, an intern scientist at The Marine Mammal Centre, California and an associate professor at the Universidad de Las Palmas de Gran Canaria, Spain. His research involves the development of acoustic technologies for the control of noise pollution in the marine environment, the study of the biological and pathological impact of noise pollution on cetacean acoustic pathways, the mathematical, physical, morpho- and electro-physiological mechanisms of the cetacean bio-sonar as well as the extraction of the information from their acoustic signals.

Dr. Michele Halvorsen (CSA) mhalvorsen@conshelf.com

"Acoustic Effects on Fish and Data Gaps"

Ph.D., Ocean Science and Marine Mammal Observer Business Line Manager, CSA Ocean Sciences Inc

Dr. Halvorsen has 10 years of project/program experience. Dr. Halvorsen's areas of expertise include marine life and biotechnology; environmental acoustic ecology; and effects of intense anthropogenic sounds such as sonar, pile driving, seismic, noise, behavior/neuroethology, fish fitness/physiology, bioacoustics, and acoustic monitoring systems, both active and passive. She has managed field research projects that involved large interdisciplinary teams and has successfully led teams to achieve program goals and deliverables. Dr. Halvorsen was the co-PI and project manager for field studies that examined the effect of the U.S. Navy's low- and mid-frequency sonar on the hearing of several fish species and co-PI for an studies involving pile driving. Dr. Halvorsen has graduate training in neurophysiology of the auditory system of mammals and fish and in neuroethology (i.e., animal behavior). Her current focus is on the effects of anthropogenic sound on the physiology and behavior of fish and marine mammals, and her research has involved barotrauma (tissue damage) response assessment of fish from pile driving, navy sonar, blasting, seismic, and tidal turbine noise. Drs. Halvorsen co-developed a Fish Index of Trauma (FIT) model that maps the exposure sound metrics with the fish's biological responses. This FIT model is applicable to any type of sound exposure (pile driving, explosives, tidal turbine, etc.) and can be used to assess general health conditions. The culmination of results from these projects has positioned Dr. Halvorsen as an expert in the effects of underwater acoustics and effects on fish.

Dr. Christine Erbe (Curtin University Perth) c.erbe@curtin.edu.au

"Noise impacts on marine mammals—what do we know? What do we need to know?"

Christine holds an MSc in physics (University of Dortmund, Germany) and a PhD in geophysics (University of British Columbia, Canada). She has worked in industry (starting as a secretary and book keeper for an IT company, growing into a private consultant and ending as Director of JASCO Australia), in government (underwater noise research & regulation, Fisheries & Oceans Canada), and in high-school education (very briefly), and recently moved back into academia as Director of CMST at Curtin University. Christine's interests are underwater sound (ambient, anthropogenic & biological), sound propagation, signal processing and noise effects on marine fauna. Several times a year, Christine is invited to speak on underwater noise at international symposia. She's a reviewer for 11 scientific journals and several international research grant schemes. She's a member of the Animal Bioacoustics Technical Committee of the Acoustical Society of America, and she's the Australian Government representative on the International Standardization Organization (ISO) working group on standardising underwater noise measurements of vessels.

Professor John Harwood (PCAD, UStAndrews) jh17@st-andrews.ac.uk

"Forecasting the population-level consequences of acoustic disturbance for marine mammals"

John Harwood is Professor of Biology at the University of St Andrews, UK. He was Director of the NERC Sea Mammal Research Unit, which advises the UK and Scottish Governments on the conservation of seals and whales, from 1978-1996, and Director of the Centre for Research into Ecological and Environmental Modelling from 2004-2009. At St Andrews, he helped establish courses on Sustainable Development, Conservation Biology, Biodiversity and Fisheries Management, and he is still active in all these areas. At the moment, his main interest is in developing methods for assessing and mitigating the effects of disturbance on marine ecosystems.

Dr. Kevin Heaney (OASIS) oceansound04@yahoo.com

"Acoustic Forecasting: Capabilities and Environmental Sensitivities"

Dr. Heaney has extensive experience in ocean acoustic propagation and modeling, optimal oceanographic sampling and data-assimilation, geo-acoustic inversion, adaptive sonar signal processing and data analysis. He has worked on a variety of programs, including long-range ocean acoustic tomography, analysis of global scale propagation measurements (including Heard Island and Perth-Bermuda), geo-acoustic inversion and rapid environmental characterization, effects of internal waves on signal coherence, and theoretical optimization of monitoring equipment for hydroacoustic stations of the Comprehensive Test Ban Treaty Organization's International Monitoring System. Dr. Heaney has successfully transitioned algorithms to NAVOCEANO, NAVSEA and CNMOC. Dr. Heaney also has significant experience in adaptive signal processing from both a modeling and an experimental perspective.

Structure of break-out groups:

Three break-out groups of 12-13 participants will be formed. Each break-out group will consider each of the three workshop Objectives, but in order to ensure that reasonable consideration is given to each objective, Break-out group A will start with Objective 1, Break-out group B with Objective 2 and Break-out group C with Objective 3. After some time each break-out group will stop working on the initial Objective and move on to the next one in line.

Approximate timings:

10 April 13:30-15:00

Break-out group A: Objective 1

Break-out group B: Objective 2

Break-out group C: Objective 3

10 April 15:15-16:30

Break-out group A: Objective 2

Break-out group B: Objective 3

Break-out group C: Objective 1

11 April 09:00-12:30

Break-out group A: Objective 3

Break-out group B: Objective 1

Break-out group C: Objective 2

5) Conclusions from legislation and literature review

The only EU legislation to explicitly address underwater noise is the Marine Strategy Framework Directive (2008/56/EC MSFD). This lists "input of energy, including underwater noise is at levels that do not adversely affect the marine environment" as one of the qualitative descriptors that can define Good Environmental Status. In a number of European processes since the adoption of MSFD, ways of better describing and measuring the pressure on the marine environment have been developed collectively. In 2010, the European Commission formally decided (2010/477/EU) that two criteria for determining the pressure on the marine environment should be used by EU Member States. These were Distribution in time and place of loud, low and mid frequency impulsive sounds (11.1) and Continuous low frequency sound (11.2). More detailed descriptions of indicators are associated with both of these Criteria. This workshop forms part of the collective way forward to use these criteria and indicators in the process of defining Good Environmental Status more quantitatively.

A number of other pieces of EU legislation (and nation legislation implementing EU legislation) include underwater sound indirectly in their implementation. These include the Habitats and Species Directive (92/43/EEC), the Environmental Impact Assessment Directive and the Strategic Environmental Assessment Directive. These deal respectively with impacts on protected species and habitats, impacts from individual developments and impacts from industry sectors. Examples of national implementation of these Directives relevant to underwater noise include:

- The UK's seismic survey guidance (JNCC, 2010) that has to be followed as a condition of consent to carry out seismic surveys.
- Germany has defined a dual sound level threshold (160 dB (SEL)/190 dB (SPL peak-to-peak) that must not be exceeded outside a 750 m radius around a pile.

<u>Experimental data availability on the effects of noise on marine biota and most pertinent data gaps</u>

- Considerably more empirical data exist for impacts of anthropogenic noise on marine mammals and fish compared to other taxa, although it should be noted that there is effectively no data to assess possible impacts of particle velocity on fish.
  - ✓ e.g. There is no data on underwater sound detection of diving birds.
  - ✓ e.g. There is very limited data on the sound detection by invertebrates, particularly and very little scientifically robust data on the effects of noise exposure.

- For all taxa, there is an apparent lack of data on chronic effects of noise exposure, as well as population and ecosystem effects.

- ✓ e.g. there is practically no information on chronic effects of noise on marine receptors.
- ✓ e.g. the biological significance of acoustic impacts is poorly understood (e.g. critical behaviour such as mating and nursing may be repeatedly disrupted, affecting survival of the population).
- ✓ e.g. the ranking of noise among environmental stressors (e.g. culling, ship strikes, pollution, prey overfishing, climate change, habitat degradation etc.) on marine receptors and the interactions of stressors are not understood.
- ✓ e.g. the manner in which repeated exposure gets accumulated by the animal and the effects of cumulative exposure are unknown. Regulation and mitigation mostly address acute exposure from a single operation or event and direct damage.
- ✓ i.e. studies on the chronic effects of noise on development and animal behaviour.

- There is a general scarcity of empirical data integration with population/ecological modelling.

- Data coverage with respect to sample size (e.g. number of individuals and species) and exposure context (e.g. behavioural and natural history of the receptor, sound source type, acoustic habitat) is generally low.

- Overall, only small numbers of studies have considered controlled exposure experiments in the presence of a real sound source to study either the physiological effects of noise or the behaviour of the animals under exposure. To date, controlled exposure data for real sources in the wild are also extremely limited.
  - ✓ e.g. CEE on fish in controlled natural or semi-natural environment (e.g. mesocosm), considering both acoustic pressure and particle velocity components of the sound field, appropriate innovative experimental setups and methods (e.g. by combining tagging, remote sensing, etc.).
  - ✓ e.g. there is a need for more comprehensive studies regarding the potential for specific sound sources to effect local sensitive biota (e.g. crustaceans and seismic air gun noise; impact piling noise and marine mammals).

Table 1 was compiled to help identify (i) knowledge gaps and (ii) research data requirements with regard to the current understanding of the potential impacts of underwater noise on individuals, populations and ecosystems.

Our understanding of the extent of current knowledge is presented for various taxa and specific consideration is given to fish larvae. In general, consideration was given to marine receptors that are i) commercially important, ii) protected by legislation and/or iii) thought or shown to be sensitive to underwater sound.

The extent of available published empirical data is indicated by colour, where green is intended to indicate existence of a very comprehensive evidence data base and thus extensive understanding of the impacts of noise, amber depicts *some* data availability and red shows areas where there is a general lack of robust empirical data and hence very limited understanding of the potential noise impacts.

This compilation looks to provide an overview of the present knowledge, and would be expected to evolve as new empirical evidence becomes available.

Table 1: Overview of knowledge gaps relating to impacts of noise on sensitive marine organisms, their populations and ecosystems.

Knowledge gaps relating to <u>underwater noise impact</u> on marine biota		**Vertebrates**					**Invertebrates**		
		Marine mammals	**Fish**	**Fish Larvae**	**Sea turtles**	**Birds**	**Crustaceans**	**Cephalopods**	**Bivalve/ Bivalve larvae**
Detection of	acoustic pressure					(No data)			
	particle motion								
Injury to organs for sound field detection	acoustic pressure			*					*
	particle motion			*					*
Behavioural response to noise	acoustic pressure								
	particle motion								
Chronic effects of noise exposure									
Population effects of acoustic disturbance									
Resulting effects on ecosystems									

*Relates to injury to larvae *per se*

Legend

	Considerable understanding/ Limited requirement for further research (focused research may be required in some areas)

	Some knowledge (Little to Fair)/ Further research required – knowledge gaps remain
	Very little understanding or published work/ Requirement for further research

6) List of Attendees

(Two delegates were unable to attend at a short notice. They are indicated by *)

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Cefas

Cefas contract report: C6082

ENV.D.2/FRA/2012/0025: Impacts of noise and use of propagation models to predict the recipient side of noise

Task 3: Roadmap

Authors: J. Fabrizio Borsani

Issue date: October 2014

NPL National Physical Laboratory

TNO innovation for life

Cefas Document Control

Title: Roadmap

Submitted to:	Lydia Martin-Roumegas
Date submitted:	31/10/2014
Project Manager:	Kelly Baker
Report compiled by:	J. Fabrizio Borsani (Cefas)
Quality control by:	Kelly Baker
Approved by & date:	John Bacon
Version:	2.4

Version Control History			
Author	**Date**	**Comment**	**Version**
J.F. Borsani	17/06/2014	Discussion document	1
J.F. Borsani	10/07/2014	Revised draft	2
J.F. Borsani	24/07/2014	Minor revisions	2.1
J.F. Borsani	10/09/2014	Minor revisions	2.2
M.Tasker	21/09/2014	Comments	
J.F.Borsani	24/09/2014	M.Tasker comments addressed	2.3
J.F.Borsani	27/10/2014	Final version	2.4

Title: ENV.D.2/FRA/2012/0025: Impacts of noise and use of propagation models to predict the recipient side of noise

Task 3: Roadmap

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Issue date: 31/10/2014

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Table of contents

1 Background

The EC Decision 2010/477/EU on criteria and methodological standards on GES of marine waters, lists two indicators for Descriptor 11 (Noise/Energy) of the MSFD 2008/56/EC. These are: Indicator 11.1.1 for 'low and mid frequency impulsive sounds' and Indicator 11.2.1 for 'Continuous low frequency sound (ambient noise)'. These indicators are relevant to displacement and masking effects respectively.

It was agreed that defining Good Environmental Status (GES) was difficult using current knowledge of impacts of anthropogenic noise on marine biota, and so initial indicators were chosen to reflect the environmental *pressures*, rather than the absolute *status*. This is particularly the case for Indicator 11.2.2, where not enough data are available to assess the impact of a masking effect on absolute levels of background noise for individual species. However, if the long-term trends are known then it may be possible to draw some conclusions about changes to environmental pressures. It was also considered that a downward trend in this indicator was more likely to lead to GES than an upward trend.

TG Noise (2014) suggests that trends alone are not sufficient to describe GES, as trends will only indicate whether the pressure on the environment (e.g. from shipping noise) is rising or falling. It is also not clear which levels of a trend-based target are safe, in which case, in the absence of evidence and as a precautionary approach, a downward trend could be adopted as an interim target until further work is completed. There is evidence that cetaceans adjust their vocalisations according to noise conditions in much the same way as birds are known to do. There is only evidence from few species where stress hormone levels increased. There is not a direct link between increases in stress hormones and any further symptoms.

The primary effect that has occurred from underwater noise is behavioural change, and that is very context specific. So to describe actual levels that will lead to GES, if such exist, further detailed appraisal is required. It is also necessary to take account of all of the other pressures acting on the environment and which will cause change, so a single value for GES for underwater noise is unrealistic, especially if such a value is a number on a sound pressure scale alone.

In the opinion of TSG Noise [TG Noise, 2014] there is still insufficient knowledge of the effects of (increased) ambient noise levels in the ocean to determine whether existing levels are too high or where GES is being achieved in respect of ambient noise.

1.1 Objective

Task 3 within the contract "ENV.D.2/FRA/2012/0025: Impacts of noise and use of propagation models to predict the recipient side of noise" states that the objective is to:

> (a) Prepare a Roadmap towards a sufficient assessment of impacts of underwater sound for all marine biota and at all levels (individual, population, ecosystem) in order to define operational targets or GES criteria (i.e. limits for impulsive and ambient underwater sound). Each element of the roadmap (i.e. proposed new research) should be specific and accompanied by an estimation of cost and a recommendation of the relevant framework for its accomplishment.
>
> (b) Prepare input to a possible revision of the Commission Decision on Descriptor 11.

2 Summary of the outcome of Task 2 (Workshop)

The fundamental outcome of the workshop held to address Task 2 is that there is insufficient knowledge for describing GES and defining targets for underwater noise in a quantitative evidence-based manner. In order to progress towards achieving that and hence facilitate establishing targets, knowledge gaps must be filled first.

<u>The following were identified as knowledge gaps and/or needs for future action to be addressed with priority:</u>

1) Underwater noise monitoring is needed for implementing the Marine Strategy Framework Directive [Dekeling *et al.* 2014]. To date, no international standards are available for underwater noise monitoring. There is a need for Member States to carry out monitoring in a standardized way, so that the results of monitoring can be displayed, evaluated and compared consistently across Member

States.

The need for monitoring standards implies that measuring as well as modelling is undertaken in a standardized way. Clearly, before standards can be written, common terminology must be agreed upon. Developing international standards may take times in excess of the immediate MSFD timeline, so that interim standard guidelines must be drafted for Member States.

2) The current understanding of the adverse effects of sound on the marine ecosystem and marine fauna is limited. The main effect that raises concern related to elevated ambient noise levels is masking. There is evidence that some cetaceans adjust their vocalisations according to noise conditions and there is also evidence that noise increases stress. The behavioural changes caused by noise are very context specific and need to be evaluated on a case-specific basis.

Data on fish and crustaceans are poor and there is a need to develop noise exposure experiments and studies, both laboratory-based as well as in the wild, to determine effects on individuals and to validate models.

With reference to both ambient noise as well as impulsive noise there is no need to study all species, but based on conservation status and sensitivity a selection of species can be defined. Also, there is a need to develop/apply models to predict effects by different regions, areas, habitats, fishing pressure, noise exposure, behavioural state, feeding and breeding. Scaling to population level effects will be difficult due to lack of knowledge of population sizes. However, effects will have to be considered at a whole ecosystem level and not at individual species level.

The introduction of thresholds and single-number based levels seems questionable, although practical in terms of defining potential mitigation, and needs to be carefully evaluated taking into consideration the advancement of science. The achievement of GES for noise alone seems at present most unlikely, as GES is linked to a variety of other concurrent factors that need further assessment. In particular, there seem to be two main issues that need to be addressed, namely, a) the inability to know what GES might be and, b) inability to assess whether the GES status of an organism is being driven by noise or due to other pressures. Such other pressures might be conflicting or additive.

3) There is a need for design and development of cost efficient monitoring tools to monitor ambient sound at the relevant frequencies for deployment across member states to obtain the data needed to address Descriptor 11.2. A common EU-wide approach to development of sensors and monitoring tools is desirable to avoid duplication and harmonize approaches.

4) In order to better re-define GES for noise, if such exist, and its relations to other descriptors, further work and guidance are needed. There is a concern whether setting thresholds for underwater noise in all contexts in European Seas is at all possible, and such work should be put in the context of the other massive pressures on the marine system. The need for cumulative and proportionate assessment of all pressures was stressed.

3 Proposed Roadmap and related Actions

With reference to the outcome of Task 2 (workshop) as summarized above, a list of steps to be taken to achieve the objectives of the task is provided below, completed with related actions and an estimate of the necessary timeframe and costs to achieve them.

1) To agree features of sound that need to be measured and to agree on terminology to be used;

2.1) To start the process of designing standards for monitoring noise; this will entail developing standards for a) measuring, and b) modelling and mapping of noise;

2.2) While standards are being developed an interim guidance must be drafted;

3) To design and complete studies aimed at filling knowledge gaps as described in 1.2;

4) To design and develop sensors, instrumentation and analysis tools that deliver the parameters required to fulfil the indicators on underwater noise;

5) With reference to the above steps eventually redefine GES for noise and draft updated descriptors.

In view of a pragmatic approach to progress in addressing the issues raised by the workshop an initial list of actions is proposed. Associated costs have been estimated within a range based on previous experience of similar tasks, such as the present EU funded project as well as the Common Sense project (http://www.commonsenseproject.eu/).

There are a range of bodies that could undertake the work described by these actions; in cases (such as standard setting), appropriate international bodies are suggested. In other cases, where a number of groups could potentially undertake the work it is recommended that an open public tender process be undertaken. In order to ensure that such calls for tender reach all parts of Europe it is recommended that international bodies such as OSPAR, HELCOM, Barcelona and Black Sea Conventions and ICES be asked to help in advertising the call.

Funding for some of these actions may be found within (but not limited) to the current LIFE+ framework, as well as with future calls within HORIZON 2020-Blue Growth. For Action 3 new INTERREG calls may be of interest at the regional level, since they involve specific SMEs to actually provide a technical component and local regulatory bodies to put monitoring in place.

3.1 Action 1. Define terminology/metrics/measures/basic intermediate time analysis to measure ambient sound (2015-2016)

A wide variety of terminology and metrics are in use across the EU to describe underwater sound. Depending upon their technical origin, scientists, developers, and military operators use their preferred metrics and carry out measurements and analysis in their individually preferred ways. These methods are not homogeneous across member states. There is an urgent need to define which features of sound need to be measured and to agree on terminology to be used. In addition, there is the need to start the process of designing standards for monitoring noise; this will entail developing standards for a) measuring, and b) modelling and mapping of noise. This is a process which has already begun within some member states and at the international level. However, developing international standards may take times in excess of the current MSFD timeline, so that interim standard guidelines must be drafted for Member States. The main work required for this action is a series of workshops to develop standards. This would need to bring together specialists, so costs would comprise travel and subsistence costs for those specialists and some local venue costs. Such workshops could be organised under TG Noise (utilising support already supplied by the

Commission), or could be organised by separate contractors. The appropriate bodies would need 1-2 years time to devise, agree and refine any proposals made. The proposals may synthesise existing ideas with newly developed methods. Costs are anticipated to be approximately €50,000 per year.

3.2 Action 2. Design scientific studies to address knowledge gaps and research priorities on crustaceans, fish and marine mammals (2015-2018)

An initial set of studies is required to improve knowledge of potential adverse effects of noise on the ecosystem. An approach that aims to define and measure adverse effects in a dose-response assessment would be most appropriate. Studies may entail controlled exposure experiments as well as laboratory based setups.

There is lack of knowledge in particular with respect to, but not exclusively: a) the long term effects of noise on marine mammals, b) the effects of noise on fish larvae, c) the effects of noise on fish populations, c) the effects of noise on crustaceans, with particular emphasis on commercially relevant species. Further, d) we need to outline a mechanism by which to define which species are relevant to the assessment of GES further to the Harbour Porpoise (relevant for the Atlantic as well as for the Black Sea) or can be used as a proxy precautionary approach. Each one of the points could be considered as a separate action.

Actions would be carried out by consortia of academic and research partners, with collaboration from industry to maximise the practical effectiveness of experimental designs. An initial timeframe proposed to achieve results from these experiments is 4 years. Costs for the work are anticipated to be in the range of €5-10 Million. Costs are high due to the requirement to deploy high value equipment for this work, particularly ship-time and framed instrumentation at sea.

3.3 Action 3. Develop suitable common sensor technology to monitor ambient sound at the relevant frequencies for deployment across member states (2015-2018).

Some member states have begun collectively to monitor ambient underwater sound (e.g. the BIAS project) and have carried out pilot studies to determine best practices or best available techniques. However, further to the inconsistency in procedures addressed in Action 1, across member states, there is a wide variety of sensors, techniques and methods to monitor sounds. The variety is also relevant to a) the deployment of instrumentation at sea, b) to the acquisition of data, c) to the recovery methods and finally d) to the analysis and storage of data. These procedures have partially been addressed at the national level as well as at an EU level (e.g. through the work of TG Noise, 2014) but development of cost-effective methods at the MSFD targeted sensors centred at the delivery of D11.2 is still at an early stage. Collaboration between member states and among research organisations, academia and industry to test and produce suitable and cost-effective instruments and techniques would be desirable to avoid duplication and harmonize approaches. The initial timeframe is estimated to be 4 years, with the potential for additional effort beyond this. Costs may initially be in excess of €6 Million for the development of sensors/tools to address point a) to d); benefits to be gained during later operational phases of the monitoring when economies of scale and mass production will enable wider adoption of these techniques across the community are expected.

3.4 Action 4. Develop a method to address the problem of defining GES for underwater sound, including setting thresholds, targets and refining descriptors. (2017-2018).

From a biological perspective thresholds are dependent on many variables and confidence levels in results are low even when using the best data available. For management purposes, thresholds should be “action-based”. From a regulatory perspective, thresholds are necessary and promote the application of mitigation measures once the impacts of noise are known. However, the concern must be expressed that thresholds may be incorrect. For example they are unlikely to be relevant over a wide geographical area. It may be impossible to set thresholds for underwater noise in all European Seas, and such work should be put in the context of other pressures on the marine ecosystems. There is an urgent need for cumulative and proportionate assessment of all pressures.

This action is aimed in developing a method to address the problem. The main activity would be to organize a series of workshops to bring together relevant experts and to draft and publish relevant reports deriving from this action. The timeframe would be set initially to two years, with a potential for reiteration at the end of every MSFD 6-year cycle. Costs may be in the range of €50,000-100,000 per year, depending upon how much of it is addressed within the activities of TG Noise or outsourced.

4 References

BIAS -Baltic Sea Information on the Acoustic Soundscape, LIFE11 ENV/SE/000841 (http://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=search.dspPage&n_proj_id=4183&docType=pdf)

Dekeling, R.P.A., Tasker, M.L., Van der Graaf, A.J., Ainslie, M.A, Andersson, M.H., André, M., Borsani, J.F., Brensing, K., Castellote, M., Cronin, D., Dalen, J., Folegot, T., Leaper, R., Pajala, J., Redman, P., Robinson, S.P., Sigray, P., Sutton, G., Thomsen, F., Werner, S., Wittekind, D., Young, J.V. (2014) Monitoring Guidance for Underwater Noise in European Seas Part I. EUR – Scientific and Technical Research series – ISSN 1831-9424, ISBN 978-92-79-36341-2

Dekeling, R.P.A., Tasker, M.L., Van der Graaf, A.J., Ainslie, M.A, Andersson, M.H., André, M., Borsani, J.F., Brensing, K., Castellote, M., Cronin, D., Dalen, J., Folegot, T., Leaper, R., Pajala, J., Redman, P., Robinson, S.P., Sigray, P., Sutton, G., Thomsen, F., Werner, S., Wittekind, D., Young, J.V. (2014) Monitoring Guidance for Underwater Noise in European Seas Part II. EUR – Scientific and Technical Research series – ISSN 1831-9424, ISBN 978-92-79-36339-9

Dekeling, R.P.A., Tasker, M.L., Van der Graaf, A.J., Ainslie, M.A, Andersson, M.H., André, M., Borsani, J.F., Brensing, K., Castellote, M., Cronin, D., Dalen, J., Folegot, T., Leaper, R., Pajala, J., Redman, P., Robinson, S.P., Sigray, P., Sutton, G., Thomsen, F., Werner, S., Wittekind, D., Young, J.V. (2014) Monitoring Guidance for Underwater Noise in European Seas Part III. EUR – Scientific and Technical Research series – ISSN 1831-9424, ISBN 978-92-79-36340-5

Robinson, S.P., Lepper, P. A. and Hazelwood, R.A. (2014) NPL Good Practice Guide *Good Practice Guide for Underwater Noise Measurement*, National Measurement Office, Marine Scotland, The Crown Estate, No. 133, ISSN: 1368-6550.

NPL REPORT AC 12

REVIEW OF UNDERWATER ACOUSTIC PROPAGATION MODELS

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OCTOBER 2014

Review of underwater acoustic propagation models

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Summary

In September 2013, the European Commission commissioned a project entitled *Impacts of Noise and use of Propagation Models to Predict the Recipient Side of Noise* (project number 1109.05/659011/SER/C.2), under a Framework Service Contract (ENV.D2/FRA/2012/0025) with the subject 'Emerging pressures, human activities and measures in the marine environment (including marine litter), led by Cefas. The project consortium members include Cefas, NPL, TNO, OASIS and JNCC (later in an advisory role).

This report is the deliverable of Task 4, '*Compile existing information on underwater sound propagation models*', of the above project, its aim being '*to critically review existing relevant literature and results from research projects and make an inventory of existing models with pros/cons and gaps, and especially the reliability and information needs required for applying these models, with assumptions and limitation explicitly mentioned'*.

Version history
Version 1.0 - Draft NPL report AIR (RES) 086 issued for Commission comment: July 2014

Version 1.1 - Report re-issued as unrestricted NPL report AC12 : October 2014 (no other edits)

ISSN 1754-2936

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CONTENTS

1 Background to ocean acoustic propagation modelling

Ocean acoustic propagation models have been widely used for several decades, to support a broad range of applications including anti-submarine warfare [Bucker, 1976], global scale underwater sound propagation [Heaney et al., 1991; Collins et al., 1995] characterisation of acoustic communications channels [Simons et al., 2001], passive acoustic monitoring of marine biota [e.g. Potter et al., 1994; Stafford et al., 1998; McDonald et al., 1999; Thode et al., 2004; Helble et al., 2013], ocean acoustic tomography [Munk and Wunsch, 1979; Cornuelle et al., 1989; Worcester et al., 1999]), ambient noise forecasting [Wenz, 1962; Heitmeyer, 2006; Merchant et al., 2012] and other oceanographic applications [Harrison 1989; Buckingham, 1992; Jensen et al., 1997]. Since the first underwater sound experiment, conducted by Colladon and Sturm in 1826 on Lake Geneva, it has been known that sound travels extremely well underwater [Lichte, 1919]. With the advent of large-scale submarine warfare during the Second World War and the subsequent Cold War, there was intense effort to understand and predict the propagation of sound in the ocean, accruing a wealth of knowledge about underwater sound propagation, and its environmental dependencies [Ainslie, 2010]. Relatively recent advances in a number of scientific disciplines have provided further confidence in the ability to predict the acoustic field for a given source, and much of the progress is founded on advancements in:

- Computational acoustics – which provided a solution to the wave equation permitting the computation of the acoustic field for a given environment;
- Bathymetric remote sensing – which provided input water depth for small and large scale problems;
- Oceanographic dynamics and modelling –the complexity of the temperature and salinity field (that drive sound speed) has been characterised and observational and modelling methods have helped quantify these fields;
- Computer hardware speed – much of the capabilities of modern ocean acoustic modelling has benefited from the rapid increase in computer processing speed (i.e. CPU) and memory access efficiency (i.e. RAM).

The outputs of an acoustic propagation model may be used to establish the time-series at a single receiver, the range/depth slice of received level (established from the propagation loss), or a geographically based plan-view of the ensonification area from a particular source.

The reduction in the level of the acoustic field between a source and a receiver position, i.e. the propagation loss, is generally stated as the difference between the source level and the sound pressure level at a receiver position, expressed in decibels (dB) relative to 1 m. This reduction will occur due to the spreading laws, although there will also be a number of environmental factors that may affect the propagation of the acoustic wave and therefore the propagation loss over a given distance, including:

- The volume characteristics
  - Water sound speed profile (driven mainly by temperature, hydrostatic pressure and salinity)
  - Water attenuation profile
  - Volume scattering characteristics
- The surface boundary
  - Surface roughness
  - Bubbles
  - Doppler shift resulting from ocean wave motion
- The seafloor/seabed boundary

- Parameterisation of the sediment via reflection coefficient or geo-acoustic parameters
- The bathymetry
- The seafloor and sub-seafloor roughness

The influence of these factors will be dependent on the geographic location and their influence may be frequency dependent. These dependencies are further discussed in Section 2 below

.

2 Ocean acoustic propagation models

2.1 Introduction

Ocean acoustic propagation models usually solve the wave equation (or Helmholtz equation), further described in Section 2.2. This is generally done for a given frequency, and broadband signals, for example, a pulse, may have to be modelled using a time-domain model. Alternatively a solution is calculated for each frequency or frequency band across the required frequency range, with the use of a suitable inverse transform. It is also worth noting that not every propagation model will consider all of the environmental factors listed in Section 1, which may influence the propagating wave.

In general, propagation modelling solutions can be divided into three large classes based upon i) the frequency characteristics of the source; ii) the environmental dependence of the propagation region; and iii) the water depth. Models within class ii) are generally categorised as *range independent* (the environmental parameters are kept fixed with range), and *range dependent* (environmental input parameters, such as water depth and sound speed, are allowed to vary with distance from the source), the latter being the preferred choice when the bathymetry or water column conditions change along the propagation path.

Given a particular frequency band and environment, the choice of a suitable propagation model can be made. There are a wide variety of models available, some of which are available for download free of charge, but these complex models require some expertise to run successfully. The available propagation models are commonly categorised based on their underlying method into the following groups [Jensen et al., 2011; Etter, 2013], which captures the most commonly used methods:

- Ray tracing
- Normal mode
- Parabolic equation
- Wavenumber integration
- Energy flux
- Finite Difference, Finite Element models

There are other methods such as the image method [Brekhovskikh, 1980] and the multipath extension [Weinberg, 1975], which are not considered here.

Note that although it is possible to model vector field quantities such as sound particle velocity, in practice this is rarely done, and most modelling is used to predict the transmission of sound energy or sound pressure.

One further parameter that influences model choice is computational cost (or model efficiency). There can be orders of magnitude differences in the required computational time for different models and a decision is required between higher fidelity/accuracy and the computational time. It should be noted that for given propagation conditions, there will be a number of modelling solutions which may provide the appropriate accuracy, and computation time may be a distinguishing factor.

2.2 Solutions to the wave equation

Underwater sound field can be described by the Helmholtz equation:

$$[\nabla^2 + k(\boldsymbol{r})^2]\emptyset(\boldsymbol{r}, f) = 0 \qquad [1]$$

where the solution $\emptyset(\boldsymbol{r}, f)$ is a function of position vector $\boldsymbol{r}$ and frequency f. The solution can be found if source and boundary condition are known.

There are a number of solutions of the wave equation depending on the methods applied to the equation. An introduction to the physics and implementation of each solution is provided in Jensen et al., [1997]. These solutions to the wave equation can generally be categorised into six propagation modelling methods each of which is outlined here, with their potential advantages and limitations, and also introduced are the qualifications to understand suitability of each model. A list of the available models is also provided in a summary book by Etter [2013].

2.2.1 Ray method

Ray method – brief description:

Following the analogy of optics, the wave equation can be solved in the high-frequency limit by integrating Snell's law and the associated eikonal equation. This ray tracing solution is highly intuitive because the sound paths can be traced and show the path of each ray. Ray tracing is very efficient (fast). Once the rays are computed, the acoustic field levels are calculated by summing the rays near the receiver. The rays are often extended in size by using the Gaussian beam approximation. Ray interaction with the seafloor is achieved using a reflection coefficient without penetration into the seafloor. Ray theory is limited in accuracy at low frequencies (typically below around 200 Hz) where diffraction is significant and where seabed penetration occurs. The ray theory approach performs poorly when there are surface ducts and other sound speed fields with discontinuities and rough surfaces. Ray theory handles arbitrary range-dependent environments, is best in deep water and is suitable at higher frequencies.

The ray method of the wave equation is a high frequency approximation solution [Officer, 1958; Boyles 1984; Brekhovskikh and Lysanov, 1982; Tolstoy et al., 1966], assuming the following form:

$$p = Ae^{j\varphi} \qquad [2]$$

where A is the amplitude and φ is the phase, both of which are functions of distance between the source and the receiver. This solution generates two separate equations when applied to the wave equation.

In practice, the amplitude of an acoustic field varies very slowly in comparison with the phase, especially at high frequency. The first solution can be simplified by ignoring the term of the second derivative of the amplitude with respect to distance, resulting in the eikonal equation, a non-linear partial differential equation. The eikonal equation can be solved numerically to produce a ray trace when the initial launch angle and sound speed profile are given. The second solution, called the transport equation, is used to determine the amplitude.

Ray-tracing models are only limited in capability as a consequence of the approximation leading to the eikonal equation since no other approximations appear in the ray-theoretic development. The physical implications of this approximation are that the curvature of a ray over a wavelength must be small; the fractional change in sound speed must be small over a wavelength; and the fractional change in *A* must be small over a wavelength.

Ray-tracing models are fast to compute, providing a pictorial representation, in the form of ray diagrams, of the field in the channel. This is useful for integrating and understanding the results. Further advantages of ray tracing are that: (i) the directionality of the source and receiver can be fairly easily accommodated, by introducing appropriate launch and arrival-angle weighting factors; and (ii) rays can be traced through range-dependent sound speed profiles and over complicated bathymetry. Conversely, the computations must be performed at all distances to the receiver. While only a few rays are required to determine the sound field at a distant receiver in deep oceans, many rays are needed in shallow water. Perhaps the most pertinent disadvantage, however, is that wave effects such as diffraction and caustics cannot easily be handled adequately by ray tracing, which limits the usefulness of this approach for the investigation of seafloor interactions and for low frequency propagation:

- *Wave diffraction allows sound to spread into the shadow zone near the boundary region of the zone, whereas ray tracing predicts no sound in the shadow zone, resulting in a very sharp contrast each side of the boundary region;*
- *At a caustic the amplitudes become singularities due to converging rays resulting in a high pressure region.*

Modified ray methods have been developed to overcome these problems for example by Keller [1962], White and Pederson [1981], and Tindle [2002].

Beam tracing [Porter and Bucker, 1987; Bucker, 1994; Weinberg and Keenan, 1996] is a variant of ray tracing. It uses the same rays as in ray tracing, but applies a beam width associated with each ray to determine the amplitude of the pressure. It overcomes the shadow zone and at caustics problems associated with the ray tracing method.

Available ray tracing programs consider only the wave field in water column, perhaps for historical reasons, as the method was intended for underwater applications. However, the effect of the seabed is taken into account through the consideration of the reflection coefficient at the interface of the water and the seabed. The surface loss caused by scattering of rough surface and air bubbles near the surface can also be included.

2.2.1.1 Example of a ray/beam tracing propagation model: Bellhop [Porter, 2011]

BELLHOP is a beam tracing model for predicting acoustic pressure fields in ocean environments. Several types of beams are implemented including Gaussian and hat-shaped beams, with both geometric and physics-based spreading laws. BELLHOP can produce a variety of useful outputs including propagation loss, eigenrays which are the rays that connect the source and receivers, arrivals, and received time-series. It allows for range-dependence in the top and bottom boundaries (altimetry and bathymetry), as well as in the sound speed profile. Additional input files allow the specification of directional sources as well as geo-acoustic properties for the bounding media. Top and bottom reflection coefficients may also be provided.

2.2.2 Normal mode method

Normal mode method – brief description:

A full-field solution to the wave equation involves using separation of variables to solve the local vertical part of the wave equation and then apply various solutions to the horizontal component. The vertical wave equation solutions are standard normal modes, or eigenvalues. The modes are then summed up in varying fashion, depending upon the horizontal propagation, at the source and receiver to generate the full acoustic field. These modes encompass the solution to the wave equation including sound speed and density discontinuities and sound field in the seabed. The horizontal component of the solution can be (i) carried out trivially for range-independent environments, (ii) solved easily using adiabatic mode theory [Tindle and Zhang, 1997] for mildly range-dependent environments, and (iii) solved explicitly using coupled mode [Collins 1993a; Preisig and Duda, 1997; Holland 2010; Heaney et al., 2012] or parabolic equation models for complex range-dependent environments. Normal mode solutions are best suited to mildly range-dependent environments and at lower frequencies as the number of modes goes up linearly with frequency. They are used extensively in both shallow and deep water.

The normal mode method was introduced into the field of underwater acoustics by Pekeris [Pekeris, 1948]. The solution for a cylindrical coordinate system can be written as:

$$p(r,z) = \sum_{m=1}^{\infty} \Phi_m(z)\Phi_m(r) \qquad [3]$$

where $\Phi_m(r)$ is a function of distance r and $\Phi_m(z)$ is a function of depth z. The mth term in the equation represents the contribution of the mth mode.

A propagating mode is formed in a underwater channel with parallel sea surface and seabed where two plane waves travel at two opposite grazing angles, one up-going and one down-going due to reflection from the sea surface and seafloor as shown in Figure 1.

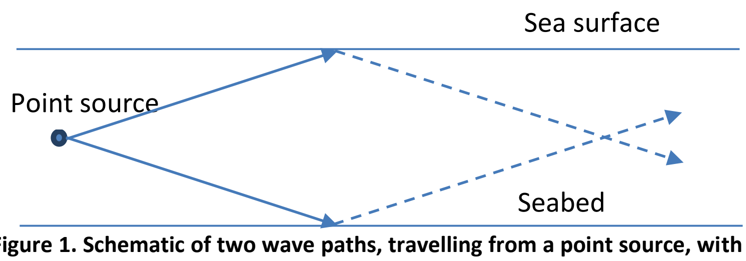

Figure 1. Schematic of two wave paths, travelling from a point source, with opposite grazing angles that have undergone reflection in an underwater channel.

Whilst, there are an infinite number of modes in an ocean channel, only a limited number of these modes can travel a long distance from a source. These are propagating modes with low amplitude attenuation and will depend on frequency, water depth, sound speed and density of the water and the seabed, and attenuation in the water and the seabed. The modes that do not propagate are leaky modes [Tindle et al., 1976; Boyles, 1984; Ainslie et al., 1998] or evanescent modes [Jensen et al., 2011]. These are modes, which have a grazing angle greater than the critical angle, or decay rapidly with distance from the water/seabed interface, resulting from the elastic properties of the seabed. Most normal mode models treat the underwater acoustic channel as a water column on top of a sediment layer that is over laid on a semi-infinite solid substrate. The sediment layer may support shear wave, with a very low shear wave sound speed.

The main challenge for the normal mode solution is to find all contributing modes from the depth dependent part of Eq. (3). The two general approaches are either to search only propagating modes or to search the propagating and some of the leaky modes (and evanescent modes if they exist). The primary advantage of searching for only the propagating modes is a simpler program and higher speed of execution. However, this approach can only be applied in the far field. The normal mode models that include the leaky modes (and evanescent modes) are better closer to the source in terms of accuracy, but they are relatively slow, due to the time consuming search for the additional modes.

The normal mode method is applicable to range independent problems where environmental parameters are constant with distance, and the method has been extended to deal with range dependent problem using adiabatic mode theory [Nagl et al., 1978], or the coupled mode method [Evans, 1983]. In this case, the propagating channel is divided into horizontal sections of discrete length with distance from the source, where the environmental parameters are constant within each section. Normal mode solutions are obtained for each of the sections, and coupling coefficients are derived based on continuity of the solutions at the interfaces of each section.

The full coupled mode method can deal with large variation of environmental parameters, where both forward and backward propagations are accounted for. However, the method is very numerically intensive [Jensen and Ferla, 1990]. An adiabatic mode method can be applied when the environmental parameters vary slowly so that a mode can adapt to the change without any energy exchange to other modes, hence the 'adiabatic mode' name. It is much more efficient using the adiabatic solution than the full coupled mode when both are applicable. In practice, there are many cases where some modes are coupled into other types of forward propagating modes. One example is a wave travelling upward in a penetrable wedge with a small slope where a propagating mode that is far away from the apex of the wedge gradually approaches the cut-off depth where the water depth is no longer able to support the mode. The grazing angle of the mode at the cut-off depth exceeds the critical angle and therefore becomes a leaky mode. The mode eventually propagates completely into the sediment with no back propagation due to the gradual change of water depth. The solution to this kind of problem is a one way coupled mode method, which is implemented in some normal mode propagation models [Porter, 1991; Ferla et al., 1993]. The execution speed of this method is naturally slower than the adiabatic mode, but much faster than full coupled mode methods.

Unlike the ray solution, the normal mode method allows the sound field to be calculated anywhere between the source and the receiver. The normal mode method is most suited to a channel where the number of modes is small, i.e. relatively shallow water channels with low frequency signals. It becomes difficult to find all the contributing modes at high frequencies in a deep water channel since the differences in the vertical wave number of different modes become increasingly small with an increasing water depth to wave length ratio.

2.2.2.1 Examples of normal mode propagation models: Kraken [Porter, 1991] and C-SNAP [Ferla, et al., 1993]

Kraken and C-SNAP are normal mode models using a coupled-mode and an adiabatic normal mode solution, respectively, which find only the propagating modes in water column. The attenuation of the propagating media and the surface roughness are included using the perturbation method [Porter, 2001]. There is also a complex version of Kraken, KrakenC, which is capable of finding the leaky modes, although, the computation time is several times longer. These example models cannot solve the field inside elastic layers (seabed) since they use an equivalent reflection coefficient at the interface to account for the effect of the layers.

The predicted propagation losses by Kraken, KrakenC and C-SNAP can be expected to be comparable at distances that only the lowest propagating modes can reach. The predicted propagation loss using KrakenC can differ from that using Kraken and C-SNAP at distances where the contribution from leaky modes requires consideration, i.e. closer to the source. All three models can be applied to range dependent problems (i.e. range dependent bathymetry and sound speed), and are also able to deal with stratified layers which support shear waves. Kraken and KrakenC, are both incorporated into AcTUP [Duncan and Maggi, 2006].

Note: *AcTUP is a MATLAB based program which includes a number of propagation models, Kraken, KrakenC, Bellhop, RamGeo, RamsGeo and Scooter, and runs through a graphical user interface. However, it should be noted when using AcTUP that it limits some of the functions available for some of the models; for example, Kraken and KrakenC cannot be used for range dependent problems.*

2.2.3 Wave number integration

Wave number integration method – brief description:

The wave equation can be solved exactly at close range using the numerical approach of spectral wavenumber integration. Such solutions are often called Fast-Field Programs (FFP). For range-independent environments they compute the exact field and are often used as benchmark solutions. The method has been extended to range-dependent environments, but this extension is not publically available, and is thus less widely used.

The wave number integration method, also known as Fast Field Program (FFP), solves the wave equation using the Green's function [DiNapoli and Deavenport, 1980; Kutschale, 1973; Schmidt, 1984; Schmidt and Jensen, 1984; Schmidt and Jensen, 1985] as a function of depth in a stratified media, where the physical properties vary only with depth. The integration is then performed over the wave number range using Fast Fourier Transformation. An approximation made with the wave number integration method is to use the asymptotic form of Hankel function, limiting to methods accuracy when the distance is less than a wavelength.

The wavenumber integration method is an exact solution, in contrast to the normal mode method, since it includes the contributions from not only the propagating modes, but also from the leaky and evanescent modes. This makes the method particularly useful in cases where the evanescent waves are important. The method can also be extended to treat range-dependent problems [Goh and Schmidt, 1996].

2.2.3.1 Example of a wave number integration propagation model: OASES [Schmidt, 2004] and Scooter [Porter, 2007]

OASES [Schmidt, 2004] and its predecessor, SAFARI [Schmidt, 1987], are widely considered to be *de facto* standards for propagation loss prediction, especially in range-independent channels due to the wavenumber integration solution being an exact solution even with an elastic seabed. These two wave number integration implementations inherently handle compressional, shear and interface [Tamir and Bertoni, 1971; Rauch, 1980] waves at all distances, as well as representing the modes accurately everywhere, including through cut-off. The range independent version of OASES is freely available.

2.2.4 Parabolic Equation method

Parabolic equation method – brief description:

Almost all acoustic modelling involves the computation of the field propagation from a source to a distant receiver. In this problem the propagation is one-way. Separating the wave equation into incoming and outgoing solutions leads to the Parabolic Equation. Neglecting incoming (back-scattered energy), the acoustic field can be computed using a marching algorithm referred to as the Parabolic Equation (PE) model. There are two classes of PE models available – the split-step Fast Fourier Transform solution developed by Tappert [1977] and the Padé expansion solution developed by Collins [1993b]. The PE is an efficient marching solution that is suitable for range-dependent environments, discontinuous sound speed profiles and is commonly used in shallow and deep water. The PE computational requirements increase with frequency squared (or $f \cdot \log(f)$ for the Fourier PE) and therefore the PE is generally used at frequencies less than 1 kHz. The split-step Fast Fourier Transform approach does not handle density discontinuities easily and therefore it is not the model of choice in shallow water.

The parabolic equation solution is derived from Eq. (1) with an approximation that only the out-going wave is considered. The propagation problem becomes an initial boundary condition problem where the propagated sound field can be calculated from the source location, where the field value is known, by marching out the solution step-by-step to the required distance.

The original version of the parabolic equation, adapted from applications in optics and geophysics, was introduced into ocean acoustics by Hardin and Tappert [1973]. A detailed description on the development of the method is available in two comprehensive reviews by Lee and Pierce [1995] and Lee et al., [2000]. Parabolic equation models have acquired popularity amongst the ocean-acoustics community not least because they have been made widely available, but also because they calculate the field over the entire water column with no additional effort and can handle range-dependent environments, over a range of water depths. In addition, elastic boundary conditions can also be included, however, this may introduce some computational constraints. Some of the PE models can also handle sound propagation with ray angles up to 90°. However, the use of PE models are generally limited to lower frequencies due to the increase in computation effort at higher frequencies.

There are two common approaches to the parabolic equation models, the split-step Fast Fourier Transform approach developed by Tappert [1977] and the split-step Padé expansion approach developed by Michael Collins [1993b].

Other solutions to the parabolic equation include the Implicit Finite Difference (IFD) scheme [Lee and Botseas, 1982] which is considered more accurate for shallow water compared with the split-step Fast Fourier Transform [Kewley et al., 1983].

2.2.4.1 Example of a parabolic equation propagation model: RAM [Collins, 1993c]

RAM (Range-dependent Acoustic Modelling) is a parabolic equation code that uses the split-step Padé algorithm to achieve high efficiency and the ability to model propagation at large angles from the horizontal. There is a trade-off between the angular range and the speed of computation that is governed by the number of terms the user specifies for the Padé approximation – the more terms, the wider the angle, but the longer the run time. RAM is capable of modelling low frequency propagation in fully range dependent environments. There are a number of modified versions of RAM, such as PEREGRINE, RAMSurf with faster execution time, not all of which are freely available. Implementations of RAM are also incorporated into AcTUP [Duncan and Maggi, 2006]; these are RAMGeo for a fluid seabed and RAMSGeo for an elastic seabed.

2.2.5 Energy flux method

Energy flux method – brief description:

A hybrid solution first developed by Weston [Weston 1959; 1968], between rays and modes is the energy flux model, based upon the Hamiltonian action [Holland, 2010]. Analytic solutions exist for simple environments (iso-velocity water, flat bottom) and extensions to depth dependent sound speeds and range dependence have been made [Harrison, 2012]. These flux-based solutions are extremely fast, handle diffraction but are not used to compute the coherent acoustic field and often neglect high spatial frequency interference. For accuracy and speed they lie somewhere between ray theory and mode theory, as the solution suggests.

Weston [1980] provided a set of equations based on the energy flux method and mode characteristics to predict propagation loss in iso-velocity underwater channels with an arbitrary seafloor profile. This approach divides the channel into four regions depending on the sound propagation mode; spherical spreading in the immediate vicinity of the source, followed by cylindrical spreading, then mode stripping and finally single mode. The propagation loss at close distance, up to the cylindrical spreading region, is subject to only spreading loss, with additional loss due to seafloor reflection loss in the mode stripping region where higher modes are attenuated more quickly as they have larger grazing angles with respect to the seafloor. The fourth region is the single mode region where all but the lowest mode have decayed away. A detailed description of the propagation losses in each of the regions is given in A Table in Appendix A.

Comparisons between the Weston energy flux model other complex models, indicate that the model can produce very good propagation loss predictions [Sertlek and Ainslie 2013; 2014].

2.2.6 Finite difference / finite element

Finite difference / finite element method – brief description:

A common, computational physics approach to solving 3D problems, is to grid the entire environment, and solve the wave equation for space and time. These Finite Difference (FD) and Finite Element (FE) models are rarely used in ocean acoustics. The computational expense of gridding each, sub-wavelength spaced, grid-point for the scale of most ocean acoustic problems is prohibitive. These solutions are generally applied to scattering or very near source propagation. They have been applied to pile-driving excitation problems and the seismic generation of low frequency modes in the oceans sound speed minimum channel.

3 Considerations for propagation modelling

3.1 Water depth and uniformity of the propagation environment (range dependence/range independence)

Ocean environments can often be classified as shallow water or deep water. The primary driver in this selection process is not the water depth, but the importance of the sound interaction with the seafloor. Specifically if the seafloor interaction is small or can be neglected, the propagation conditions are considered as deep water. For basin scale open ocean propagation, for example, the presence of a SOFAR (SOund Fixing and RAnging) channel (a deep sound channel), may result in most of the energy arriving at a distant receiver having been refracted away from the sea-surface and from the seafloor. Such efficient propagation is then largely a function of range-dependent variations in the sound speed, and is less dependent on the seabed characteristics. In contrast, shallow water propagation will generally be dominated by boundary interactions (seafloor, sea surface) and often the geo-acoustic parameters of the seafloor will be the primary environmental parameter that affects the acoustic propagation.

In most ocean environments, particularly over large distances, the bathymetry and the sound speed field can be expected to vary with distance. Such environments will require a range dependent model.

Range dependence versus range independence:

Model selection may be divided into those solutions that handle range-independent (or mildly range-dependent) propagation environments, and those that support arbitrary range-dependence. For range-independent environments, normal modes, wavenumber integration and analytic energy flux solutions are often used as they support a fast run time. For scenarios where strong range-dependence exists, the more appropriate choice may be the parabolic equation solution and ray theoretical solutions. Coupled mode solutions have accuracy comparable to the parabolic equation solution, but are generally not preferred because of their relative computational cost.

The representation of the seabed, for a given propagation model, can have a significant influence on the outputs of the model. It is not always possible to establish the exact acoustic properties of the seabed, particularly as a function of depth below the seabed and furthermore, any underlying geology may not always be fully characterised or understood. This often requires a compromise when implementing the seabed in a propagation model and not all propagation models treat the seabed in the same way. The choice of propagation model should thus consider the extent to which seafloor conditions might influence the propagating sound.

Additionally, the seabed can be treated as a fluid or a solid medium (i.e. supporting shear wave propagation). For sediments, these are often saturated and so can exhibit viscoelastic properties.

3.2 Frequency range

The frequency band of interest is the primary discriminator between propagation models. For low-frequency sound, the parabolic equation solution and the normal mode solution, represent the most appropriate model choice at lower frequencies. For high frequency computations ray tracing or energy flux models are generally used.

Shallow water - low frequency	Shallow water - high frequency	Deep water - low frequency	Deep water - high frequency
Ray theory	*Ray theory*	*Ray theory*	*Ray theory*
Normal mode	*Normal mode*	*Normal mode*	*Normal mode*
Wave number integration	*Wave number integration*	*Wave number integration*	*Wave number integration*
Parabolic equation	*Parabolic equation*	*Parabolic equation*	*Parabolic equation*
Energy flux	*Energy flux*	*Energy flux*	*Energy flux*

Green – suitable: Amber – suitable with limitations: Red – not suitable or applicable

Another consideration when selecting a propagation model is the bandwidth characteristic of the signal, i.e. narrowband vs. broadband. Normal mode, wavenumber integration and parabolic equation models are computed in the frequency domain. For broadband signals this can become computationally intensive, requiring the calculation of the propagation loss at multiple frequencies. Furthermore, it might be necessary to construct the signal in the time domain by inverse-Fourier-transforming (IFFT) the frequency-domain solution. Whilst this approach is accurate, it can become computationally intensive, requiring modelling of many frequencies, particularly for signals with a wide bandwidth. Ray and energy flux models can be solved with travel time along the ray or bundle computed in-stream, providing a solution of a pressure time-series that is generally computationally less intensive.

Note on frequency averaging:
For propagating signals within a defined band, for example within specific third-octave frequency bands, a propagation model may be required that accounts for the range of frequencies within the band. Many models run in the frequency domain, producing propagation loss data for single frequency excitation that exhibit strong amplitude fluctuations due to the coherent interference effects. For a broadband signal, an average of the propagation loss for the entire frequency band is required (this is likely to exhibit much smoother spatial variation than for individual frequencies within the band). This can be achieved by running a model at a number of frequencies within the band and averaging the results, or by performing an equivalent averaging process as a function of distance [Harrison and Harrison, 1995].

3.3 Three-dimensional modelling

Most propagation models are two-dimensional solutions, calculating the propagation loss along a transect, which does not include horizontal refraction, reflection or diffraction (i.e. each transect modelled is independent of the neighbouring transect). In many cases, such models provide sufficient accuracy and can provide three-dimensional maps by combining, often through interpolation, a number of two-dimensional (distance and depth) transects.

However, in some instances the use of two-dimensional models may not be sufficient to accurately model the sound propagation. A possible example includes a scenario where an island or land mass is situated between the source and receiver. A two-dimensional model will result in a shadow behind the land mass where the modelled transects intersect the land mass. In reality, diffraction will occur causing bending of the sound around the land mass. In such cases, it may be necessary to use a three-dimensional model, which accounts for horizontal diffraction to accurately represent the sound field. Other scenarios where two-dimensional models may not provide sufficient accuracy may be environments characterised by sub-surface obstacles such as sand banks, or where there is a strong up-sloping or down-sloping seabed, such as propagation around continental shelves.

In general, three-dimensional implementations can be computationally intensive, and it may be appropriate to utilise a two-dimensional solution, which will be sufficient in most cases.

4 Input data and factors influencing accuracy

4.1 Representation of the sound source

Most propagation models make simplified assumptions about the nature of the acoustic source, for example, that it behaves as a monopole point source. These simplifying assumptions are often necessary to make the computational problem tractable. However, real acoustic sources are not point sources, but are instead distributed sources of sound, although most will approximate to a point source when observed from a sufficient distance (where all the sound waves appear to diverge from an "acoustic centre"). Thus, for many acoustic sources where predictions are required for a considerable distance away from the source, the simplification of the source representation will be appropriate.

However, it is not always possible to represent a source as monopole point and it is not always common practice to establish such a monopole source level. For example, neither the ANSI/ASA standard for measuring the radiated noise level from a ship [ANSI/ASA S12.64-2009] nor the equivalent ISO Publically Available Specification [ISO PAS 17028, 2012] require that a monopole point source level be calculated. Rather, an 'affected source level' [ANSI/ASA S12.64-2009] or 'radiated noise level' [ISO PAS 17028, 2012] is calculated from the *in situ* measurement data. To establish a monopole source level would require correction for the Lloyd's mirror effect and absorption in the water. For example, in the case of ambient sound mapping based on Automatic Identification System (AIS) information for ships, using an 'affected source level' or 'radiated noise level' parameter would introduce significant errors into the estimated noise levels. Similarly, other distributed sources or arrays cannot easily be represented as a point source. Particular examples include pile driving, where the source extends both out of the water and into the seabed, and seismic airgun arrays, which can be made up of many point sources at some depth below the surface.

Note on the use of source level:

Care should be taken when using available or published source level data to ensure it is in the appropriate form, or is the appropriate type of source level for use in the propagation model of choice

4.2 Environmental data availability and its accuracy

Underwater sound propagation is influenced by the local propagation environment, which may vary spatially and temporally. As such the accuracy of a propagation model output relies on representative environmental input data to the model. As discussed in the previous sections, environmental variables such as *bathymetry*, *seabed properties* and *sound speed profile*, for example, all influence the propagating sound and changes in these parameters may lead to considerable differences in the characteristics of the propagated sound. Other more specific model input parameters, such as wind speed, used as a proxy input when surface scattering requires consideration, for example, may also represent a source of uncertainty, and should be considered carefully.

In this section, consideration is given to model input data for bathymetry, sound speed and acoustical seabed characterisation, highlighting some of the most common sources of uncertainty. In addition, the sources of some commonly used, publically accessible environmental data are provided.

4.2.1 Bathymetry

Bathymetry is particularly important for shallower water propagation. It is not just the water depth, which influences the propagation, but also the shape of the seabed. Near continental shelves or in regional seas, the sloping seabed can have a significant influence on the propagating sound.

Very high-resolution bathymetric survey data may be available in some cases, generally in relation to a particular local site, with specific stakeholder interest. Global bathymetry data, or bathymetry data from another source, may then be used for the adjacent areas, outside the spatial extent of the site-specific survey data. Such global bathymetric data may be obtained from the General Bathymetric Chart of the Oceans (GEBCO, http://www.gebco.net/), and is available at a resolution of 30 seconds, or lower.

Whilst higher resolution bathymetry data may provide a fine scale representation capable of capturing small scale seabed features, such as sand waves and ripples, which can influence the propagating sound, these seabed features are dynamic and might be expected to change with time.

Besides the resolution and accuracy of the bathymetry data, the accuracy of the modelled outputs, may also be influenced by the vertical datum. This can typically be based on the mean sea level or the lowest astronomical tide. Whilst this parameter is usually less important in deep water, it can have a significant effect on the assumed water depth in shallow coastal regions, with considerable tidal changes.

Subsequently, tidal variation can be another factor that may require consideration, especially in shallow coastal regions, where tidal variation may correspond to a substantial ratio of the water depth. It is worth noting that tidal variation can be very localised.

4.2.2 Seabed properties

The acoustic properties of the seabed are an important parameter in acoustic propagation modelling in shallow water. In general, they will determine how much sound is reflected from the seabed and how much sound, re-enters the water column after transmission through the seabed. A stratified seabed can, for example, result in bending of the sound waves, and a hard seabed layer, such as rock, can reflect the sound. Both can result in sound energy being retransmitted into the water column.

It is often possible to build the acoustic properties of the sediment (as a half-space, for example), and in some cases the stratification of the seabed, into an acoustic propagation model. However, the accuracy of this is often limited by the availability of the actual data at a sufficient spatial scale and with the necessary resolution such that the data are representative of the actual environment. It can also be challenging, or in some cases not possible, to build the necessary variations with distance into a range dependent acoustic propagation model.

Seabed core data can often provide information of the underlying geology, although the specific characteristic might be localised and it might not be correct to extrapolate this across a broader region.

Seabed survey data may be used to provide information about the upper sediment layer, such as that provided by EMODnet/EUSeaMap (http://jncc.defra.gov.uk/page-5040). However, this sediment information has to be converted into acoustic properties for the seabed and sufficient information is not always available to correlate with published acoustics properties of various sediment types [e.g. Hamilton and Bachman, 1982; Hamilton, 1980; and 1985; Lurton, 2003; Ainslie, 2010].

4.2.3 Sound speed profile

The sound speed profile can have a significant influence on how the sound propagates, especially in deep water. The sound speed profile is dictated by changes in the water temperature, pressure and salinity, with depth. Where there is variation in the sound speed with depth, bending and trapping of the sound can occur, which in some cases can lead to the sound travelling substantially further due to reduced spreading and less interaction with the seafloor and sea surface (sound is trapped in the SOFAR channel, for example).

In shallow water, although the sound speed profile may influence propagation through bending of the sound, the bathymetry and sediment acoustic properties generally constitute the more influential propagation parameters.

The sound speed profile may be measured *in situ*, and may also be obtained from global data sets, such as the data available from the World Ocean Atlas (WOA) database (http://www.nodc.noaa.gov/OC5/indprod.html), providing information about the geographic and seasonally variability.

4.2.4 Sea surface

The rough sea surface, and associated wind-generated bubbles, is usually characterised by means of a wind speed (at a height of 10 m). The conversion, and the resulting effects on propagation, are the subject of ongoing research [Hall 1989; Keiffer et al., 1995; Novarini et al., 1998; Norton and Novarini, 2002; Ainslie, 2005].

4.2.5 Model input data uncertainty

Given that environmental input data are generally limited, and some might be critical to the performance of the acoustic propagation model, it is important to understand the influence that the accuracy of the environmental data has on the outputs of the model, i.e. the uncertainty in the modelled output as a function of the uncertainty associated with the input data. In general, the influence of the uncertainty in the environmental input data on the propagation efficiency may be assessed through sensitivity analysis, where the value of a parameter is varied, with other variables fixed for control. The same approach may be employed to assess the effect of data resolution on the modelled output.

5 Specific considerations for sound mapping

As discussed in previous sections, propagation models compute the propagation loss, which is often used to generate a sound map (i.e. a visual representation of the acoustic field around the source). This relies on the acoustic source information being available in a suitable form for use as an input to the model (this is most often in the form of a monopole source level).

In some cases sound maps might be required which represent multiple sources, for example, shipping sound maps or operational wind farm maps. In this case, the contributions in space may require summation, either coherently or incoherently, to represent the resulting sound field.

The production of a sound map will often specifically require sound propagation over large distances (often tens of kilometres, and sometimes hundreds or even thousands of kilometres), where substantial variations in the propagation environment can be expected (see Section 4.2). This will inherently place demands on the model such as range dependence, and, for a broadband signal, frequency dependence. It will generally also require the model to be computationally efficient particularly if propagation across large spatial scales is considered.

When producing a sound map, consideration needs to be given to the process of gridding the data in terms of spatial resolution. This may be influenced by the resolution in the available bathymetric data. A decision must be made as to whether the model produces data resolved in terms of water depth (such that the acoustic field variation with depth may be calculated), or whether the average of the sound energy with depth is calculated (as produced by an energy flux approach). The former requires considerably more intensive computation. In the azimuthal direction (the plane of the water surface), the grid is typically Cartesian with data calculated for each node in the grid. A grid based on radial transects will suffer decreasing spatial resolution with increasing distance from the source. Propagation over large areas may therefore require higher radial resolutions and interpolation, and it is important that any interpolation undertaken as part of the mapping is acknowledged and clearly described.

It should be noted that sound maps will usually comprise of a series of two-dimensional slices through the water column (distance versus depth) at a succession of bearings, rather than be fully three-dimensional. Consequently, such maps can exhibit “shadow zones” where the modelled sound cannot penetrate behind obstacles such as small islands. When modelling over large areas, particularly in regional seas, the interactions with land masses can become more important (see Section 3.3 for more details on three-dimensional modelling).

6 Benchmarking and experimental validation of propagation models

Many of the freely available propagation models developed over the years have been extensively benchmarked. There have also been a number of workshops and special conference sessions based on model comparisons [e.g. Spofford, 1973; Davis et al., 1982; Felsen, 1986; Felsen, 1987; Jensen and Ferla, 1990; Goh et al., 1997].

An example of a benchmarking comparison is provided here using a Pekeris channel [Pekeris, 1984] with a water depth of 35 m, and a sediment seabed. The acoustic properties of the channel are listed in Table .

Table 1. Parameters of the propagation environment used for underwater sound propagation modelling benchmark presented in Figure 2 and Figure 3.

Propagation medium	Depth (m)	Compressional sound speed (m/s)	Density (kg/m^3)	Compressional sound wave attenuation (dB/wavelength)
Water	35	1490	1000	0
Fine sand	Infinite	1706	1941	0.9

Propagation losses are predicted over a distance of 20 km with ten different calculations at two frequencies, 160 Hz and 1 kHz, shown in Figure 2 and Figure 3, respectively. The modelled propagation loss indicates complicated propagation at close range, with a number of modes, both, propagating, and leaky, contributing to the acoustic field. Higher modes with large grazing angles are subject to more reflection loss from the seabed, and thus decay more rapidly. The modelled results in Figure 2 and Figure 3 show that the pattern of the propagation loss curve becomes more regular, at greater distances from the source, where a smaller number of low order modes are dominant. The resulting propagation losses from each of the models are in very good agreement with the largest discrepancy occurring at the maximum modelled distance of 20 km (about 1 dB from the results of the OASES model, which is used here as a reference).

Such benchmarking comparisons provide critical information on the model accuracy and possible range of application, identifying limitations of certain models, for particular test cases. Ideally, the modelled data should be compared with experimental data and if agreement within the uncertainties can be achieved then this provides considerable confidence in the model. It should, however, be noted that validation against experimental data ideally requires measured acoustic data with minimal uncertainty, and high confidence in the environmental input parameters for the model. Lack of confidence in environmental data may introduce uncertainty in the input parameters of the model, and the predicted results may not be a representative. Published comparisons of modelled propagation loss with in-situ measurement data, such as work by Dosso and Chapman [1984; 1987], for example, increase confidence in the predictive ability of propagation models.

To overcome the significant challenge of carrying out experimental validations over large distances for a range of scenarios and environmental conditions, it is often more practical to carry out the measurements under laboratory conditions. This allows control over the environmental parameters, such that they can be modelled representatively, and further allows greater control over the experimental setup to achieve good uncertainties. These comparisons provide a good reflection of the physical world in its mathematical description

[Wang, 1989; Ainslie et al., 1993; Wang et al., 1994; Collis et al., 2007; Sturm et al., 2007, Rodrıguez et al., 2012]. To simulate long distance propagation in the laboratory environment, the comparison can be simply scaled with frequency. The main drawback of this approach is that the frequency dependent absorption coefficient cannot be scaled and requires correction.

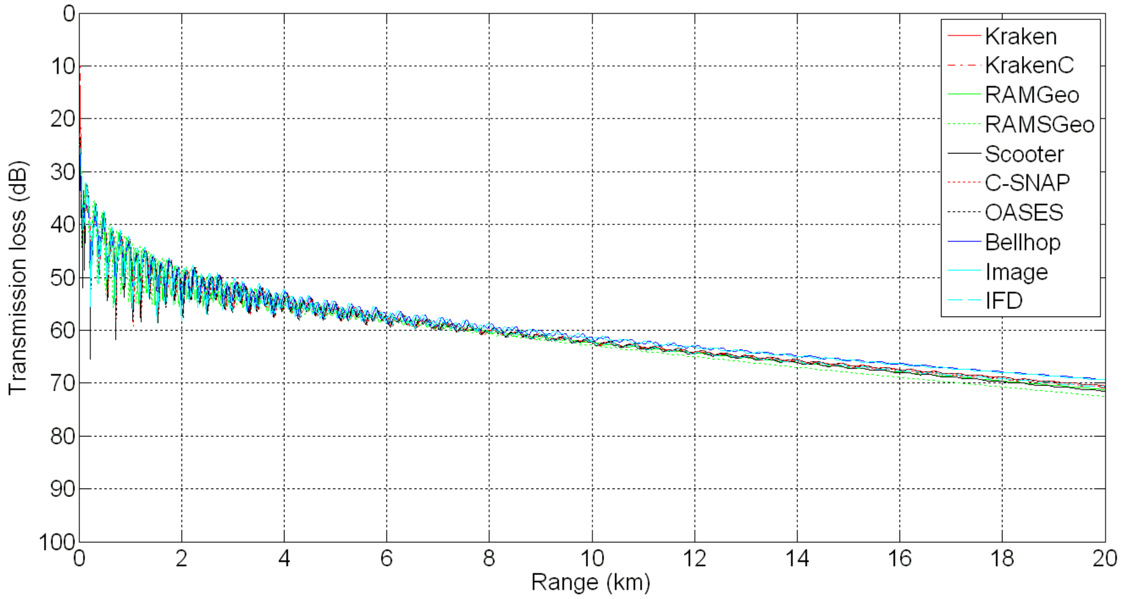

Figure 2: Comparison of modelled propagation loss [dB re 1 m] for a number of commonly used numerical propagation models. Propagation loss is shown as a function of distance for a 160 Hz sound, adopting the model input parameters listed in Table .

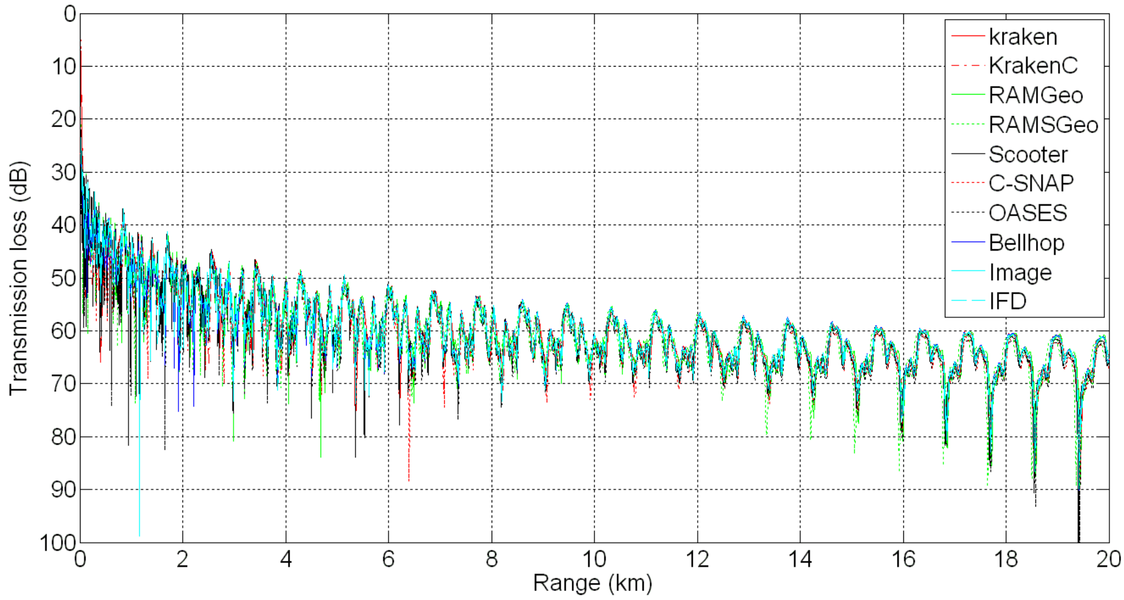

Figure 3: Comparison of modelled propagation loss [dB re 1 m] for a number of commonly used numerical propagation models. Propagation loss is shown as a function of distance for a 1 kHz sound, adopting the model input parameters listed in Table .

7 Conclusions

A number of ‘off-the-shelf’ acoustic propagation modelling solutions have been developed, and are used relatively widely. The solutions, many of which are readily downloadable from different sources, employ particular solutions to the wave equation, all of which have been reviewed here. These solutions each have advantages and disadvantages in relation to their suitable frequency range, water depth, computational requirements and their ability to include range dependent variables, which are summarised in Table 2. Many of these models have been ‘benchmarked’ and in some cases have been compared with measurement data, for particular environments, providing increased confidence in their ability to be used as a predictive utility. However, the accuracy of the modelled output will be critically dependent upon, not just the model used, but also the input parameters used for the model. For underwater acoustic propagation models, these parameters can be extensive and can include, for example, bathymetry, seabed data, sound speed profile, and sea surface roughness. In general, these variables can be obtained from open sources and provide a reasonable approximation, however, the limitations in applying these input data to acoustic propagation models needs to be understood, particularly in relation to sound maps involving large propagation areas.

Table 2: Inventory of some commonly used, freely available, ocean acoustic propagation modelling implementations, outlining the model suitability, with model source reference also provided.

Method	Model Name	Shallow water		Deep water		Range dependent	Availability	Originator
		LF	HF	LF	HF			
Ray	BELLHOP	NO	YES¤	YES‡¤	YES¤	YES¤	http://oalib.hlsresearch.com/Rays/index.html	*M. Porter* Heat, Light, and Sound Research, Inc. La Jolla, CA, USA
Normal mode	Kraken	YES	YES‡	YES‡	NO	YES	http://oalib.hlsresearch.com/Modes/index.html	*M. Porter* SACLANT Undersea Research Centre, Italy
Wave number integration	SCOOTER	YES	YES	YES	YES‡	NO	http://oalib.hlsresearch.com/FFP/index.html	*M. Porter* Heat, Light, and Sound Research, Inc. La Jolla, CA, USA
	OASES	YES	YES	YES	YES‡	YES†	http://lamss.mit.edu/lamss/pmwiki/pmwiki.php?n=Site.Oases	*H. Schmidt* Massachusetts Institute of Technology, MA, USA
Parabolic equation	RAM	YES	NO	YES	YES‡	YES	http://oalib.hlsresearch.com/PE/index.html	*M. Collins* Naval Research Laboratory, Washington, USA
	IFD	YES	NO	YES	YES‡	YES	Ocean Acoustic Propagation by finite difference methods, Pergamon Press, Oxford, 1988	*D. Lee and S. T. McDaniel* Naval undersea warfare centre CA, USA
	MMPE	YES	NO	YES	YES‡	YES	http://oalib.hlsresearch.com/PE/index.html	*F. Tapper and K. Smith* U.S. Naval Postgraduate School, and Rosenstiel School of Marine and Atmospheric Sciences, USA
	P-CAN	YES	NO	YES	YES‡	YES	http://oalib.hlsresearch.com/PE/index.html	*G. Brooke* Defence Research Establishment Atlantic, Canada

‡ Suitable with limitations. † A range dependent version OASES exists, however, it is not freely available.
¤ Requires a suitable, simplified, sound speed profile at any frequency

8 References

Ainslie, M. A., Wang, L. S., Harrison, C. H. and N. G. Pace, 1993, Numerical and laboratory modeling of propagation over troughs and ridges, *J. Acoust. Soc. Am.*, 94, 2287-2295

Ainslie, M. A., Packman, M. N. and C. H. Harrison, 1998, Fast and explicit Wentzel–Kramers–Brillouin mode sum for the bottom-interacting field, including leaky modes, *J. Acoust. Soc. Am*. 103, 1804-1812

Ainslie, M. A., 2005, Effect of wind generated bubbles on fixed range acoustic attenuation in shallow water at 1-4 kHz, *J. Acoust. Soc. Am.*, 118, 3513-3523

Ainslie, M. A., 2010, *Principles of Sonar Performance Modeling*, Springer

ANSI/ASA S.12.64-2009/Part 1, 2009, Quantities and Procedures for Description and Measurement of Underwater Sound from Ships – Part 1: General Requirements, American National Standard Institute, USA

Brekhovskikh, L. M., 1980, *Waves in Layered Media*, 2nd edn., Academic press

Brekhovskikh, L. M. and Y. P. Lysanov, 1982, *Fundamentals of Ocean Acoustics*, Springer-Verlag, Berlin

Boyles, C. A., 1984, *Acoustic Waveguides,* John Wiley and Sons, New York

Bucker, H. P., 1976, Use of calculated sound fields and matched-filed detection to locate sound sources in shallow water, *J. Acoust. Soc. Am., 59*, 368-373

Bucker, H. P., 1994, A simple 3-D Gaussian beam sound propagation model for shallow water, *J. Acoust. Soc. Am.*, 95, 2437-2440

Buckingham, M. J., 1992, Ocean-acoustic propagation models, *J. Acoustique*, 223-287

Collins, M. D., 1993a, The adiabatic mode parabolic equation, *J. Acoust. Soc. Am.*, 94, 2269-2278

Collins, M. D., 1993b, A split-step Pade solution for the parabolic equation method, *J. Acoust. Soc. Am.*, 93, 1936-1942

Collins, M. D., 1993c, User's Guide for RAM Versions 1.0 and 1.0p, Naval Research Laboratory, Washington, DC

Collins, M. D., McDonald, B. E., Heaney, K. D. and W. A. Kuperman, 1995, Three-Dimensional Effects in Global Acoustics, *J. Acoust. Soc. Am.*, 97, 1567-1575

Collins, J. Siegmann, W., Collins, M., Simpson, H. and R. Soukup, 2007, Comparison of simulations and data from a seismo-acoustic tank experiment," *J. Acoust. Soc. Am*. 122, 1987–1993

Cornuelle, B. D., Munk, W. and P. F. Worcester, 1989, Ocean acoustic tomography from ships, *J. Geophys. Res.*, 94, 6232-6250

Davis, J. A., White, D. and R. C. Cavanagh, 1982, NORDA Parabolic Equation Workshop. Report TN-143, Naval Ocean Research and Development Activity, NSTL Station, MS

DiNapoli, F. R. and R. L. Deavenport, 1980, Theoretical and numerical Green's function field solution in a plane multi layered medium, *J. Acoust Soc. Am.*, 67, 92-105

Dosso, S. E. and N. R. Chapman, 1984, Acoustic propagation in a shallow sound channel in the Northeast Pacific Ocean, *J. Acoust. Soc. Am.*, 75, 413-418

Dosso, S. E. and N. R. Chapman, 1987, Measurement and modeling of downslope acoustic propagation loss over a continental slope, *J. Acoust. Soc. Am.*, 81, 258-268

Duncan, A. J. and A. L. Maggi, 2006, A consistent, User friendly interface for running a variety of underwater acoustic propagation codes, *Proc. of Acoustics*, 471-477

Etter, P. C., 2013, *Underwater Acoustic Modeling and Simulation*, 4th edn,. CRC Press

Evans, R. B., 1983, A coupled mode solution for acoustic propagation in a waveguide with stepwise depth variations of a penetrable bottom, *J. Acoust. Soc. Am.*, 74, 188-195

Felsen, L. B., 1986, Quality assessment of numerical codes, part 2: benchmarks. *J. Acoust. Soc. Am. Suppl 1.*, 80, S36–S37

Felsen, L. B., 1987, Numerical solutions of two benchmark problems. *J. Acoust. Soc. Am. Suppl 1.*, 81, S39–S40

Ferla, C. M., Porter, M. B. and F. B. Jensen, 1993, C-SNAP: Coupled SACLANTCEN normal mode propagation loss model, SACLANTCEN SM-274, Le Spazia

Goh, J. T. and H. Schmidt, 1996, A hybrid coupled wave-number integration approach to range-dependent seismoacoustic modelling, *J. Acoust. Soc. Am.*, 100, 1409-1420

Goh, J. T, Schmidt, H., Gerstoft, P., and W. Seong, 1997, Benchmarks for Validating Range-Dependent Seismo-Acoustic Propagation Codes, *IEEE J. Ocean Eng.*, 22, 226-236

Hall, M. V., 1989, A comprehensive model of wind-generated bubbles in the ocean and prediction of the effects on sound propagation at frequency up to 40 kHz, *J. Acoust. Soc. Am.*, 86, 1103-1117

Hamilton, E. L., 1980, Geoacoustic modelling of the sea floor. *J. Acoust. Soc. Am.*, 68(5), 1313-1340

Hamilton, E. L. and R. T. Bachman, 1982, Sound velocity and related properties of marine sediments, *J. Acoust. Soc. Am.*, 72, 1891-1904

Hamilton, E. L., 1985, Sound velocity as a function of depth in marine sediments, *J. Acoust. Soc. Am.*, 78, 1348-1355

Hardin, R. H. and F. D. Tappert, 1973, Application of split-step Fourier method to the numerical solution of nonlinear and variable coefficient wave equation, SIAM Rev. 15, 423

Harrison, C. H., 1989, Ocean propagation models, *App. Acoustics*, 27, 163-201

Harrison, C. H. and J. A. Harrison, 1995, A simple relationship between frequency and range averages for broadband sonar, *J. Acoust. Soc. Am.*, 97, 1314-1317

Harrison, C. H., 2012, Retrieving ray convergence in a flux-like formalism, NATO CMRE 2012

Heaney, K. D., Kuperman, W. A. and B. E. McDonald, 1991, Perth-Bermuda sound propagation, 1960, Adiabatic mode interpretation, *J. Acoust. Soc. Am.*, 90, 2586-2594

Heaney, K. D., Campbell, R. L. and J. J. Murray, 2012, Comparison of hybrid three-dimensional modeling with measurements on the continental shelf, *J. Acoust. Soc. Am.*, 131, 1680-1688

Heitmeyer, R. M., 2006, A probabilistic model for noise generated by breaking waves, *J. Acoust. Soc. Am.*, 119, 3676-3693

Helble, T. A., D'Spain, G. L., Hildebrand, J. A., Campbell, G. S., Campbell, R. L. and K. D. Heaney, 2013, Site specific probability of passive acoustic detection of humpback whale calls from single fixed hydrophones, *J. Acoust. Soc. Am.*, 134, 2556-2571

Holland, C. W., 2010, Propagation in a waveguide with range-dependent seabed properties, *J. Acoust. Soc. Am.*, 128, 2596-2609

ISO/PAS 17208-1:2012 Acoustics — Quantities and procedures for description and measurement of underwater sound from ships. Part 1: General requirements for measurements in deep water, International Organization for Standardisation, Geneva, 2012.

Jensen, F. B., and C. M. Ferla, 1990, Numerical solutions of range-dependent benchmark problems in ocean acoustics. *J. Acoust. Soc. Am.*, 87, 1499–1510

Jensen, F. B., Kuperman, W. A., Porter, M. B., and H., Schmidt, 1997, *Computational Ocean Acoustics*, Springer (reprinted from 1994 AIP Press)

Jensen, F. B., Kuperman, W. A., Porter, M. B., and H. Schmidt, 2011, *Computational Ocean Acoustics*, 2nd edn., Springer

Keiffer, R. S., Novarini, J. C. and Norton, G. V., 1995, The impact of the background bubble layer on reverberation-derived scattering strengths in the low to moderate frequency range, *J. Acoust. Soc. Am.* 97, 227-234

Keller, J. B., 1962, Geometrical Theory of Diffraction, *J. Opt. Soc. Am.*, 52, 116–130

Kewley, D. J., Lam, S. F. and G. Gartrell, 1983, Practical solutions of the parabolic equation model for underwater acoustic wave propagation, Computational Techniques and Applications, ed. J. Noyes Sidney, Amsterdam, 669-684

Kutschale, H. W., 1973, Rapid computation by wave theory of propagation loss in the Arctic Ocean, Report No. CU-8-73, Columbia University, Palisades, New York

Lee, D., and G. Botseas, 1982, IFD: An implicit finite-difference computer model for solving the parabolic equation, US Naval Underwater System Centre TR No 6659

Lee, D., and A. D. Pierce, 1995, Parabolic equation development in recent decade, *J. Comp. Acoust.*, 3, 95-173

Lee, D., Pierce, A. D., E. C. Shang, 2000, Parabolic equation development in the twenty century, *J. Compu. Acoust.*, 8, 527-637

Lichte, H., 1919, Über den Einfluß horizontaler Temperaturschichtung des Seewassers auf die Reichweite von Unterwasserschallsignalen, *Physikalische Zeitschrift*, 17, 385-389

Lurton, X., 2003, *An introduction to underwater acoustics*, Elsevier

McDonald, M. A. and C. G. Fox, 1999, Passive acoustic methods applied to fin whale population density estimation, *J. Acoust. Soc. Am.*, 105, 2643-2652

Merchant, N. D., Blondel, P., Dakin, D. T. and D. T. Dorocicz, 2012, Averaging underwater noise levels for environmental assessment of shipping, *J. Acoust. Soc. Am.*, 132(4), EL343-349

Munk, W. and C. Wunsch, 1979, Ocean acoustic tomography: a scheme for large scale monitoring, *Deep Sea Res. (A)*, 26, 123-161

Nagl, A, Uberall, H., Haug A. J. and G. L. Zarur, 1978, Adiabatic mode theory of underwater sound propagation in a range-dependent environment, *J. Acoust. Soc. Am.*, 63, 739-749

Norton, G. V. and Novarini, J. C., 2002, Including attenuation and dispersion in time domain modeling of broadband sound propagation in dispersive oceanic media, *J. Acoust. Soc. Am.*, 111 (5), 2352-2352

Novarini, J. C., Keiffer, R. S., Norton, G. V., 1998, A model for variations in the range and depth dependence of the sound speed and attenuation induced by bubble clouds under wind-driven sea surfaces, *IEEE Journal of Oceanic Engineering*, 23, 423 - 438

Officer, C. B., 1958, Introduction to the Theory of Sound Transmission, McGraw-Hill, New York

Pekeris, C. L., 1948, Theory of propagation of explosive sound in shallow water, *Geol. Soc. Am. Mem.*, 27

Porter, M. B. and H. P. Bucker, 1987, Gaussian beam tracing for computing ocean acoustic fields. *J. Acoust. Soc. Am.*, 82 (4), 1349-1359

Porter, M. B., 1991, "The KRAKEN normal mode program", SACLANT Undersea Research Centre Memorandum (SM-245) / Naval Research Laboratory Mem. Rep. 6920.

Porter, M. B., 2001, *The KRAKEN normal mode program*, SACLANT Undersea Research Centre

Porter, M. B., 2007, Acoustics Toolbox, Available fromhttp://oalib.hlsresearch.com/FFP/index.html

Porter, M. B., 2011, *The BELLHOP Manual and User's Guide: Preliminary Draft,* Heat, Light, and Sound Research, Inc., La Jolla, CA, USA

Potter, J. R., Mellinger, D. K. and C. W. Clark, 1994, Marine mammal call discrimination using artificial neural networks, *J. Acoust. Soc. Am.*, 96, 1255-1362

Preisig, J. C. and T. F. Duda, 1997, Coupled Acoustic Mode Propagation Through Continental-Shelf Internal Solitary Waves, *IEEE J. Ocean Eng.*, 22, 256-270

Rauch, D., 1980, Experimental and theoretical studies of seisimic interface waves in coastal waters, *Bottom Interacting Ocean Acoustics*, W. A. Kuperman and F. B. Jensen Eds, Plenum Press, New York. 307-327

Rodrıguez, O. C., Collis, J. M., Simpson, H. J., Ey, E., Schneiderwind, J. and P. Felisberto, 2012, Seismo-acoustic ray model benchmarking against experimental tank data, *J. Acoust. Soc. Am.,* 132, 709-717

Schmidt, H., 1984, Modelling of pulse propagation in layered media using a new fast field program, Hybrid Formulation of Wave Propagation and Scattering, L.B. Felsen Ed., Martinus Nijhoff, Dordrecht, The Netherlands, 337-356

Schmidt, H. and F. B. Jensen, 1984, An efficient numerical solution technique for wave propagation in horizontally stratified ocean environments, Saclant ASW Research Centre Memo. SM 173

Schmidt, H. and F. B. Jensen, 1985, A full wave solution for propagation in multilayered viscoelastic media with application to Gaussian bean reflection and fluid-solid interfaces, *J. Acoust. Soc Am.,* 77, 813-825

Schmidt, H., 1987, SAFARI (Seismo-acoustic fast field for range-independent environments) User's Guide, SACLANT ASW Research Centre, La Psezia, Italy

Schmidt, H., 2004, OASES, User Guide and Reference Manual, ver 3.1, MIT

Simons, D., McHugh, R., Snellen, M., McCormick, N. H. and E. A. Lawson, 2001, Analysis of Shallow-Water Experimental Acoustic Data Including Comparison With a Braodband Normal Mode Propagation Model, *IEEE J. Ocean Eng.*, 26(3), 308-323

Sertlek, O. and M. A. Ainslie, 2013, Propagation loss model comparisons on selected Scenarios from the Weston memorial workshop, UAC2013, 441-447

Sertlek, O. and M. A. Ainslie, 2014, A depth-dependent formula for shallow water propagation, *J. Acoust. Soc. Am.*, (In press).

Spofford, C. W., 1973, A synopsis of the AESD Workshop on Acoustic Propagation Modeling by Non-Ray-Tracing Techniques. Report TN-73-05, Office of Naval Research, Washington DC

Stafford, K. M., Fox, C. G. and D. S. Clark, 1998, Long-range acoustic detection and localization of blue whale calls in the northeast Pacific Ocean, *J. Acoust. Soc. Am.,* 104, 3616-3625

Sturm, F., Sessarego J.-P. and D. Ferrand, 2007, Laboratory scale measurements of across-slope sound propagation over a wedge-shaped bottom, *2nd International Conference & Exhibition on Underwater Acoustic Measurements: Technologies & Results*, FORTH, Heraklion, Crete, Greece, 25-29 June 2007, edited by John S. Papadakis and Leif Bjorno, Vol. III, 1151-1156

Tamir, T., and H. L. Bertoni, 1971, Lateral Displacement of Optical Beams at Multilayered and periodic structures, *J. Opt. Soc. Am.,* 61, 1397-1413

Tappert, F, D., 1977, The parabolic approximation method, in Wave Propagation and Underwater Acoustics. vol. 70, J. B. Keller and J. S. Papadakis, Eds., 224-287

Thode, A., 2004, Tracking sperm whale (*Physer macrocephalus*) dive profiles using a towed passive acoustic array, *J. Acoust. Soc. Am.,* 116, 245-254

Tindle, C. T., Stamp, A. P., and Guthrie, K. M., 1976, Virtual modes and the surface boundary condition in underwater acoustics, *J. Sound Vib.* 49, 231–240.

Tindle, C. T. and Z. Y. Zhang, 1997, An adiabatic normal mode solution for the benchmark wedge, *J. Acoust. Soc. Am.*, 101, 606-609

Tindle, C. T., 2002, Wavefronts and waveforms in deep-water sound propagation, *J. Acoust. Soc. Am.* 112, 464-475

Tolstoy, I. and C.S. Clay, 1966, Ocean Acoustics: Theory and Experiment in Underwater Sound, McGraw-Hill, New York

Wang, L. S., 1989, *Sound propagation in wedge shaped channels*, Ph.D. thesis, University of Bath, Bath, England

Wang, L. S., Ainslie, M. A., Pace, N. G. and C. H. Harrison, 1994, Sound propagation in shallow warer environments, *Ultrasonics,* 32, 141-147

Weinberg, H., 1975, Application of ray theory to acoustic propagation in horizontally stratified oceans, *J. Acoust. Soc. Am.,* 58 (1), 97-109

Weinberg, H. and R. E. Keenan, 1996, Gaussian ray bundles for modeling high-frequency propagation loss under shallow-water conditions, *J. Acoust. Soc. Am.*, 100 (3), 1421-1431

Wenz, G. M., 1962, Acoustic ambient noise in the ocean: spectra and sources, *J. Acoust. Soc. Am.*, 34, 1936-1956

Weston, D. E., 1959, Guided propagation in a slowly varying medium. Proceedings of the Physical Society, 73(3), 365

Weston, D. E., 1968, Sound Focusing and beaming in the interference field due to several shallow-water modes, *J. Acoust. Soc. Am.*, 44, 1706-1712

Weston, D. E., 1980, Acoustic flux formulas for range-dependent ocean ducts, *J. Acoust. Soc. Am.*, 68 (1), 269-281

White, D. W. and M. A. Pedersen, 1981, Evaluation of shadow zone fields by uniform asymptotics and complex rays, *J. Acoust. Soc. Am*., 69, 1029–1059

Worcester, P. F., Cornuelle, B. D., Dzieciuch, M. A., Munk, W. H., Howe, B. M., Mercer, J. A., Spindel, R. C., Colosi, J.A., Metzger, K., Birdsall T.G., and A. B. Baggeroer, 1999, A test of basin-scale acoustic thermometry using a large aperture vertical array at 3250 km range in the eastern North Pacific Ocean, *J. Acoust. Soc. Am.*, 105, 3185-3201

Appendix A Energy flux (Weston) model

Appendix A Table 1: Propagation loss by Weston model

Spherical	$TL = 10\log[R^2]$	R<H_a/2θ_c
Channelling	$TL = 10\log[RH_aH_b/2H_c\theta_c]$	H_a/2θ_c<R<6.8H_a/α θ_c^2
Mode stripping	$TL = 10\log\left[RH_aH_b\left(\alpha\int_0^R \frac{dR}{H^3}\right)^{1/2}/5.22\right]$	6.8H_a/α θ_c^2<R<27$k^2H_a^3/(2\pi)^2\alpha$
Single mode	$TL = 10\log[RH_a\,H_b/\lambda] + \frac{\lambda^2\alpha}{8}\int_0^R \frac{dR}{H^3}$	R>27$k^2H_a^3/(2\pi)^2\alpha$

where H_a is the depth at source, H_b is the depth at receiver, H_c is the minimum depth along the bathymetry profile. θc is the critical angle given as in Eq. 1, α is the seabed reflection loss gradient (loss per unit angle in dB/rad), k=2π/λ is the wave number and λ is the wave length of the signal. The water depth has to be deep enough to support at least one mode, for example, for the lowest mode: $H\sin\theta_c > \frac{\pi-\rho_{sed}/\rho_w}{2\pi}$, where ρ_w and ρ_{sed} are density of water and sediment.

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TNO 2014 R11167 | Final report

Use of Sound Maps for monitoring GES: Examples and way ahead

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Copy no	
No. of copies	
Number of pages	35 (incl. appendices)
Number of appendices	
Sponsor	
Project name	SVOW - CEFAS Tender C6082
Project number	060.04880

Contents

1. Introduction

1.1 Background

The Marine Strategy Framework Directive (MSFD) requires EU Member States to achieve or maintain Good Environmental Status (GES) by the year 2020. One of eleven descriptors (Descriptor 11) of GES is:

"Introduction of energy, including underwater noise, is at levels that do not adversely affect the marine environment"

The 2010 Commission Decision [EC, 2010] published two Indicators of Descriptor 11, one of which (Indicator 11.1.1) is related to sources of impulsive sound and the other (Indicator 11.2.1) to continuous low frequency sound. This second Indicator is of particular relevance to this report, and for this reason is reproduced here asFigure 1.

11.2. Continuous low frequency sound

— Trends in the ambient noise level within the 1/3 octave bands 63 and 125 Hz (centre frequency) (re 1μPa RMS; average noise level in these octave bands over a year) measured by observation stations and/or with the use of models if appropriate (11.2.1).

> *Indicator 11.2.1: Trends in the annual average of the squared sound pressure associated with ambient noise in each of two third octave bands, one centred at 63 Hz and the other at 125 Hz, expressed as a level in decibels, in units of dB re 1 μPa, either measured directly at observation stations, or inferred from a model used to interpolate between or extrapolate from measurements at observation stations* [Van der Graaf, 2012].

Figure 1: Indicator 11.2.1, upper: [EC, 2010] and lower: as interpreted by expert advisory group Technical Sub-Group (TSG) Noise [Dekeling et al, 2014a]

Indicator 11.2.1 requires EU Member States to monitor trends in ambient noise. This monitoring is to be achieved by an appropriate combination of modelling and measurement. While there is no explicit requirement on Member States to monitor shipping noise, the two one-third octave bands centred at 63 Hz and 125 Hz were chosen to be representative of shipping [Dekeling et al, 2014b].

The use of sound propagation models for generating sound maps has been the theme of three recent sound mapping workshops: The Cetaceans and Sound ('Cetsound') workshop in Washington, USA [cetsound (Washington)], a collaboration between the two EU-funded projects [AQUO] and [SONIC] in Madrid, Spain [Aquo-Sonic (Madrid)], and an international workshop held in Leiden, Netherlands, [Anon., 2014]. This use was also the theme of one of the invited experts during the Noise Impact Workshop held in Brussels [Borsani, 2014], Task 2 of the present project.

This report first presents a range of sound maps. These have been generated with the aim of showing the predicted contribution from shipping on the Dutch North Sea (Sec. 0), and were derived using the Aquarius sound mapping framework (see Sec. 0). Further, a comparison of model predictions with measurements (Sec. 0) is presented. The report concludes with a Roadmap (Sec. 0) describing a proposed way ahead towards use of sound maps for assessment of Descriptor 11 (Indicator 11.2.1) of GES.

1.2 Objective

In September 2013, the European Commission commissioned a project entitled Impacts of Noise and use of Propagation Models to Predict the Recipient Side of Noise (project number 1109.05/659011/SER/C.2), under a Framework Service Contract (ENV.D2/FRA/2012/0025) with the subject ‘Emerging pressures, human activities and measures in the marine environment (including marine litter), led by Cefas. The project consortium members include Cefas, NPL, TNO, OASIS and JNCC (later in an advisory role).

This report is the deliverable of Task 5, ‘Develop sound maps’, of the above project, its aim being “to obtain state of the art sound maps, identify gaps in capability, and to develop a strategy for filling those gaps to cover all EU locations of interest and for all sound sources of relevance to Descriptor 11 of Good Environmental Status, in particular for Indicator 11.2.1.”

2 Sound maps: contribution due to shipping in the Dutch North Sea

2.1 Introduction

In this section, maps are presented of annually averaged sound pressure level (SPL) due to shipping (using annually averaged shipping density from Automatic Identification System (AIS) data) in one decidecade band (a decidecade is a frequency ratio equal to one tenth of a decade). This quantity is referred to above as a “one-third octave”, following widespread common practice, because it is approximately equal to one third of an octave [ISO 266, 1997], [IEC 61260, 1995]. In the remainder of this Report, the more precise term decidecade is used [ISO/CD 18405].

2.2 Methodology

TNO has developed the sound mapping framework Aquarius for generating underwater sound maps. While the framework was developed for modelling shipping sound, it can also be used to model other anthropogenic underwater sound sources such as airguns and explosives. The framework is coupled to various external databases to define the environment .

The sound maps presented in this section are based on an average distribution of ships in the exclusive economic zone (EEZ) of the Netherlands. The average shipping density map (see Figure 2) shows the average number of ships of a certain class within a grid cell for a specified time interval. This makes it possible to approximate the temporally averaged SPL in a computationally efficient way.

The Aquarius sound mapping framework, originally developed using Weston’s flux theory [Weston, 1976] for a review of North Sea underwater sound sources in 2009 [Ainslie et al, 2009], has recently being enhanced to incorporate depth-dependent wave theory corrections using a hybrid propagation algorithm based on mode and flux theories [Sertlek & Ainslie 2014a]. It was used to compute the propagation loss. See [Wang et al, 2014] for an up-to-date review of propagation models for sound mapping. The number of discrete modes is chosen to provide accuracy at low frequency without a large computational overhead. This modelling approach is fast and accurate (see Section 0 on validation) for broadband calculations in iso-velocity water. It also takes into account range dependent water-depth and sediment type. It calculates the incoherent propagation loss, including the depth dependent properties, using wave theory. Various other acoustic propagation models are included in the sound mapping framework. This makes it possible to compare different propagation models and numerically validate the selected modelling approach. This approach also allows the use of different models for different frequencies, optimizing both accuracy and computation time. As the propagation loss is calculated 2D (range versus depth), it is only possible to approximate a 3D distribution of the SPL by means of interpolation from 2D slices, referred to as the “N×2D” approach.

The modular character of the sound mapping tool allows fast computation of sound maps for a wide range of frequencies and on a large spatial scale, while maintaining the flexibility to study more complex, computationally expensive scenarios.

2.3 Inputs

Various inputs are required for the computation of the annual average shipping sound maps.
Ships are modelled as point sources at a specified depth below the sea surface and a specified source level. The source level of each ship is calculated using the model by [Wales and Heitmeyer, 2002]. For the case study from the Dutch North sea presented here, the source depth consistent with use of the Wales-Heitmeyer source level was estimated as 5 m below the sea surface, based on information from [Gray & Greeley, 1980] and [Arveson & Vendittis, 2000]. The spatial distribution of the shipping traffic was computed using a density map for the year 2007 (generated by MARIN and provided to TNO via IMARES). Ships outside of the Dutch EEZ were not taken into account. The density grid with a resolution of 5 km by 5 km was used, obtained from a sequence of AIS snapshots separated by 2 minutes in time. An 'AIS snapshot' is a map displaying all locations off ships fitted with AIS transponders for an instant in time.) AIS is an automatic tracking system used on ships and by vessel traffic services for identifying and locating vessels by electronically exchanging data with other nearby ships, AIS base stations, and satellites. The International Maritime Organization's International Convention for the Safety of Life at Sea requires AIS to be fitted aboard international voyaging ships with gross tonnage of 300 or more, and all passenger ships regardless of size. All EU fishing boats over 16 m length are required to have AIS. Hence, an AIS snapshot gives a good, though not necessarily complete, indication of the instantaneous shipping density. Figure 2 illustrates the annually averaged shipping density map for the EEZ in 2007.

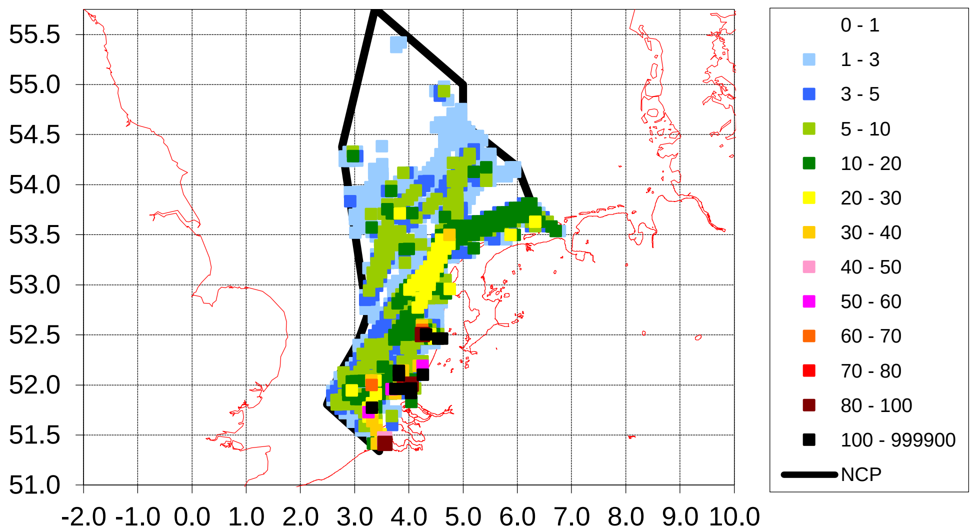

Figure 2: Shipping density map with a resolution of 5 km x 5 km for the year 2007. The values in the legend indicate the annual average shipping density in ships/1000 km^2) . The axes represent latitude and longitude (WGS84).

The environment is defined by the bathymetry, the physical properties of the seabed and water, and the roughness of the sea surface. The bathymetry was obtained from the EMODnet portal for Bathymetry [EMODnet, 2014]. This dataset contains data from the local hydrography offices, improving the base GEBCO dataset with a resolution of 1/8 min. The effects of surface scattering and bubbles on sea surface reflection loss have been modelled using Eq. 8.22 of [Ainslie, 2010] and the fourth power averaged local wind speed, i.e., $\left(\overline{v_{10}^4}\right)^{\frac{1}{4}}$. The fourth power is used because reflection loss scales with the fourth power of wind speed [Weston & Ching, 1989, Ainslie 2005]. The water was modelled using a uniform sound speed of c_0=1500 m/s and a density of 1000 kg/m^3. The absorption loss α in dB/km was modelled using the equation of Thorp [Thorp, 1967]. The seabed was modelled as medium sand with a compressional sound speed c_1=1797 m/s and density ρ_1=2086 kg/m^3 with an absorption given by α_b=0.88 dB/λ [Ainslie, 2010].

2.4 Sound maps

Maps are shown (see Figure 3) for SPL in decidecades with nominal centre frequencies 125 Hz, 1 kHz and 8 kHz and for broadband SPL. Precise centre frequencies follow [IEC 61260, 1995]. Broadband SPL maps (all decidecades with centre frequencies between 32 Hz and 80 kHz) are given with and without M-weighting, for pinnipeds in water and cetaceans [Southall et al, 2007] (see Figure). In all cases the receiver depth is 2 m above the seabed.

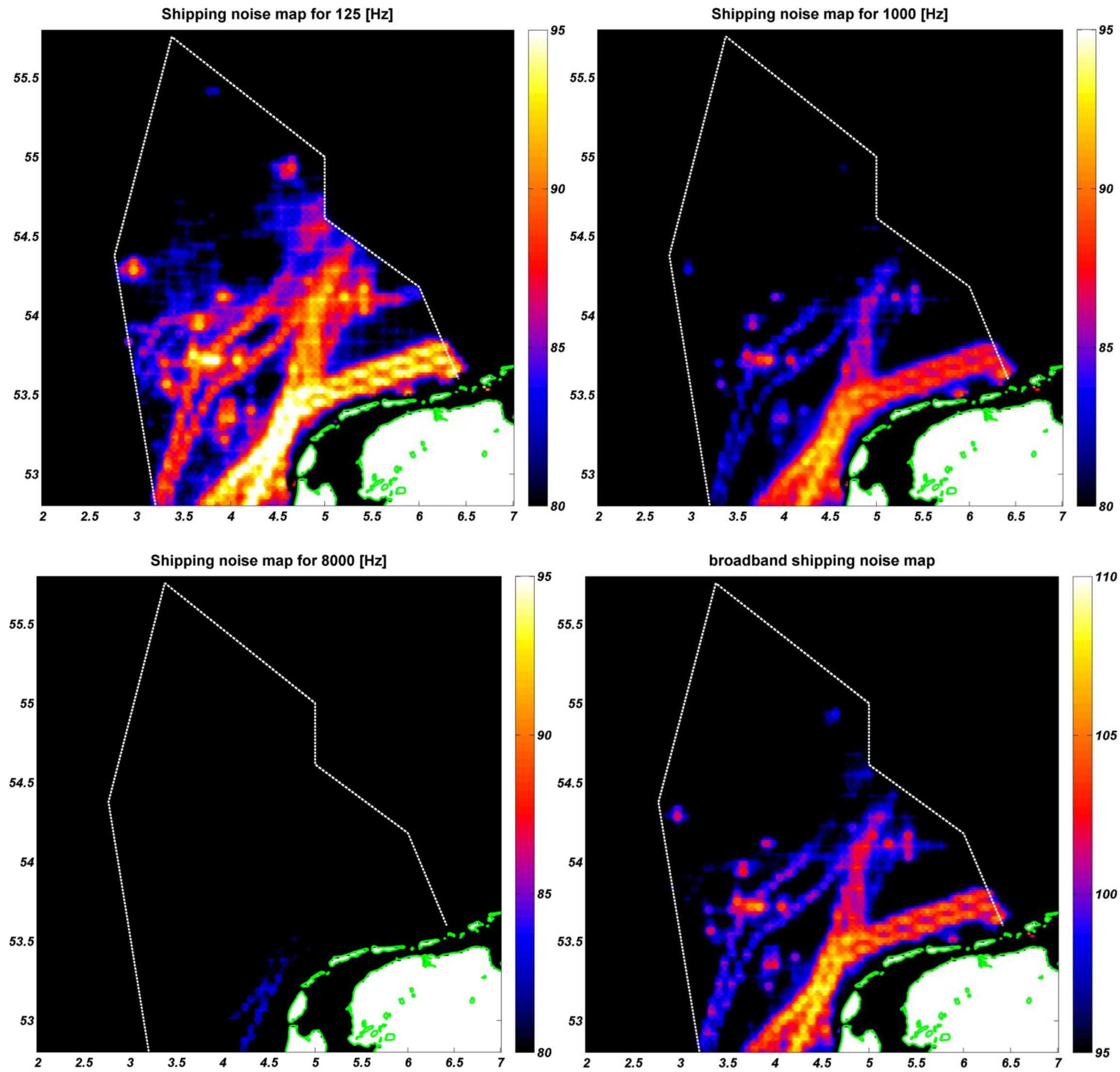

Figure 3: Shipping sound maps: unweighted SPL [dB re 1 μPa] in decidecades centred at 125 Hz (upper left), 1 kHz (upper right), and 8 kHz (lower left); unweighted broadband SPL (lower right). The green border indicates the land boundary and the white border the Exclusive Economic Zone (EEZ) of the Netherlands.

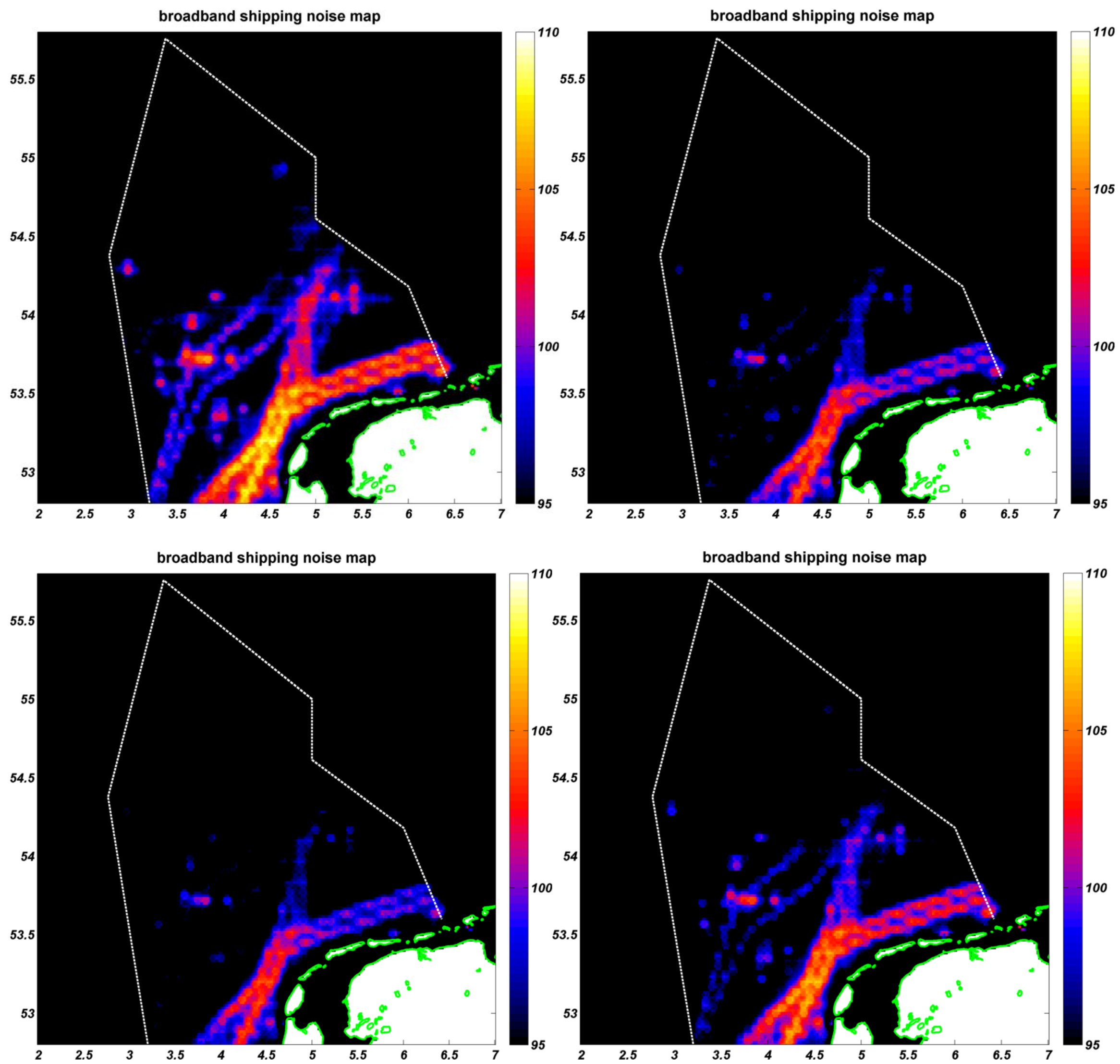

Figure 4: Shipping sound maps. Broadband M-weighted SPL [dB re 1 μPa]: for low-frequency (LF) cetaceans (upper left), mid-frequency (MF) cetaceans (upper right), high-frequency (HF) cetaceans (lower left), and pinnipeds in water (lower right). The green border indicates the land boundary and the white border the Exclusive Economic Zone (EEZ) of the Netherlands.

3 Validation

3.1 Background

Section 3 presents the work undertaken to quantify the accuracy of Aquarius, and its sensitivity to uncertainties of the environment and the source models. This model validation was done using the underwater sound measurements done in 2009 by TNO for the construction of the “Tweede Maasvlakte”, (Second Maasvlakte, or ‘Maasvlakte 2’ [maasvlakte2, 2014]) an expansion of the Port of Rotterdam port.

Sound pressure was recorded by TNO’s autonomous acoustic measurement system ‘SESAME’ at a fixed location for a period of two weeks (26 September to 6 October 2009), at two depths (2 and 7 m above the seabed) [Ainslie et al, 2012]. Also, for the duration of this measurement, the wind speed and spatial distribution of the shipping traffic were logged. Source levels of the dredgers were taken from a separate set of measurements designed for that purpose [de Jong et al, 2010]. See also Heinis et al, 2013 (risk assessment during Port of Rotterdam construction) for more information.

Measurements presented are for 29 September 2009 between 6:32:08 and 17:40:19 Rotterdam Local time (UTC +01:00), for the receiver at height 2 m from the seabed.

3.2 Methodology

In contrast to the shipping density maps used for Section 0, snapshots were computed for the validation. The advantage of using snapshots is that this allows studying the temporal variability and statistics of the sound, allowing the direct validation of the propagation loss if the source level is known. The disadvantage of introducing the temporal variability is the increased computational effort. The computational effort can be reduced by pre-computing the propagation loss (PL) in a lookup table. However, in order to keep the data size of the PL lookup table within bounds, compromises are required in the number of dimensions. The preferred modelling approach is therefore dependent on the application.

3.3 Inputs

Various inputs are required for the computation of the snapshots.

The source level spectra of the dredgers were reported in [de Jong et al, 2010]. Levels were measured for passing, dredging, direct sand dumping, rainbowing and pumping. Depending on the speed and location of the dredgers (in combination with a log describing the activities of the dredgers), the most appropriate source level was estimated. For ships for which no measured source level was available, the [Wales and Heitmeyer, 2002] spectrum was assumed. The chosen source depth is 4 m below the sea surface for all ships and dredgers [de Jong et al, 2010]. The choice of depth here is driven not by any consideration of the “depth” of a ship, or of any sound source within a ship, but of consistency with the choice of depth for the nominal point source chosen for the original measurement of source level, which in this case was 4 m [de Jong et al, 2010]. The spatial distribution of the shipping traffic was available from

AIS data logged during the measurement campaign. Based on the AIS data it was possible to estimate the speed of the ships. The Wales and Heitmeyer source level model is independent of ship speed, but applies for ships at their regular cruising speed. At that speed the radiated sound is generally dominated by propeller cavitation noise. This sound is absent for stationary ships, unless they are operating propellers or thrusters to maintain their position. For lack of a general model for the radiated machinery noise of stationary ships, ships were assumed to be silent when moving slower than 2 knots.

The environment is defined by the bathymetry, the physical properties of the seabed and water, and the roughness of the sea surface. The bathymetry was obtained from local survey data with a very high resolution. This allows to model blocking of acoustic energy from the sources disappearing behind the long thin curved island shaped like a boomerang (see Figure 5) [Ainslie et al, 2012], which would not be represented in the coarser resolution bathymetry data, and which in any case predates the Maasvlakte 2 construction period. The water was modelled with a uniform sound speed of c_0=1500 m/s and a density of 1000 kg/m^3. The absorption loss in the water was modelled using the equation of Thorp [Thorp, 1967]. The seabed was modelled as medium sand c_1=1797 m/s, ρ_1=2086 kg/m^3 with an absorption given by α_b=0.88 dB/λ [Ainslie, 2010]. The effects of surface scattering and bubbles were modelled using Eq. 8.22 of [Ainslie, 2010], using the local wind speed from a nearby measurement station [Ainslie et al, 2012]. Figure 6 illustrates the bathymetry and photographic images of the considered area.
Wind generated sound was modelled using the areic dipole source factor spectrum from Eq. 8.206 of [Ainslie, 2010].

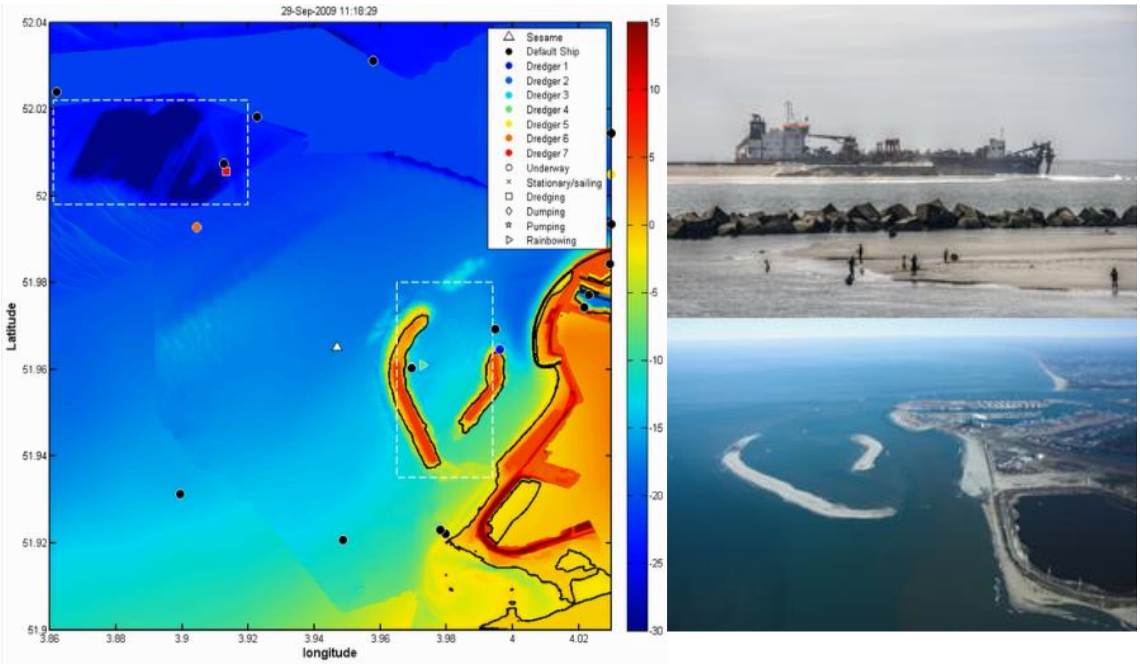

Figure 5: Bathymetry (depth in metres) and distribution of sources and corresponding activities. The white boxes (dashed line) indicate the dredging (top left) and dumping (between the curved sand dunes) regions. The marker symbols indicate the dredger activity and the colour the dredger ID. The black colour indicates unknown ships for which the Wales and Heitmeyer spectrum was used. The white triangle indicated the location of the acoustic measurement system SESAME). The right figures are photographs of the area.

3.4 Model data comparison

Measurements were made at two heights (2 m and 7 m) above the seabed at the Sesame location illustrated in Figure 6. As the measured levels are very similar, the model predictions are only given for 2 m above the seabed, across the entire region, and for decidecade bands between 32 Hz and 80 kHz. Figure illustrates the modelled broadband SPL at 2 m above the seabed. The discontinuities result from the assumption that sound travels in straight horizontal lines, with no refraction or diffraction in the horizontal planes (the so-called “N×2D” approximation). While computing snapshots helps understand the behaviour of the model, the direct model data comparison allows a more detailed understanding of the accuracy. Figure and Figure 8 directly compare the modelled and measured decidecade bands SPLs at the measurement location.

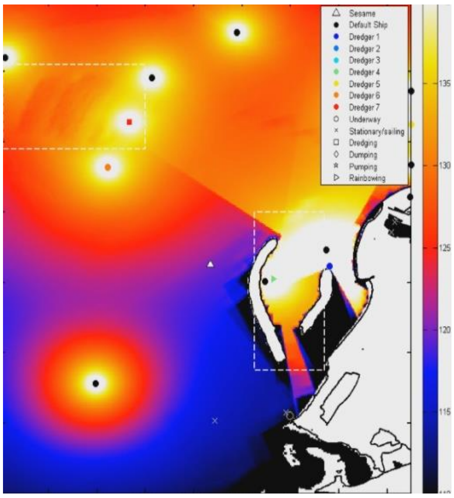

Figure 6: Predicted broadband SPL [dB re 1 □Pa] (32 Hz to 80 kHz) for a snapshot at 11:18:29 local time (UTC +01:00). on 29 September 2014, and the receiver at 2 m above the seabed. The measurement location is located at 51.9652° latitude and 3.9468° longitude.

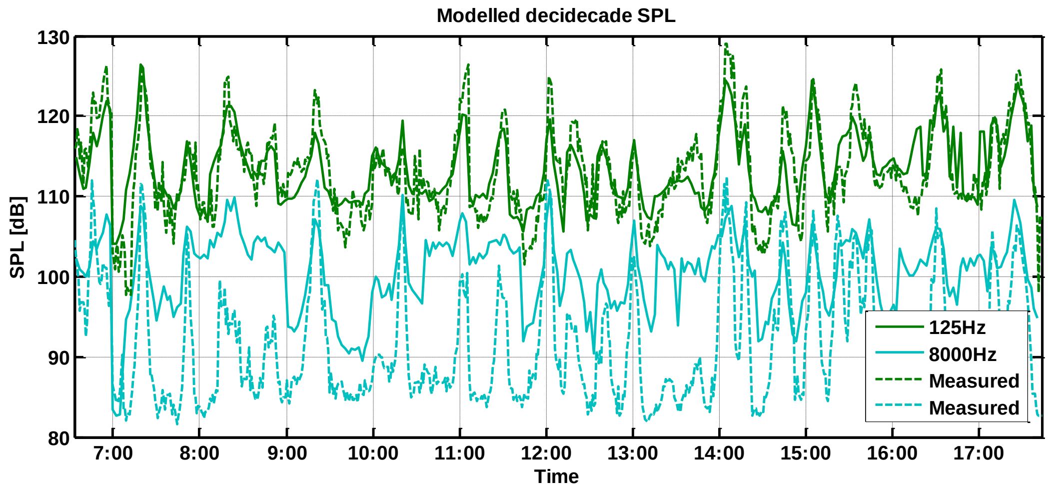

Figure 7: Modelled (solid) and measured (dashed) SPL [dB re 1 µPa] at 2 m above the seabed for the 125 and 8000 Hz decidecade bands at the Sesame location illustrated in Figure . Model predictions are for ship-generated sound only. Date is 29 September 2009 Rotterdam local time (UTC +01:00). The difference between the modelled and measured data are discussed in Section 0.

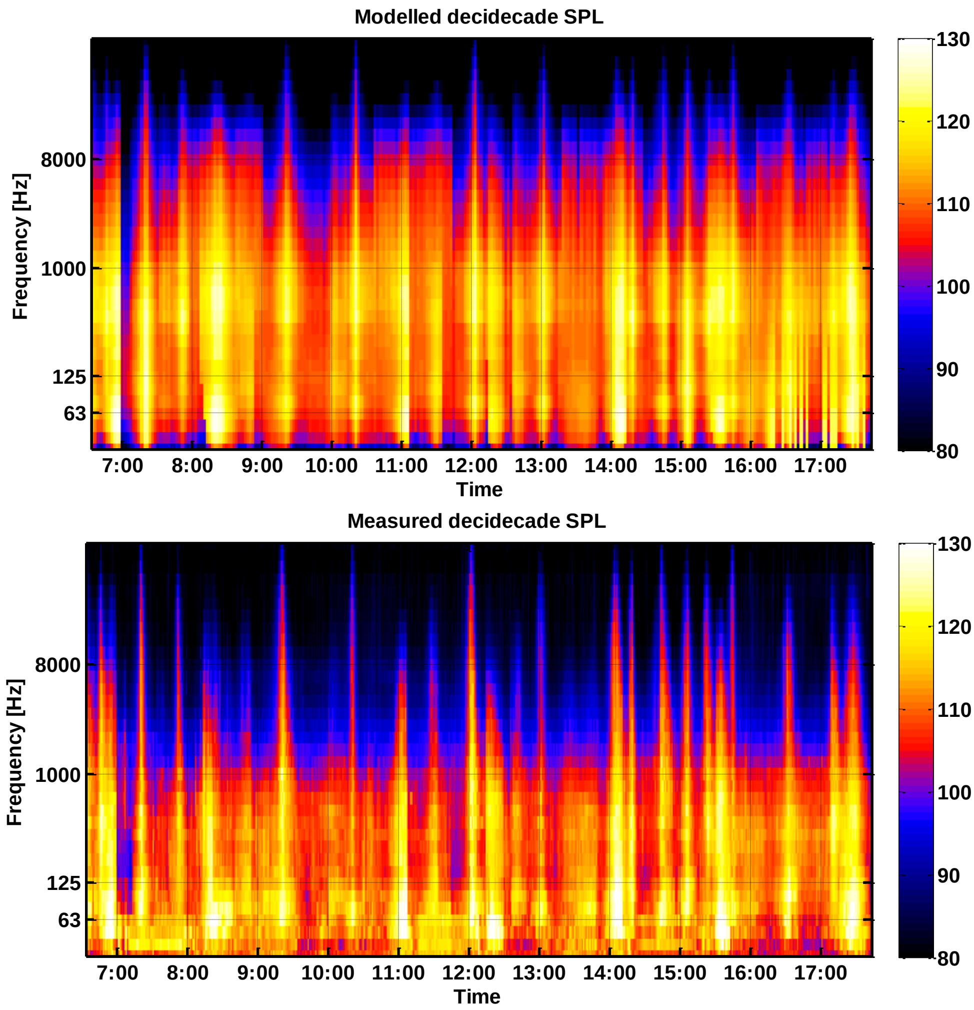

Figure 8: Modelled (top) and measured (bottom) SPL [dB re 1 μPa] at 2 m above the seabed for all decidecade bands (32 Hz up to 80 kHz) at the Sesame location illustrated in Figure 8. Model predictions are for ship-generated sound only. Date is 29 September 2009 Rotterdam local time (UTC +01:00). The differences between the modelled and measured data are discussed in Section 0.

3.5 Comparison with other model(s)

During the Madrid sound mapping workshop [Aquo-Sonic (Madrid)], comparisons were made between the depth average broadband SPL computed with the hybrid method of [Sertlek & Ainslie, 2014a] and other methods, such as the parabolic equation model RAM, for a synthetic shipping distribution in the Skagerrak Sea, north of Denmark for a set of synthetic scenarios with a defined set of environmental parameters. These comparisons will be reported on in the SONIC project. The computation time for generating the sound maps using the hybrid propagation algorithm was in the order of tens of minutes, while the computation time for the RAM model was in the order of days.

For examples demonstrating the accuracy of the propagation model on some synthetic test cases designed to test sonar equation, see [Sertlek & Ainslie, 2013, 2014a, 2014b].

3.6 Accuracy

When computing sound maps, many parameters are uncertain. Uncertainties and assumptions in the snapshot modelling presented in Section 0 result in a discrepancy between modelled and measured levels. This section discusses accuracy of the modelling approach.

3.6.1 Sound generated by shipping

For the Maasvlakte 2 simulation, the source level of seven dredgers was measured for transit, dredging, direct sand dumping, rainbowing and pumping activities [de Jong et al, 2010]. Levels were extrapolated for frequencies where levels were not available using the trends of other dredgers if available. The source level (SL) for frequencies between 8 kHz and 80 kHz were extrapolated linearly in log (frequency) by assuming a constant gradient above 6.3 kHz. For some of the dredgers, the low frequency SL was estimated using the trend from other measured dredgers. The source level of the other ships was approximated using the model by Wales and Heitmeyer at all frequencies. Above 1 kHz, such an extrapolation leads to higher source level than an extrapolation based on the measurements of Arveson & Vendittis [Ainslie, 2010 (p423)]. The directional behaviour of the ship radiated sound was not taken into account, and the ships were all modelled as point sources at 4 m depth. Besides the uncertainty in the source level, also the activity of the ships was estimated based on AIS data. Some useful information can be extracted from AIS data, although the reliability of, for example, the navigation status parameter is dependent on the crew and may not always be accurate.

Hence, the uncertainty in the source level estimation for the individual ships in each snapshot is rather large. Concerning the 'type A' [ISO GUM] statistical uncertainty, [Wales & Heitmeyer, 2002] indicate that 'the standard deviation of the measured spectra on which their model is based varies about a nominal value of about 5.3 dB for frequencies below about 150 Hz and then decreases to a nominal value of about 3.1 dB for frequencies greater than 400 Hz'. The standard deviation of the estimated dredger source levels [de Jong et al, 2010] is about 5 dB. No attempt has been made to quantify the additional 'type B' uncertainty associated with, for example, assumptions about the navigation status of the ships, the lack of speed dependence in the source level model and the extrapolation of the measured source level spectra to higher frequencies.

3.6.2 Environment

The acoustical parameters describing the environment were chosen as realistic as possible based on the available data. No adjustment was made to reduce the difference between the modelled and the measured levels. The surface loss was estimated using the measured local wind speed. The sediment was modelled as a fluid approximating a medium sand seabed, typical for this region [Ainslie et al, 2012].

3.6.3 Model applicability

For frequency-depth combinations very close to cut off where just one mode propagates, it becomes more complicated to predict the propagation loss. At frequencies above 4 kHz, the dependence of propagation loss on surface roughness and wind-generated bubble population is not well understood and requires further investigation [Ainslie, 2005].

Besides the propagation loss applicability, a cause of bias is the absence of other sound sources (e.g., wind [Dreschler et al, 2009]) in the model that contribute to the underwater sound in the measured data. There is evidence in Figure 9 that wind generated sound becomes important above about 10 kHz, especially for the 90 % exceedance level and the median. The effect of ship speed on radiated sound (presently approximated by a sharp cut off for an arbitrary ship speed of 2 knots) needs further investigation.

3.6.4 Quantification of error

Studying the differences between the model and the measurements, it is observed that the adopted modelling approach can accurately predict the sound pressure level at the hydrophone for the lower frequencies. Especially individual passages of dredgers for which the source level was measured are accurately represented. Figure 9 shows the statistics of the measured and modelled levels illustrated earlier in Figure and Figure for an 11 hour period on 29 September 2009. The model tends to underestimate SPL by about 5 dB at low frequency (up to ca. 100 Hz) and overestimate SPL by a similar amount at frequencies above ca. 500 Hz. At higher frequencies still (above 30 kHz) the model underestimates SPL again, by an amount that increases with increasing frequency. The most likely reason for these high frequency errors is the omission of the contribution from wind, the likely magnitude of which is shown by the black line of Figure 9.

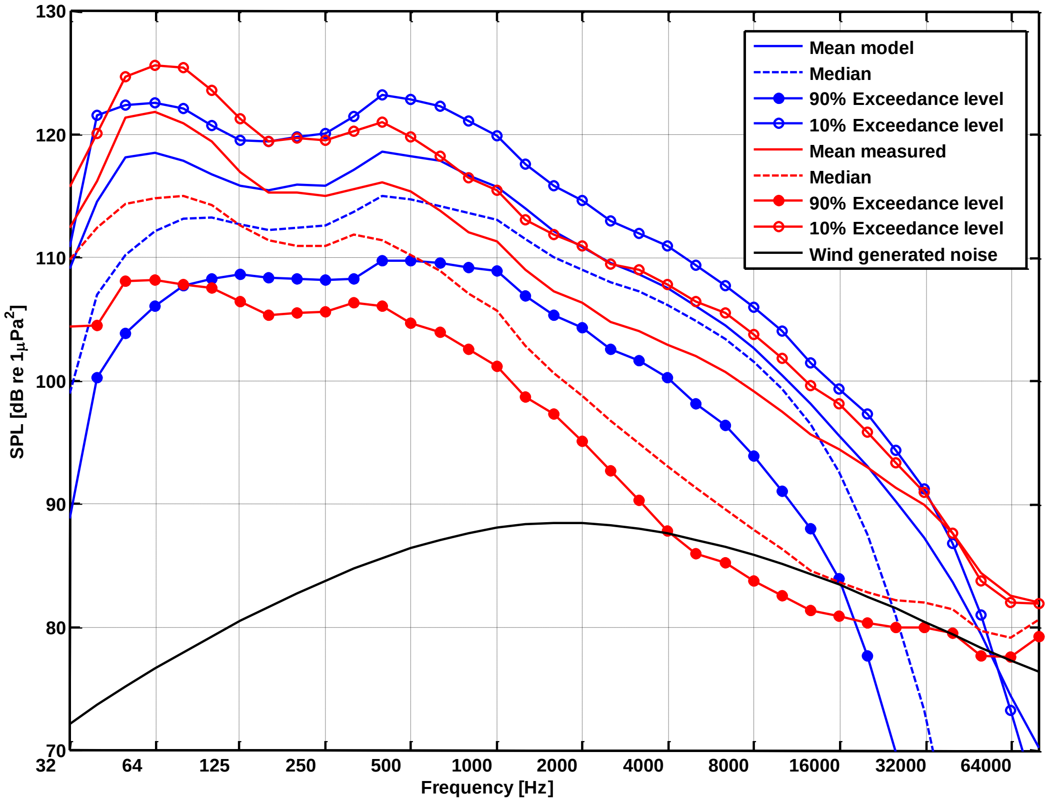

Figure 9: Mean, median and exceedance levels for both the measured and modelled receiver SPL [dB re 1 μPa]. The black curve is the temporally averaged wind generated sound. The modelled results include ship generated sound only. Statistics are for 6 s snapshots, once per minute. The statistics are computed for the distribution of mean-square sound pressure in each 6-second time window.

The most likely explanation for the overestimation of the SPL between 1 kHz and 10 kHz is the treatment of surface reflection loss, which includes the effect of rough surface scattering enhanced by the presence of near-surface bubble clouds [Ainslie, 2005], but neglects the effect of absorption by the bubbles, which at 8000 Hz and above is expected to dominate [APL 1994, Ainslie 2010]

4 Roadmap

The goal of this roadmap is to describe an approach that would lead to the development of a consistent methodology for each Member State to assess the environmental status related to ambient noise, with particular attention to Indicator 11.2.1 of Descriptor 11. Evaluation of GES involves both a quantification of the current ambient noise levels, an estimate of non-anthropogenic background levels and an understanding of the adverse effects of sound on the marine ecosystem and marine fauna. This document focuses on the first two, in the form of a geographically projected sound map, as illustrated in Figures 3 and 4 in Section 1.2 above. A combined measurement and modelling approach is required to accurately generate a sound map with the spatial coverage required for evaluation of GES. An approach based upon only measurements will be sparsely geographically sampled (or prohibitively expensive) and will not permit estimation of natural ambient levels that would exist in the absence of anthropogenic sources. A modelling-only approach risks being biased by estimation error of the acoustic propagation environment and the precise description of the sources used in the model.

In the following, the terms “low frequency”, “intermediate frequency” and “high frequency” are used to indicate the frequency ranges 10 Hz to 1 kHz, 1 kHz to 10 kHz, and 10 kHz to 100 kHz, respectively.

4.1 What sound maps are needed?

Sound maps need to cover the frequency bands of interest to the estimation of GES. In their interpretation of CD 2010 [EC 2010], TSG Noise (Dekeling et al 2014b) has recommended low frequency bands of one decidecade for sound pressure level around 63 and 125 Hz to focus on shipping and other man-made sounds. In addition to these required frequencies, sound maps at intermediate frequency or high frequency might be useful for other sound sources. [Dekeling et al 2014b]

For the low-frequency (63 Hz and 125 Hz) bands the primary anthropogenic source is shipping. Other human sound-producing activitites of importance in this band are explosions, pile-driving and seismic surveying [Hildebrand 2009, Ainslie et al 2009]. Natural sources of low frequency sound are wind, lightning and some marine mammal sounds. Frequencies above 125 Hz highlight other anthropogenic sources such as sonars, explosions, wind farms, echo sounders and acoustic deterrents. They highlight other natural phenomenon such as wind, rain, lightning and marine mammal sounds.

Two primary inputs are required for accurate sound map generation using ocean acoustic propagation models. The first is the source level spectrum and temporal and spatial distribution of the sources; the second is an adequate description of the acoustic environment. The temporal distribution is also needed for all sources at a minimum resolution of one year, for the purpose of quantifying the trend in the annual average SPL for Indicator 11.2.1. For many activities (seismic surveys, wind farm construction, explosions), a higher temporal resolution might be needed, depending on the activity and on the intended use of the sound maps. AIS reports the location, speed and length of various surface vessels, a huge asset in the modelling of ambient noise. At any given moment the position of all large ships in coastal waters can be known with sufficient precision. Determination of locations of fishing and pleasure-craft vessels without AIS is problematic. Ignoring these vessels can, in some circumstances, lead to underestimating the ambient noise level. Given a ship's location and speed, the challenge is to estimate the acoustic source level (and spatial distribution of the sound input into the sea) for each ship. There are models for mapping ship length and speed to source spectrum level vs. frequency but these models are based upon a small sample of ships and there is great variability from ship to ship. Two significant advances are required to improve the source level model for sound map generation. The first is a measurement program to support the development of better models for the source spectra of surface ships. The second is inclusion of information in the AIS stream that pertains more directly to the sound radiated by the ship. For impulsive sources such as pile driving, seismic exploration and explosions understanding of the pulse repetition rate and the source geometry (array for seismic, spatial extent for piles) is required.

The second primary driver of fidelity in acoustic sound maps is the environmental input. Ocean acoustic models have addressed the challenge of solving the wave equation. Their accurate use, however, depends upon an accurate input of the propagation channel characteristics, which includes the ocean sound speed (driven by temperature and to a lesser extent salinity), the seafloor (bathymetry and sound speed/attenuation characteristics) and the sea-surface. In some places a monthly climatology sound speed is sufficient for such modelling. There are regions of intense oceanography where a high-resolution dynamical ocean model may be required to obtain an understanding of the ocean. In shallow water, where interaction with the seafloor (and surface) will dominate it is expected that the geo-acoustic parameters (sediment compressional speed, shear speed, density and attenuation) will be the most important environmental input parameter. These can often be challenging to measure directly and some form of acoustic inversion might be required.

The output for estimating the current environmental state of the ocean and performing trend estimation is a set of spatial sound maps covering the relevant Member State seas (see below). These should include each frequency band of interest and at a minimal temporal resolution to resolve the seasonal dependence of the sound levels. Oceanography, wind speeds and rain, shipping lane changes and ice coverage can all affect the seasonal dependence of the ambient sound levels.

4.2 Illustration of deep water sound map

Our focus and main examples in this report are on shallow water broadband noise. Some EU Member States need to monitor deep water low frequency sound, and for this reason we consider it appropriate to include an illustration of a deep water sound map at 63 Hz. The region between Madeira and the Canary Islands is chosen for this illustrative example because of the relatively deep water and expected high density of merchant shipping traffic in this region. For low frequency modelling in deep water, the parabolic equation (PE) model is used because of its efficiency, accuracy and ability to handle the range-dependent environment.

For this example the OASIS Peregrine Model is used. Peregrine is a re-coding of the RAM PE model into C with an extension to 3D environments and 3D propagation modelling [NPL GPG 133 2014]. Figure 10 b) illustrates the Nx2D solution of the PL for a point source about half way between Madeira and Tenerife. A single slice of the 63 Hz propagation loss is shown in Figure 10 a). Note the multipath interference, and the range-dependence of this particular slice. The sound speed data are taken from the World Ocean Atlas 2009 and the bathymetry data from ETOPO. Both of these are publicly available databases. The sediment is modelled as soft sand. For this example, the average shipping density values are taken from a US Navy database (HITS) for this study, but Member States can access a global shipping database, or use measured AIS information as in the previous example. The shipping density was quantised and mapped to a 15 km grid. Each grid point was then run to all other points using the Nx2D Peregrine model. Peregrine incoherently averages the acoustic intensity (more precisely, the mean-square sound pressure) after propagation in about 15 km range bins according to the output sampling handling the spatial integration problem while incorporating the range-dependent propagation effects. An example of an output of a sound map is shown in Figure 10 d). The source level for a ship is taken from Wales and Heitmeyer and is 178 dB re 1 μPa m for the decidecade centred at 63 Hz. The output noise field is integrated across the one decidecade frequency band.

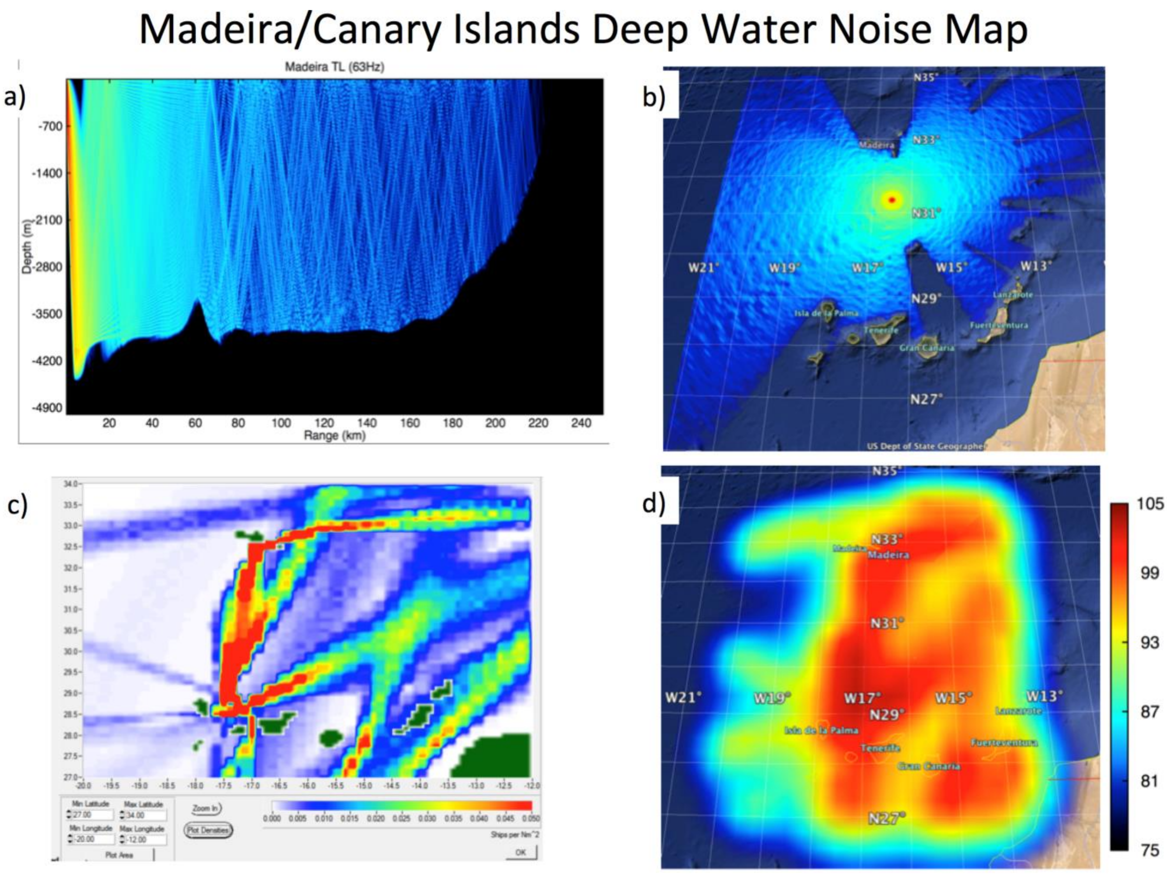

Figure 10: Deep-water noise map illustrative example using the Parabolic Equation model (PEREGRINE). a) single slice propagation loss at 63 Hz for a shallow source [dB re 1 m]. b) Plan view N×2D PL from a location between Madeira and Tenerife [dB re 1 m]. c) Surface shipping density annual average (Tankers/Merchants) d) Noise map for surface shipping alone in decidecade band centred at 63 Hz [dB re 1 μPa].

4.3 Methodology

The best way to develop an accurate understanding of the ambient noise environment is to conduct an iterative approach utilising both measurements and models. Initial measurements should be focused on quantifying the baseline sound level. In parallel, a series of measurements should be planned to fill knowledge gaps such as propagation loss, geo-acoustic parameters and source characteristics. Spectrograms of the ambient noise can help determine the relative contributions of local vs. distant shipping, wind, impulsive seismic sources etc. Subsequent modelling can be done with some confidence in the environmental inputs to generate sound maps for combinations of sources including anthropogenic (ships, seismic exploration, pile-driving, dredging, explosions) and natural (wind, lightning, rain, marine life). Follow-on measurements can be used to tune the model (via acoustic and environmental assimilation) and to monitor regions where modelling requires improvement.

4.4 Role of models

Models can be used to inform the placement of measurements and to extrapolate from measurements to generate estimates of the ambient noise field for all regions of a Member State’s seas. Where the natural ambient sound is swamped by anthropogenic sound, models are the only way to estimate the natural background ambient sound level. A list of modelling approaches (ray tracing, normal mode, parabolic equation, wavenumber integration, and energy flux) is given in Task 4 [NPL GPG 133 2014]. Here we point out that 63 Hz and 125 Hz are low frequency and the models best suited for low frequency propagation are those based on normal mode or parabolic equation approaches, the latter being more suitable for environments with range-dependence. For high frequency sound maps, ray tracing and energy flux models are more suitable [NPL GPG 133 2014]. To evaluate the impact of impulsive sources (seismic, lightning, pile-driving, explosives), broadband models need to be included. Some models can be used to compute broadband impulse responses.

Inputs to the models fall into two categories: characterization of environment, and characterization of source. Access to sufficient environmental data can be challenging. In many local waters, particularly near ports, the bathymetry and the sediment characteristics are quite well known. In deep water, this is rarely the case, although the global bathymetry is sufficient and the sediment type can be less important there. Member States presumably have a knowledge of the seasonal temperature and salinity structure of their seas, whether via national or regional oceanographic services, or European (myoceans) or global databases (World Ocean Atlas). Many regions have publicly available dynamic ocean models running for time/space dependent sound speed information. Source location and source level information is a challenge as well. Knowledge of shipping routes, as well as AIS and radar coverage should be available to Member States. There are measurements of source level available from [Scrimger & Heitmeyer, 1989] and [Wales & Heitmeyer, 2002], but models based on these measurements might need improvement based upon measurements and other characteristics of the ship [AQUO, SONIC].

4.5 Role of measurements

A modelling-only approach to demonstration of GES is insufficient given the challenges of generating accurate sound maps in the absence of guiding measurements. The measurement approach should be to both inform and to validate the sound map model approach. Initial measurements should be done to establish background levels, measure the propagation environment, and assess the kinds of sources that dominate in a particular area and develop an understanding of the temporal/spatial variability. A long-term measurement programme would involve several permanent hydrophone installations. A long-term goal would be for the data from these measurements to be incorporated into the model through adjustments of the environmental parameters and the source distribution and level model.

4.6 How to use model predictions in combination with measurements

The assessment of Good Environmental Status will likely require a reliable estimate of the ambient noise level and its changes over the regions covered by the seas of a Member State [Dekeling et al 2014b]. This is only possible by means of an considered combination of measurements and models. We envisage that measurements would be carried out at a small number of sites (possibly as few as one per basin, although this must be regarded as an absolute lower limit – normally a larger number of receivers would be needed) and these would be used to both inform and corroborate the modelling, providing a confidence measure of the anthropogenic and natural sound levels at a known position. This approach of data-assimilative modelling is analogous to that used in the weather forecasting and hindcasting systems of national meteorological institutions. This roadmap consists of four steps:

1) A priori modelling
2) Initial measurements for validation (quantification of errors)
3) Iterative approach to modelling with feedback from observations (initial estimates of 11.2.1)
4) Mature results for Indicator 11.2.1.

The first step provides input on the spatial distribution of sound within the seas of a Member State. This informs the site selection of the second step – a few long-term measurements. These measurements can then be used to quantify the errors in the model predictions, highlighting frequency bands of mismatch, and errors both on the levels and temporal distributions of the noise. Note that spatial information is likely lacking in these few local measurements. The third, iterative and on-going step is to use measurements to help provide input to the models so that a robust, data-driven, reliable estimate of the noise can be achieved and reported back to the EU. This last measurement approach can include environmental measurements (temperature/salinity, bathymetry, wind-speed), source level measurements for ships, wind, pile drivers, as well as ambient noise measurements that can be used to integrate into the spatial description of GES. This four-step process is outlined in more detail in the sections below.

4.6.1 STEP 1: a-priori model prediction

The objective of the first step is to evaluate the spatial variability of the expected anthropogenic noise. In order to compute the noise level the following environmental information must be collected (whether from measurements, archives, or global databases)

- Seasonal Temperature/Salinity for sound speed (available from myocean.eu or [World ocean atlas])
- Bathymetry (available from e.g. [emodnet],[etopo] [gebco])
- seabed parameters (possibly available from local hydrographic oceanography service; if grain size is known, conversions to geoacoustic parameters are available (Lurton 2002, Ainslie 2010); alternatively a global sediment database exists (BST - requests to US Naval Oceanographic Office));
- Sea surface conditions (wind speed at 10 m height from myocean.eu or national meteorological office); if the wave height is needed, this can be estimated from the wind speed [Ainslie, 2010]; at high frequency the near-surface bubble distribution is needed; this can be estimated using the Hall-Novarini model [Ainslie, 2010])

Source level information for the computation of ambient noise must be gathered for the following sources:

- Surface ship distribution (AIS)
- Surface ship source level (e.g., [Wales & Heitmeyer, 2002]) and source depth [Gray & Greeley], [Gauss, 2012])
- Source level for wind noise [Ainslie, 2010]

As demonstrated above, this information can be entered into an ocean acoustics model (chosen according to the water depth and frequency band of interest). Sound maps can then be computed including contributions from AIS-registered shipping. Surface loss and bottom loss models are needed for ray trace and energy flux models. Alternatives for consideration are described by [APL, 1994], Gauss et al [Gauss, 2002] and [Ainslie, 2010].

Table 3[1] – Suitability of modelling approaches depending on frequency and water depth (see also Task 4 report)

	low frequency (10 Hz < f < 1000 Hz)	intermediate frequency (1 kHz to 10 kHz)	high frequency (10 kHz to 100 kHz)
shallow (continental shelf): 20 m < H < 200 m)	parabolic equation mode sum (coh) mode sum (inc) flux integral	ray sum (inc) flux integral	ray sum (inc) flux integral
deep (ocean basin + continental slope): 200 m < H > 4000 m)	parabolic equation mode sum (coh) ray sum (coh) ray sum (inc)	ray sum (inc) flux integral	ray sum (inc) flux integral

To supplement the table, some general statements are made concerning applicability of some of the methods:

[1] notes to table:
models considered: PE, modes (coh and inc), rays (coh and inc), flux
“modes” = adiabatic mode model
“flux” = flux/mode hybrid

Coupled modes and FE models are not considered suitable at this time, as the necessary computational power is not yet available. The models considered (see [NPL GPG 133 2014]) are parabolic equation, adiabatic normal mode sum (coherent or incoherent), ray sum (coherent or incoherent) and flux integral methods.

High frequency models need to incorporate a good surface loss model (some suggestions are made for mid-frequency and high-frequency models in [Ainslie, 2010 (pp 364-369)];

For the seabed the question arises of what geoacoustic model to use above 10 kHz. See Table 4.17 (4.18) of [Ainslie, 2010 p176 (p178)] for geoacoustic parameters suitable for use between 10 kHz and 100 kHz (1 kHz and 10 kHz).

For wave models, computation time increases with increasing frequency. If this becomes an issue due to limited computer power, it might be necessary to resort to a faster method, in which case care is needed to quantify any potential error made by the faster method.

For ray models, a simplified sound speed profile is needed to avoid cut-off ducts, or ducts not well cut on. If used close to a boundary (up to about 5 wavelengths distance from the sea surface), coherent summation should normally be used.

For adiabatic normal mode models, the sound speed profile should have no more than one sound speed minimum to avoid mode accounting problems.

For flux models, if used in deep water, there is likely to be a need to include for a modification to include convergence effects as in [Harrison, 2013].

4.6.2 *STEP 2: Select measurements for quantification of error*

The next step is to deploy a small set (one per basin at least) of acoustic recording devices to measure a reasonable time (encompassing several seasons to ensure a variety of wind and rain conditions, though not necessarily continuously) of ambient noise across the frequency band of interest. With the emphasis of Indicator 11.2.1 on 63 Hz and 125 Hz, the most important locations for these measurements will be those where shipping dominates [Dekeling et al 2014b]. This can be seen both in the AIS surface shipping density estimates and in the results of the model-only output of STEP 1. These measurements can be used to quantify the error in the GES estimate from the *a priori* modelling. The model-data comparison should happen on both a short term (1 min) and a long-term (1 month or greater) time average. This provides information on where and how the model is capturing the distribution of sound pressure levels.

4.6.3 *STEP 3: Iterative approach combining measurements and models (initial estimates of 11.2.1)*

The final step (which would be repeated iteratively) is to incorporate the information gained from measurements into the model to generate the highest fidelity spatially dependent GES for the seas of the Member States. In addition to the STEP 2 measurements taken to quantify error, other measurements can be taken to provide dynamic information such as:

- Source level of individual ships or ship categories (replacing average values in coarse time)
- Possible changes in propagation environment (e.g. wind-speed or rainfall rate, sediment parameters)

As well as supporting measurements of:

- Environmental properties like sea water temperature and salinity profiles, bathymetry, geoacoustics, surface properties (e.g. via inversion from PL measurements)
- Source properties (level and distribution)
- Direct model calibration (e.g. PL, SL, source depth)

Step 3 also implies incorporation of relevant research results for issues such as

- uniform treatment of surface interaction (bubbles + rough surface scattering) 1-100 kHz (high frequency effect)
- treatment of solid seabed where needed (local effect)
- 3D effects (horizontal refraction) where needed (local effect)
- convergence effects [Harrison 2013] (deep water effect – needed for flux method only)
- improved source model for ships (to increase fidelity of ship noise modelling)
- incorporate source models for anthropogenic sources other than ships (where needed): pile driving, airguns (plus explosions or sonar where needed locally)
- incorporate models for natural sources such as wind, rain and lightning

4.6.4 *STEP 4: Mature results for Indicator 11.2.1*

The iterative combination of models and measurements should lead the Member States to the position of confidence in the models to accurately represent the current state of the environment within its waters. This could provide a comparison of the anthropogenic and naturally occurring ambient noise. Once the data have been incorporated, a series of maps would be generated showing the yearly average of the total and anthropogenic only noise estimates. It is suggested that these be computed as pressure-squared and then averaged over depth, possibly weighted according to the expected depth distribution of selected species or groups of species. The results can then be displayed as a 2D map. Note that although yearly averages are a suggested output, the acoustic modelling would be done on a seasonal time-scale to incorporate changes in the environment, (temperature/salinity/surface roughness/ice cover) and the source level distribution (ships, wind/weather, ice). A suitable spatial resolution needs to be determined at a regional level.

4.7 Need for standardization

Underwater noise monitoring is needed to support implementation of the Marine Strategy Framework Directive [Dekeling et al 2014a]. At present there are no international standards available for underwater noise monitoring [Dekeling et al 2014b]. If ambient noise monitoring methods are not standardised, the monitoring will be carried out by different Member States in different and possibly incompatible ways, making the results difficult or impossible to compare. There is therefore an urgent need for international standardisation of ambient noise monitoring, which in turn implies a need for both standardised measurement methods and standardised modelling methods. A pre-requisite for writing any International Standard involving an application of underwater acoustics is an internationally agreed terminology with which to write it. We therefore propose a way ahead involving the development of a terminology standard, separate measurement and modelling standards, and finally an international ambient noise monitoring standard.

4.7.1 Standardisation of underwater acoustical terminology

The development of an internationally agreed terminology for underwater acoustics is well underway. The working group Underwater Acoustical Terminology (ISO/TC 43/SC 3/WG 2, hereafter abbreviated 'WG2') of the International Organization for Standardization (ISO), was created in October 2012 with the purpose of developing an International Standard in three years. The first step in this process was a Committee Draft (ISO/CD 18405), which was approved by ISO ballot in January 2014. At the time of writing, WG2 is working on a Draft International Standard, planned for completion in October 2014, and is on target for the publication of a full International Standard (ISO 18405) in 2015. This International Standard will provide the agreed terminology that is essential for the development of further standards by ISO in the domain of underwater acoustics.

If applied consistently, ISO 18405 will provide the terminology needed, not just for future ISO standards related to underwater acoustics, but for effective communication between stakeholders generally, whether for science, regulation, industry or dissemination to the general public. If ISO 18405 is published in 2015, it will be due for its first review in the period 2017-2020. The caveat "if applied consistently" is an important one, because ISO 18405 cannot be applied retrospectively to standards that were published before its development. The consequences of this caveat are explored below (see Section 0 on the Harmonisation of IEC and ISO standards).

4.7.2 Standardisation of underwater noise monitoring

A full underwater noise monitoring standard requires both a measurement element and a modelling element. Rather than attempting this all in one go, it makes sense to simplify the task by first developing separate measurement and modelling standards that can later be combined into a single full monitoring standard.

The development of an international underwater noise monitoring standard is likely to take about 6 years. If started in 2015, this could therefore be completed by 2021, involving the following intermediate steps:

- development of measurement standard (2015-2019);
- development of modelling standard (2016-2020);
- development of combined monitoring standard (2017-2021).

Member States are required to monitor underwater sound from 2014, so national and regional monitoring plans will need to be put in place before the International Standard becomes available. Such national and regional plans should be based on the best available guidelines (see e.g. [NPL GPG 133 2014], [Dekeling et al, 2014b] and [Anon., 2014].

4.7.3 Harmonisation of IEC and ISO standards

Standards involving a significant element of electrical technology (for example, for calibration of electroacoustic transducers) are usually developed not by ISO but by the International Electrotechnical Commission (IEC). Of particular relevance to underwater acoustics are a number of transducer calibration standards published or under development by IEC [IEC60565: 2006.]. These IEC standards use IEC terminology in the form of the International Electrotechnical Vocabulary (IEV) [IEC 60050, 1994], which is not fully compatible with ISO terminology [ISO 80000-8:2007; [ISO/CD 18405] (an example is the term “sound pressure”, which is defined differently by IEC than by ISO). ISO 80000-8:2007 is part of the International System of Quantities (ISQ), a 14-part standard jointly developed by ISO and IEC. See Table 4 for details and other examples. Table 3 provides the same information, presented in such a way to make explicit the different meanings attributed by international standards to terms such as “sound pressure” and “sound pressure level”.

Table 4 – terminology for physical quantities related to sound pressure in the IEV, ISQ and ISO/CD 18405

quantity[2]	IEV [ref]	ISQ [ISO 80000-8:2007]	ISO/CD 18405
$p(t)$	instantaneous sound pressure	sound pressure	sound pressure
p_{RMS}	sound pressure	n/a	root-mean-square sound pressure
$10\log_{10}\frac{p(t)^2}{p_0^2}$ dB	n/a	sound pressure level	n/a
$10\log_{10}\frac{p_{\mathrm{RMS}}^2}{p_0^2}$ dB	sound pressure level	n/a	sound pressure level[3]

Table 5 – physical quantities represented by "sound pressure", "sound pressure level" and related terminology in the IEV, ISQ and ISO/CD 18405

name	IEV	ISQ	ISO/CD 18405
instantaneous sound pressure	$p(t)$	$p(t)$ (implied)	$p(t)$ (implied)
mean-square sound pressure level	n/a	n/a	$10\log_{10}\frac{p_{\mathrm{RMS}}^2}{p_0^2}$ dB
root-mean-square sound pressure	n/a	p_{RMS} (implied)	p_{RMS}
root-mean-square sound pressure level	n/a	n/a	$10\log_{10}\frac{p_{\mathrm{RMS}}^2}{p_0^2}$ dB
sound pressure	p_{RMS}	$p(t)$	$p(t)$
sound pressure level	$10\log_{10}\frac{p_{\mathrm{RMS}}^2}{p_0^2}$ dB	$10\log_{10}\frac{p(t)^2}{p_0^2}$ dB	$10\log_{10}\frac{p_{\mathrm{RMS}}^2}{p_0^2}$ dB

If an ISO measurement standard requires use of a transducer calibrated using an IEC standard, the user of both standards needs to learn two different languages, resulting in the cost associated either with the extra effort or an increased risk of misunderstanding, or both. The risk of misinterpretation can be mitigated by developing a joint IEC-ISO terminology based on the ISQ. If started in 2015, a joint terminology standard could be developed by 2018, in time for use in the first review of ISO 18405 in (say) 2017-2020, and for the development of the monitoring standard (2017-2021).

[2] The quantity $p(t)$ is the contribution to the instantaneous pressure due to the presence of sound. The quantity p_{RMS} is the root-mean-square value of $p(t)$. The quantity p_0 is the reference sound pressure, equal to 1 μPa.
[3] In ISO/CD 18405, the term "sound pressure level" is defined as a synonym of both "root-mean-square sound pressure level" and "mean-square sound pressure level".

Standardisation timeline 2015-2021

2015: finalise ISO 18405:2015 Underwater Acoustics - Terminology
2015: start development of joint ISO/IEC terminology standard
2015: start development of measurement standard (best done jointly by ISO/IEC)
2016: start development of modelling standard (ISO)
2017: start development of monitoring standard (ISO)
2017: start review of ISO 18405
2018: publication of joint ISO/IEC terminology standard (in ISQ)
2019: finalise modelling standard (ISO)
2020: finalise measurement standard
2020: finalise ISO standard 18405:2020
2021: finalise monitoring standard (ISO)

5 Acknowledgements

The authors thank Stephen Robinson of NPL and Christ de Jong of TNO for their careful reviews.

6 References

[Ainslie, 2005], Ainslie, M. A. (2005). "Effect of wind-generated bubbles on fixed range acoustic attenuation in shallow water at 1–4kHz". *The Journal of the Acoustical Society of America, 118(6), 3513-3523.*

[Ainslie, 2010], Ainslie, M. A. (2010). "Principles of sonar performance modeling." Springer.

[Ainslie et al, 2009], Ainslie, M. A., De Jong, C. A. F., Dol, H. S., Blacquière, G., & Marasini, C. (2009). "Assessment of natural and anthropogenic sound sources and acoustic propagation in the North Sea. " *TNO report TNO-DV, C085*. Available online: http://www.noordzeeloket.nl/overig/bibliotheek.asp

[Ainslie et al, 2012], Ainslie, M. A., De Jong, C. A. F., Janmaat J., Heemskerk H.J.M, "Dredger noise during Maasvlakte 2 construction: Noise maps and risk assesment." *TNO report 2012 R10818*

[Anon., 2014], "Draft joint workshop report: predicting sound fields; global soundscape modelling to inform management of cetaceans and anthropogenic noise**"**. Available from: "https://events.iwc.int/index.php/scientific/SC65B/paper/viewFile/802/870/SC-65b-Rep03rev.pdf"

[APL, 1994], Jackson, D. R. (1994). "APL-UW high-frequency ocean environmental acoustic models handbook". Applied Physics Laboratory, University of Washington, Technical Report, 9407.

[Aquo-Sonic (Madrid)], Meeting report in preparation.

[AQUO], Information on the "Achieve quieter oceans by shipping noise footprint reduction (AQUO) " European project can be found on: http://www.aquo.eu/

[SONIC], Information on the "Suppression Of underwater Noise Induced by Cavitation (SONIC)" European project can be found on: http://www.sonic-project.eu/

[Arveson & Vendittis, 2000], Arveson, P. T., & Vendittis, D. J. (2000). "Radiated noise characteristics of a modern cargo ship". *The Journal of the Acoustical Society of America, 107(1), 118-129.*

[Borsani, 2014], Borsani J.F. (2014) "Impacts of noise and use of propagation models to predict the recipient side of noise", *Cefas project report C6082*

[Cetsound (Washington)], Cetsound workshop report available from : http://cetsound.noaa.gov/report.html

[de Jong et al, 2010], de Jong C.A.F., Ainslie M.A., Dreschler J., Jansen E., Heemskerk E., Groen W., "Underwater noise of Trailing Suction Hopper Dredgers at Maasvlakte 2: Analysis of source levels and background Noise". *TNO-DV report 2010 C335.*

[Dekeling et al 2014a], "Monitoring Guidance for Underwater Noise in European Seas, Part I: Executive Summary", Dekeling, R.P.A., Tasker, M.L., Van der Graaf, A.J., Ainslie, M.A, Andersson, M.H., André, M., Borsani, J.F., Brensing, K., Castellote, M., Cronin, D., Dalen, J., Folegot, T., Leaper, R., Pajala, J., Redman, P., Robinson, S.P., Sigray, P., Sutton, G., Thomsen, F., Werner, S., Wittekind, D., Young, J.V. JRC Scientific and Policy Report EUR 26557 EN, Publications Office of the European Union, Luxembourg, 2014, doi: 10.2788/29293, ISBN 978-92-79-36341-2. Available from: http://publications.jrc.ec.europa.eu/repository/handle/111111111/30979

[Dekeling et al 2014b], "Monitoring Guidance for Underwater Noise in European Seas, Part II: Monitoring Guidance Specifications", Dekeling, R.P.A., Tasker, M.L., Van der Graaf, A.J., Ainslie, M.A, Andersson, M.H., André, M., Borsani, J.F., Brensing, K., Castellote, M., Cronin, D., Dalen, J., Folegot, T., Leaper, R., Pajala, J., Redman, P., Robinson, S.P., Sigray, P., Sutton, G., Thomsen, F., Werner, S., Wittekind, D., Young, J.V. JRC Scientific and Policy Report EUR 26555 EN, Publications Office of the European Union, Luxembourg, 2014, doi: 10.2788/27158, ISBN 978-92-79-36339-9. Available from: http://publications.jrc.ec.europa.eu/repository/handle/111111111/30973

[Dreschler et al, 2009], Dreschler J., Ainslie M.A., Groen W.H.M., "Measurements of underwater background noise Maasvlakte 2", *TNO-DV 2009 C212*

[Emodnet, 2014], public Bathymetry database available online at: http://www.emodnet-hydrography.eu/)

[Etopo, 2014], public Bathymetry database available online at: http://www.ngdc.noaa.gov/mgg/global/global.html

[EC, 2010] Commission Decision No. 2010/477/EU on criteria and methodological standards on good environmental status of marine waters, 2010 O. J. L 232/14.

[Gauss, 2012] Gauss, R. C., Gragg, R. F., Wurmser, D., Fialkowski, J. M., & Nero, R. W. (2002). Broadband models for predicting bistatic bottom, surface, and volume scattering strengths (No. NRL/FR/7100--02-10). NAVAL RESEARCH LAB WASHINGTON DC.

[Gebco(+), 2014] public Bathymetry database available online at: http://www.gebco.net/

[Gray & Greeley, 1980], Gray, L. M., & Greeley, D. S. (1980). "Source level model for propeller blade rate radiation for the world's merchant fleet. " *The Journal of the Acoustical Society of America, 67(2), 516-522.*

[Harrison, 2013] Harrison, C. H. (2013). Ray convergence in a flux-like propagation formulation. *The Journal of the Acoustical Society of America*, *133*(6), 3777-3789.

[Heinis et al, 2013], Heinis, F., de Jong, C.A.F., Ainslie, M.A., Borst, W., & Vellinga, T. (2013). "Monitoring programme for the Maasvlakte 2, part III–the effects of underwater sound. "

[Hildebrand, 2009], Hildebrand, J. A. (2009). “Anthropogenic and natural sources of ambient noise in the ocean. ” *Marine Ecology Progress Series*, *395*(5).

[IEC 60050:1994] IEC 60050:1994, International Electrotechnical Vocabulary, part 801: Acoustics and Electroacoustics, (section 801-32 covers terms for underwater acoustics), International Electrotechnical Commission (IEC), Geneva.

[IEC60565:2006], IEC60565: 2006 Underwater acoustics-Hydrophones - Calibration in the frequency range 0.01 Hz to 1 MHz, IEC 60565 - 2006 (EN 60565: 2007, BS60565:2007), International Electrotechnical Commission, Geneva, 2006

[IEC 61260:1995], IEC 1995 (EN 61260), Electroacoustics - Octave-band and fractional-octave-band filters, International Electrotechnical Commission, Geneva, Switzerland, 1996.

[ISO - GUM], JCGM 100 series, Guides to the expression of uncertainty in measurement (GUM series). Available from: http://www.iso.org/sites/JCGM/GUM-introduction.htm

[ISO 266:1997] ISO 266:1997, Acoustics - Preferred frequencies (1997)

[ISO 80000-8 2007], ISO 80000-8:2007, Quantities and units – part 8: Acoustics, International Organization for Standardisation (ISO), Geneva.

[ISO/CD 18405], ISO/CD 18405 Underwater acoustics terminology

[Maasvlakte 2, 2014], Website on the extension of the Rotterdam port https://www.maasvlakte2.com/en/index/

[NPL GPG 133 2014] Good Practice Guide for Underwater Noise Measurement, National Measurement Office, Marine Scotland, The Crown Estate, Robinson, S.P., Lepper, P. A. and Hazelwood, R.A., NPL Good Practice Guide No. 133, ISSN: 1368-6550, 2014.

[Lurton 2002], Lurton, X. (2002). An introduction to underwater acoustics: principles and applications. springer.

[Wang et al, 2014], Wang L., Heaney K., Pangerc T, Theobald P, Robinson S, Ainslie M.A. (2014), "review of underwater acoustic propagation models", *NPL report AIR (RES) 086*

[Scrimger & Heitmeyer, 1989], Scrimger, P., & Heitmeyer, R. M. (1991). Acoustic source-level measurements for a variety of merchant ships. *The Journal of the Acoustical Society of America*, *89*(2), 691-699.

[Sertlek & Ainslie 2013], Sertlek H.O., Ainslie M.A. (2013), “Propagation loss model comparisons on selected scenarios from the Weston memorial workshop.” *UA2013 1st international Conference and Exhibition on underwater acoustics*.

[Sertlek & Ainslie, 2014a], Sertlek, H. Ö., & Ainslie, M. A. (2014). A depth-dependent formula for shallow water propagation. The Journal of the Acoustical Society of America, 136(2), 573-582.

[Sertlek & Ainslie 2014b], Sertlek H.O., Ainslie M.A. (2014), “A fast algorithm for the computation of incoherent propagation loss for variable water depth: a validation study” *UA2014 2nd International Conference and Exhibition on underwater acoustics*.

[Southall et al., 2007], Southall**,** B. L., Bowles, A. E., Ellison, W. T., Finneran, J. J., Gentry, R. L., Greene Jr., C. R., Kastak, David, Ketten, D. R., Miller, J. H., Nachtigall, P. E., Richardson, W. J., Thomas, J. A., and Tyack, P. L., Marine Mammal Noise Exposure Criteria: Initial Scientific Recommendations, Aquatic Mammals, 33 (4), pp. 411-509.

[Thorp, W. H. (1967)] Thorp, W. H. (1967). Analytic Description of the Low-Frequency Attenuation Coefficient. The Journal of the Acoustical Society of America, 42(1), 270-270.

[Wales & Heitmeyer, 2002] Wales, S. C., & Heitmeyer, R. M. (2002). An ensemble source spectra model for merchant ship-radiated noise. The Journal of the Acoustical Society of America, 111(3), 1211-1231.

[Wenz, 1962], Wenz. G.M., Acoustic ambient noise in the ocean: Spectra and sources, J. Acoust. Soc. Am. vol. 34, p. 1936–1956, 1962.

[Weston, 1976], Weston, D. E. (1976). Propagation in water with uniform sound velocity but variable-depth lossy bottom. Journal of Sound and Vibration, 47(4), 473-483.

[Weston & Ching, 1989], Weston, D. E., & Ching, P. A. (1989). Wind effects in shallow-water acoustic transmission. The Journal of the Acoustical Society of America, 86(4), 1530-1545.

[World Ocean Atlas], World Ocean Atlas 2013 (WOA13) is a set of objectively analyzed (1° grid) climatological fields of in situ temperature, salinity, dissolved oxygen, Apparent Oxygen Utilization (AOU), percent oxygen saturation, phosphate, silicate, and nitrate at standard depth levels for annual, seasonal, and monthly compositing periods for the World Ocean. Available from: http://www.nodc.noaa.gov/OC5/woa13/

7 Signature

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