Potential effects of seismic surveys on harbour porpoises

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Report number C126/15
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Summary

The scale of seismic surveys on the Dutch continental shelf (DCS) is not well known and the same applies for its effects on the harbour porpoise. This leads to a lack of information which can be used during the licensing process of seismic research and for the further implementation of the Marine Strategy Framework Directive and the Dutch harbour porpoise conservation plan. In addition, it is not clear which knowledge gaps still exist.

In this study relevant information was gathered based on a literature review on the following topics:

1. The extent of seismic surveys on the Dutch continental shelf;
2. Potential effects on harbour porpoises;
3. Mitigation measures;
4. Identification of knowledge gaps and their prioritization for future research.

Several seismic sampling techniques are applied at the North Sea; single line sampling (2D) and multiple line sampling (3D). Repeated or time-lapsed 3D also occurs, and is known as 4D-sampling.

One of the main conclusions of the literature reviewed by the EU Technical Subgroup on Noise, “TSG noise” showed that noise of shipping and seismic airgun surveys are the main anthropogenic contributors to low frequency underwater sound. Source levels (zero-to-peak) produced by airgun arrays are ranging from 209 dB re 1 μPa m (very low) to 253 dB re 1 μPa m (very high). Real measurement data on long distance aversive noise levels are few and based on incidental sources. The recently developed propagation model AGORA by TNO predicts lower propagation losses at distances > 5 km than measurements in shallow waters of the Dutch continental shelf have shown. The provision of seismic survey data by use of the NLOG web portal is mainly concerning 3D-surveys and not covering 2D-surveys. The contribution of 2D-seismic on the DCS applied in coastal projects, like wind farms is significant. Between 2003 and 2007 a total of 9000 km were monitored, mainly in the coastal zone of the DCS.

Harbour porpoises and other marine animals exposed to underwater sound can be adversely affected, e.g. by temporary reduction in hearing sensitivity, behavioural changes and even injury or death. It seems unlikely however that seismic surveys will cause primary blast injury on harbour porpoises. Field observations in the North Sea showed avoidance of harbour porpoises to smaller airgun arrays (490 inch3), as well as a reduction in feeding activity within a radius of 10 km. For large arrays (4820-6712 inch3) avoidance responses have been reported in British Columbia for up to 70 km.

The results of modelling work by 'RWS werkgroep onderwatergeluid' (Heinis et al, 2014) predicted an effect on the North Sea porpoise population as a result of seismic surveys that was of the same order of magnitude as predicted effects that could occur due to pile driving of wind turbine foundations.

Monitoring strategies during seismic surveys (visual as well as acoustic) are likely to be ineffective in detecting porpoises in time to avoid hearing effects, but this will depend on the type of array (and corresponding effect distances) and on the effect mitigated for (Permanent Threshold Shift or Temporary Threshold Shift). Deterring animals, e.g. by Acoustic Deterrent Devices (ADD) or soft start, are likely to have some effect on porpoises, but it is unclear whether all animals respond in time to avoid hearing impacts. Continued use of airguns, or use of ADDs during line changes may also act as a deterrent, but may also disturb animals longer than necessary. Most current mitigation measures aim to reduce effects close to the actual seismic operation but are not able to mitigate the larger scale behavioural disturbance of harbour porpoises that is expected to occur and potentially could lead to population level effects. Due to the limited knowledge about habitat use of harbour porpoises in the North Sea (and on the DCS in particular), it is unclear how effective and useful restrictions of certain areas for seismic activities are.
Ship-based monitoring of the exclusion zone is not effective for reducing potential behavioural disturbance of harbour porpoises that can occur at distances of tens of kilometers.

During this study several knowledge gaps have been identified and prioritized. We recommend to address at least the main gaps in future research programs:

1. Improve the availability and quality of seismic survey data, in particular data essential for impact assessment;
2. Determine the occurrence of simultaneous execution of seismic surveys in different areas and develop acoustic and behavioural research on harbour porpoise in the appropriate areas and distance ranges presently lacking. Additionally, perform background noise measurements to compute an annual record of the soundscape on the DSC (TSG noise 2014c). Questions like the applied seismic technique and ISO-normalized acoustic measures, disturbance distance, duration of disturbance should be addressed by this research. In order to follow these guidelines participation of other North Sea countries is recommended;
3. As a reference to harbour porpoise responses to seismic exposure, knowledge on the seasonal distribution, densities and demographic parameters is required, which can be obtained by conducting aerial surveys of harbour porpoises on the Dutch Continental Shelf in different seasons of the year, and by collating current scattered knowledge on basic demographic parameters (e.g. reproduction rate, mortality,) and identify the relevant research needs.
4. To improve and validate sound prediction tools and their inputs to reliably predict seismic sound levels at maximum distances at which behavioural disturbance occurs;

This research is part of the Beleidsondersteunend Onderzoek Effecten seismiek op zeezoogdieren (t2) (BO-11-018.02-039) program of the Ministry of Economic Affairs (EZ).
1 Introduction

Sound is important in marine life, especially in marine mammals which use it for communication, navigation, orientation, feeding and the detection of predators. Marine organisms which are exposed to anthropogenic noise can be adversely affected both on a short timescale (acute effect) and on a long timescale (permanent or chronic effects). Adverse effects can be subtle (e.g. temporary reduction in hearing sensitivity, behavioural effects) or obvious (e.g. injury, death). Underwater noise was therefore identified as pollutant in the marine environment in article 3-8 of the European Marine Strategy Framework Directive (MSFD)\(^1\).

There are several sources of underwater sound. Natural ambient underwater sound is caused by wind, waves, turbulence, currents, precipitation and marine life. The main sources of man-made (anthropogenic) noise in the North Sea are pile-driving for the development of offshore wind farms, seismic surveys for hydrocarbon exploration, detonation of unexploded ordnance and commercial shipping (Ainslie et al. 2009). Additional sources are the use of active sonar during military exercises and from fishing vessels (fish finders), drilling, dredging and operational noise from offshore installations.

The European MSFD aims for Member States to achieve or maintain Good Environmental Status (GES) in the marine environment. Seismic surveys have been identified by the EU Task sub-group underwater noise (TSG-Noise) as one of the sound sources that requires monitoring for assessing the effects on marine life (Dekeling et al. 2014a, 2014b, 2014c). The MSFD has led to the Dutch implementation of the Marine Strategy, and has set conservation aims for impulsive sound sources (including seismic surveys), with the aim to prevent negative effects of these specific activities on a population level or on the ecosystem, specifically for marine fauna (NL Marine Strategy 2012, Dekeling et al. 2014a, 2014b, 2014c). Under the EU Habitats Directive the harbour porpoise is a protected species. A North Sea Conservation Plan developed within ASCOBANS has led to the national implementing of a conservation plan for the harbour porpoise (Camphuysen & Siemensma, 2011). During the elaboration of the porpoise conservation plan it became clear that regulations concerning the production of underwater sound by seismic survey were virtually lacking, unlike in neighbouring countries. At that time no conditions were imposed when a license to operate was issued. In the NL Marine Strategy (2012) it was confirmed that regulations would be drafted for seismic surveys and from January 2014 onwards seismic surveys carried out on the Dutch Continental Shelf (DCS) needed a ‘Flora- en faunawet’ dispensation and ‘Natuurbeschermingswet’ permittance (MS2014).

1.1 Problem Definition

There is quite some knowledge about potential impacts of seismic surveys on a variety of marine mammals. It is also known that seismic surveys have a relatively large contribution to the extent of underwater sound in the North Sea. However, the scale of seismic surveys on the Dutch Continental Shelf (DCS) and the effects on species particularly sensitive to noise, such as the harbour porpoise, is not well known.

Adequate information for management purposes (licenses /adaptations to legislation) is therefore not available. Nor is it clear which knowledge gaps still exist. This information is also urgently needed for further policy development within the MSFD and the Dutch harbour porpoise conservation plan.

1.2 Objectives and scope

The goal of this study is to gather relevant information based on a literature review on the following topics:

1. The extent of seismic surveys on the DCS (activities, noise levels and characteristics, how often, where, when, trends).
2. Potential effects on harbour porpoises (communication, disturbance, injury etc.) and how these effects relate to those of windfarm pile driving.
3. Mitigation measures (national, international, future developments, effectiveness, applicability of existing protocols such JNCC / German standards).
4. Identification of knowledge gaps (regarding exposure, effects and mitigation) and their prioritization.

This information can be used by policy makers for the implementation of measures in the regulations of seismic surveys. Furthermore, the relevant knowledge gaps which have been identified can be addressed in future research programs.
2 Physical ranges of seismic operations

To investigate the impact of seismic operations on marine mammals on the DCS, knowledge is required on the physical scale, in terms of the range of the acoustic emissions, the spatial distribution and temporal occurrence throughout the year.

In this section we provide background information on basic seismic operational principles and techniques as well as the characteristics of the sound produced. We also review the current data available on the spatial and temporal use of seismic operations on the DCS, and their potential effect on harbour porpoise.

In this report we focus on the sound emissions of the actual seismic research activities. Other sources of sound that are associated with seismic surveys like shipping or helicopters are not included.

2.1 Principles of seismic operation

To study offshore geological subsurface layers, oil and gas exploration a range of seismic instruments is applied with the physical scale adapted to the exploration conditions, the required resolution of imaging and operational conditions. Basically a single transient or impulse is generated in the water towards the subsurface earth body (Figure 1). A seismic source can be regarded as a "point-source" part of the acoustic pressure wave that propagates horizontally in the water volume (Caldwell & Dragoset, 2000). Acoustic waves reflected by subsurface layers are picked up by an array of hydrophones (e.g. "streamer"), positioned behind and in-line with the sound source. From the received sound wave image, geological structure can be made visible. The sound source and adjacent streamer are most commonly towed at 5 to 10 m below the water surface with the streamer section as long as 10 km.

![Figure 1. Marine seismic acquisition – pulses of sound energy penetrate the subsurface and are reflected back towards the hydrophones from subsurface layers](image)


2.2 Seismic instruments and acoustic ranges

In the field of seismic exploration a wide range of sound sources are applied, each with its specific sound characteristics and operational benefits. The effects on marine animals depend not only on the produced sound pressure but also on the produced frequency bandwidth and the repetition rate with respect to the hearing sensitivity (see Chapter 3 for more details). There are two basic categories, the air-driven sources known as “air, sleeve and waterguns” and the electrically powered systems, like “sparkers”, where a high-voltage energy source is discharged over multiple spark tips. Sparkers are applied in case of sandy, silty and clayey sediments with energy peaking in a higher frequency range than airguns. The subsurface penetration depth depends on the supplied energy (kJoules) and can be as deep as 500 to 750 m (Labaune et al., 2005).

The comparison of basic seismic sources illustrated in Figure 2 shows that the frequency range increases inversely proportional to the applied power.

![Relative comparison of power and frequencies for various seismic sound sources. (Derived from Trabant, 1984)](http://woodshole.er.usgs.gov/operations/sfmapping/seismic.htm)

Figure 2. Overview of main acoustic properties of common seismic sources

The resolution of the received signal increases proportionally with the frequency bandwidth and inversely proportionally with the rising and falling edges of the impulses. As the hearing thresholds levels of the target animal is inversely proportional to frequency (see Chapter 3), sources with lower output levels peaking at higher frequency ranges, like chirp-type of transducers could have similar impact as LF sources, like airguns. The application of the type of seismic source depends on the subsurface depth and the accuracy/resolution requirements of the subsurface image.

3 http://woodshole.er.usgs.gov/operations/sfmapping/seismic.htm
2.3 Seismic sampling techniques

In order to keep track of the major differences of seismic operations the most relevant conditions for the exposure, the seismic sampling techniques and the relation to pulse power are explained. The seismic source is an arrangement of multiple sources or cells to develop the required power and to reduce air bubble production and improve imaging resolution (Upadhyay, 2013).

Seismic operations involve two basic ways of sampling (Figure 3):

1. A single line sampling technique, referred as 2D-seismic with a single source array and streamer;
2. A multiple line sampling, referred as 3D-seismic, where a square area of the subsurface is sampled. Hence, such a configuration is built of an array multiple lines of seismic sources and streamers all towed in parallel.

![Figure 3. Basic difference between 2D- & 3D-seismic sampling (OGP report 448, 2011)](image)

2D-seismic are single line observations of the subsurface with a smaller range of the seismic power or in coastal areas with intensified shipping and involve a broader spacing of transects (≥1 km).

3D-seismic involves a sampling with higher resolution, which, depending on the number of streamers, could be 15 to 20 times higher than 2D sampled areas (Figure 2, OGP report 448, 2011). 3D-surveys are more complex with more sophisticated equipment and involve greater operational investments. The accuracy of the produced 3D-image of the subsurface is crucial, with a controlled stable position of the physical centre point of the array an operational requirement. Consequently data of 3D-surveys are more detailed than 2D-surveys as shown by the operational logs found on the NLOG web portal (DNZ 2011).

4D-seismic refers to repeated or time-lapsed 3D of earlier 3D tracks with some period of time between the initial and subsequent surveys (OGP report 448, 2011). The aim of 4D-surveys is to monitor the exploration of the resource over time in order to maximise the exploration of a resource. 4D-surveys have increased significantly since the mid-1990s and represent a high share of current seismic operations (DNZ, 2011). To maximise the exploration of a resource high resolution alternative sources could be a future requirement. The impact on marine mammals will differ with the technique used.
2.3.1 Spatial use and survey operations

In order to address the impact of seismic operations, differences in the operational aspects of 2D- and 3D-seismic sampling are important in relation to the impact on marine mammals. A seismic operation highly depends on the location of the target area, for example if it takes place in open sea or in coastal zones with intensive shipping and the occurrence of obstacles of oil rigs and windfarms. The size of a 3D-survey area is referred to in square kilometres (km²). A 3D-survey addressed as “small” can involve 300 km², larger 3D-surveys may cover 1000 to 3000 km².

2D-transects include interruptions of the acoustic emissions, while positioning the towed seismic array for a counter course. 3D-transects are commonly sailed uninterruptedly in parallel tracks according to a “racing track” pattern (Figure 4) or in more complex designs (e.g. continuous line acquisition, CLA mode), depending on the locations, obstructions, tidal & sea state conditions. The streamer length of sparker type of sources is usually shorter and operated from medium to small vessels, hence the operation is more sensitive to the sea state (waves, wind) and supports only 2D-imaging (OGP report 448, 2011). The operational conditions of alternative sources and new techniques to a particular sampling mode were reviewed by Weilgart (2010).

![Figure 4. Typical 3D “racing track” type of survey design (OGP report 448)](image)

2.4 Source references and range of the exposure

In air-driven seismic sources the emitted acoustic sound pressure is related to the supplied air pressure, the dimensions of the airgun source array, the cell volume and the number and configuration of cells. In electrically powered sources the developed acoustic sound pressure is proportional to the ratio of the buffered and discharged energy, in most cases the energy stored in a capacitor array. In both techniques the discharged power is referred to the energy in kJoules. These parameters are the main parameters for the developed strength of the source often expressed in terms of Source Level (SL).

The firing interval is a balance between the air pressure capacity and the numbers of cells in an array and will practically not be lower than once per three seconds. The firing interval of electrically driven sources is more flexible to produce multiple “bursts” at higher firing rates.
To summarise, the impact on marine mammals depends on knowledge on the following acoustic parameters:

- **The physical range of the seismic source:**
  - The strength of the source (Source Level), relates to capacity, numbers of cells and total volume (inch³), air pressure, energy (kJoule);
  - The method of sampling (e.g. 2D, 3D);
  - Frequency bandwidth;
  - The firing interval and the duration of a single impulse.

- **The spatial and temporal distribution:**
  - The positions and timing of the exposed distance for each shot;
  - Multiple operations in more than one area of the DCS.

The final TSG noise report (Dekeling et al., 2014c) defined the following list of parameters as a requirement for the survey producer to be collected in a national common Regional Sea noise register:

- Position data (geographic position (lat/long), licensing block/area)
- Date of operation
- Source properties:
  - Essential (minimum)
    - Source level or proxy;
    - Source spectra;
    - Duty cycle;
    - Duration of transmissions (and actual time/time period);
    - Directivity*;
    - Source depth;
    - Platform speed.

*The directivity refers to the seismic source energy direction, of which much is guided downward. Data of directional plots are required in advance of a survey to assess the significance.

### 2.5 Acoustic properties of seismic sources

#### 2.5.1 Airgun sound source signature

A single airgun produces a bubble to bubble type of emission (Ziolkowski et al., 1982; Sertlek and Ainslie, 2015), which damps out as a function of time and affects the resolution of the subsurface image. The effects of multiple sources and the suppression of air bubble to bubble production are reviewed by Upadhyay (2013). To suppress the air-bubble production multiples airgun sources (“cells”) are clustered in an array in close range of each other and occur in all sampling techniques described. In 3D-seismic the array design is more complex and consists of an array of multiple parallel towed lines with the highest power in the most frontal section, declining towards the aft part with the position of each cell and capacity accurately designed (Figure A3).

#### 2.5.2 Airgun operational acoustic ranges

As airgun sources are applied in 90 % of the seismic operations and most of the available literature on measured sound levels refers to this type of operation (Goold & Fish, 1998; Thompson et al., 2013; ARCADIS, 2015) studies on the impact on harbour porpoise is referring to airgun operation, although sources with higher frequency emissions and lower sound pressure levels could have similar effect. The seismic acoustic signature consists of a repetition of single transients with varying interval and duration.
of transient. In the marine environment impulsive noise occurs on a natural basis (by marine animals for echo-location, communication and foraging) and as a consequence of human activity, like pile driving, seismic research and detonation of unexploded ordnance.

Airguns produce high impulsive sound pressure levels of predominantly low frequency sound by releasing controlled volumes of high pressure air into the water creating an oscillating bubble (Appendix A, Figure A3 and A4), with 90 % of the energy in the 70 to 140 Hz bands. Airguns are towed at a fixed water depth ranging between 3 m to 10 m below the sea surface, generally at about 6 m and rigged between floats at the surface. The applied airgun air pressure is in the range of 2000 psi (138 bar), while the firing interval ranges between 5 to 15 seconds.

The airgun capacity is referred to by its volume in litres (L) or in cubic inches (inch³, or in³). A 3D- airgun array consists of 3 - 6 sub-arrays called “strings”, each string containing 6 - 8 individual cells, so that the array usually involves between 18 and 48 cells. The airgun array volume is the sum of the volume of each cell, and can range from 3000-8000 inch³ (49.2-131.6 L). Operations on the DCS involve a volume of 1500 to 5000 inch³ (DNZ, 2011).

2.6 Acoustic terms and definitions relevant for seismic operation

In literature of seismic industry sound pressure of airguns is often reported as “peak-to-peak” (p-p) pressure in unit bar-meter (bar m). The bar is a unit of pressure equal to 100 kPa. The unit 1 bar m can be converted to the Pascal range (normally used to characterise underwater sound pressure) as shown in the next steps (Ainslie et al., 2009):

- 1 bar ≈ 100 kPa, so a bar metre can be converted to a pascal metre unit:
- 1 bar m ≈ 105 Pa m ≈ 1011 μPa m, or equivalently:
- 1 bar² m² = 1022 μPa² m².

Sound Pressure Levels based on measurement data are mostly referred to as “Root Means Square” (RMS), which hampers direct comparison of data with the total amplitude of the bipolar impulse (“peak to peak”), or to one of the parts (“zero to peak”) as references. For an ideal sinusoidal signal the RMS level is 9 dB lower than the peak to peak value and 3 dB lower than the zero-peak value. As the transients produced by seismic sources are not based on ideal sinusoids any simple conversion formulae is approximate and guidelines and proxies are required to compare acoustic data sources of seismic surveys and to investigate the impact to marine mammals.

The first steps towards international consensus on acoustic references and procedures for measuring underwater sound were defined by international working groups chaired by TNO (de Jong et al., 2011) and the National Physical Laboratory (NPL), Middlesex, UK (Robinson, 2011) and consensus reported inAinslie (Ed.) (2011) and further developed in the sessions of TSG noise working group sessions (Van Der Graaf, 2012 and Dekeling, 2014c).

The levels of acoustic quantities are expressed in two basic logarithmic rules (in decibels, dB):

- the level of a “field” quantity [3-21 of ISO 80000-3:2006],
- the level of a “power” quantity [3-22 of ISO 80000-3:2006].

The level $L_F$ of a field quantity $F$ is $L_F = 20 \log_{10}(F/F_0)$ dB, where $F_0$ is the reference value of the field quantity (referred to as “20logF rule”).

Similarly, the level $L_P$ of a power quantity $P$ is $L_P = 10 \log_{10}(P/P_0)$ dB, where $P_0$ is the reference value of the power quantity (referred to as “10logP rule”).
Dekeling et al. (2014c) proposed to use a mixed rule, with the $20\log F$ rule for the Sound Pressure Level (SPL) related quantity with $1 \, \mu Pa$ as factor reference and for the Source Level (SL) quantity with $1 \, \mu Pa \, m$ as factor reference) and the $10\log P$ convention for others (e.g., $1 \, \mu Pa^2 \, s$ for SEL and $1 \, \mu Pa^2 \, m^2 \, s$ for energy source level).

An overview of acoustic definitions is reported by Ainslie (Ed.) 2011 and as Glossary in van der Graaf et al. (2012). In this review we refer to the DIS18405 and DIS 18406 terminology or additionally to Dekeling et al. (2014c) with the most relevant underwater acoustic terms for the impact of seismic noise on harbour porpoise:

- **The energy source level (ESL) $L_{E,SL}$** refers to level of the energy source factor $S_E$ against a specified reference factor $S_0$ and is a measure of power, following the "$10\log P$ rule" (in dB re 1 $\mu Pa^2 m^2 s$).
  - For short pulses, changes in the shape of the pulse can occur over time (e.g., due to multipath propagation). Unlike the SPL measure, the energy source level SEL is not affected by changes in pulse shape, and so it is a more robust measure than zero to peak, peak to peak or RMS sound pressure for the characterization of short pulses. In addition the SEL_{ss} of a single impulse is a more practical measure for reporting the received levels. (Dekeling et al., 2014c).

- **The source level (SL) $L_{SL}$** refers to the strength of the source.
  - According the "$20\log F$ rule", unit in dB re 1 $\mu Pa^2 m^2$ (Dekeling et al., 2014c).
  - In literature (Dragoset, 2000, in Ainslie (Ed.), 2011) "source strength" $F$ refers to the zero to peak source level of the dipole formed by airgun array plus surface image according to $SL_{zp} = 20 \log_{10} (F/(\mu Pa \, m))$ dB (Ainslie (Ed.), 2011).

- **The sound pressure level (SPL) $L_{P, SPL}$** is a field quantity and follows the "$20\log F$ rule", additional factors to define are frequency bandwidth and time duration.
  - **Peak SPL** $L_{P,Peak}$ expresses the level of the peak sound pressure $P_{Peak}$, against a specified reference pressure $P_0$ the peak sound pressure (unit in $\mu Pa$).
  - **RMS SPL** $L_{P}$ expresses the level of the root-means-square pressure $P_{RMS}$, against a specified reference pressure $P_0$ (unit in $\mu Pa$). $L_P$ measurements are used to quantify continuous noise, like ambient noise (section 2.6.1). The $L_{eq}$ is used in air-born acoustics and refers to the averaged equivalent RMS noise level over a one-minute period.

- **The maximum of the compressional pressure of the transient, peak sound pressure (in Pa), indicative for the maximum sound pressure magnitude at one location.**

- **Sound Exposure Spectral Density ($E_F$)** refers to the unweighted sound exposure $E$ per unit of bandwidth in units of Pascal squared per Hertz (unit in Pa$^2$ s/Hz) (DIS 18405).
  - The hearing in marine mammals is limited by a subset of sound frequencies, depending on their perception mechanisms. It is therefore necessary to describe how the power of sound relates to the frequency (Van der Graaf et al., 2012). The Sound Exposure Spectral Density ($E_F$) represents the average sound pressure for each band of width 1 Hz.

- **The sound exposure level (SEL) $L_{SEL}$** refers to the accumulated sound level over a defined duration, often 1 second (unit in dB re $\mu Pa^2 s$) within a specified bandwidth.
  - Unit according the "$10\log P$ rule" proposed by (Dekeling et al., 2014c).
  - The SEL enables the comparison of sounds of different durations.

- **The SEL of a single transient or ”strike“ ($SEL_{ss}$)** refers to the total sound level with the duration typically chosen as 5 and 95 % of the total energy, where the energy has reached 90 % contents, known as $T_{90}$ (Madsen, 2006). The signal corresponding to the $T_{90}$ time window is filtered in one-third octave bands to investigate the energy distribution over the frequency bandwidth.
When considering the impact on marine organisms, broader frequency bands are often chosen, with one-third octave bands most commonly used (van der Graaf et al., 2012) and defined in ISO 13261-1:1998. Given the minor changes in frequency ratio the use of “one-third octave” as a synonym of decidecade is deprecated (DIS 18405).

- The cumulated sound exposure level ($SEL_{cum}$) refers to the level of the cumulated sound exposure over multiple transients (used in the latest draft DIS 18406).
- This $SEL_{cum}$ outcome is sometimes weighted using species-specific weighting functions (e.g. Southall et al., 2007; Tougaard et al. 2014).

### 2.6.1 Background Noise

The first TSG noise sessions (Van der Graaf et al., 2012) indicated the lack to define elevations of ambient noise from anthropogenic sources that would cause the marine environment to not be at GES. The origin is a lack of knowledge on the impact of elevated ambient noise on the marine environment. Hence an advise on a threshold level of ambient noise that could be set as a target for this indicator. Shipping and seismic surveys have shown to be the main contributors to low frequency ambient noise (Ainslie (ed.) 2011). A first step would be to define measures and terms for ambient noise trends as recommended by TSG Noise to Member States and “to start a measurement programme as soon as possible in order to be able to define the current levels and trends in ambient noise (from shipping) by 2018”.

In the MSFD (Dekeling et al., 2014c, Indicator 11.2.1.) Member States are required to monitor annually the averaged background noise, in particular in one-third octave bands centred at 63 Hz and 125 Hz. The purpose of this section is to present annually averaged noise maps in one of these frequency bands for anthropogenic noise sources on the DCS (Dekeling et al., 2014c). Qualifications for ambient and background type of noise were addressed by van der Graaf et al. (2012) as: “Ambient noise is commonly defined as background noise without distinguishable sources”. However, this means that identifiable sources will have to be considered as party of the result. Other contributing sources are related to “self-noise” related to the deployed equipment, like flow noise and cable strum and non-acoustic contributions such as electrically induced noise (“pick-up noise”), all contributing to the recorded signals. These contributions should be minimized and should not be added to the trends. Trends defined in TSG noise are: “general direction in which something is developing or changing. In the context of monitoring, ‘trend’ refers to year-to-year (or longer) changes in a specific quantity” (van der Graaf et al., 2012).

TSG noise (Dekeling et al., 2014c) concluded to aim for a metric of continuous ambient noise that reflects cumulative chronic effects of shipping noise and advised to adopt the arithmetic mean (AM). The AM-approach will include all sounds, so there is no risk of neglecting important ones and the result is independent of snapshot duration. However, a concern was raised that this approach could also mask important acoustic cues (Tasker et al., 2010), such as the duration of the period of (relative) silence between intermittent sounds.

TSG noise recommended sound pressure level as a function of time, with an averaging time to be specified and to use a snapshot duration not exceeding one minute. Such an approach could be the $L_{eq}$ metric of air acoustics. The European Noise Directive uses the AM (in the form of an annually averaged $L_{eq}$) for airborne noise. This quantity is normally measured in different settings, like “fast” mode, in which the sampling within the fixed one-minute period variable, like 125 ms as used a recent analysis of the emissions of a single airgun (Hermannsen et al., 2015). For ambient noise a 1 s sampling would be recommended to keep track of the 1 Hz spectral levels.
2.7 Acoustic seismic properties based on real measurement sources

Knowledge on the propagation of seismic sound in shallow waters like on the DCS (< 50 m depth) is sparse, especially for the components radiated in the horizontal direction into the water column, and outside the frequency band of interest for seismic inspection. Caldwell & Dragoset (2000) estimated that of a typical 3D-seismic array the SPL developed in horizontal direction is significant and can be 20 dB lower than the SPL in vertical direction. Large airgun arrays generate typical peak-to-peak energy source levels in the range 222-261 dB re 1 μPa²m²s (DeRuiter et al., 2006) with the energy peaking in the range 10 to 250 Hz. However, energy at higher frequency range can be significant. Madsen et al. (2006) showed that airgun arrays may generate significant sound energy at frequencies many octaves higher than the designed range. Blackman et al. (2004), Caldwell and Dragoset (2000), Goold and Fish (1998) showed that the airgun energy source level at frequencies up to at least 1 kHz is about 40 dB re 1Pa²/Hz less than at 50 Hz, while at 10 kHz an energy level could still be 160 dB re 1 μPa² (Goold & Fish, 1988).

The radiated sound by airgun arrays measured at some distance was characterized by sound pressure level, peak sound pressure, or sound exposure level (e.g. Madsen, 2006; Ainslie, 2010, Caldwell & Dragoset, 2000). Hermannsen et al. (2015) tested a single airgun in shallow water conditions at different volumes (10, 25 and 40 inch³) and measured the emission at three air-pressure ranges (53-56, 114-117 and 120-122). Back calculated levels at the source for the one-minute averaged SPL (L_RMS) and SEL showed respectively levels of 200 dB re 1 μPa (sampled over a 125 ms time window) and (SEL) 192 dB re 1 μPa²s. The propagation losses over the measured distance range of 1300 m was according to a 18Log(r) geometric model. They found that a relatively small size gun can produce significant levels and that the risk of causing hearing damage when using single airguns in shallow waters is small for both pinnipeds and porpoises. However, there is substantial potential for significant behavioral responses out to several km from the airgun, well beyond the commonly used shut-down zone of 500 meters.

In Table 1 an overview of research references is shown based on measured noise data applicable for the exposure of the impact on harbour porpoise.

Table 1. Overview of seismic airgun studies with results of noise levels and distance ranges.

<table>
<thead>
<tr>
<th>Seismic source (inch³)</th>
<th>SL (dB re 1 μPa m)</th>
<th>SPL (dB re 1 μPa)</th>
<th>SEL (dB re 1 μPa²s)</th>
<th>L_pp (dB re 1 μPa)</th>
<th>Distance range (km)</th>
<th>Reference</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>2120 (2D)</td>
<td>140 (200 Hz)</td>
<td>165-172</td>
<td>165-172</td>
<td>242-253</td>
<td>5 to 10</td>
<td>Thompson et al. (2013)</td>
<td>Location Moray Firth. Firing interval 5-6 s Waterdepth airgun 50 m, measured depth 10 m</td>
</tr>
<tr>
<td></td>
<td>90 (20 kHz)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Goold &amp; Fish (1998)</td>
<td>Location west Wales. Hydrophone array/guarding vessel, limited range ≤ 8 km mainly ahead of the airgun vessel.</td>
</tr>
<tr>
<td>470 (2D)</td>
<td>120-125*</td>
<td>140 – 148*</td>
<td>61.8</td>
<td></td>
<td></td>
<td>ARCADIS (2015)</td>
<td>Survey area 33 x 36 km² north of Wadden islands. No data &gt; 30 km. Background noise 120 to 130 dB re 1 μPa²</td>
</tr>
<tr>
<td>3147 (3D)</td>
<td>138 to 175</td>
<td>162 to 202</td>
<td>0.668 to 30</td>
<td></td>
<td></td>
<td></td>
<td>*(taken from reported graphs)</td>
</tr>
</tbody>
</table>
In the Arcadis (2015) research project a large variation due to the aspect angle relative to the array direction was measured: sound exposure levels were up to 15 dB lower for angles away from broadside. The local background SPLs were in the range of 120 to 130 dB re 1 µPa, while the SPLs in the shortest range were between 150 and 180 dB re 1 µPa. The measured signals were strongly frequency dependent. For nearby shots, the third-octave band SELs peaked between 125 and 250 Hz and were approximately 40 dB lower at 10 kHz. Pulse durations were not systematically investigated, but pulses stretching up to 0.5 s due to propagation in shallow water can be observed for some examples in ARCADIS (2015).

Sound exposure levels reported by Thompson et al. (2013) for a 470 inch³ airgun array are somewhat lower than for the for the 3147 inch³ array measured by ARCADIS (2015). For the 470 inch³ airgun array SEL of approximately 160 dB re 1 µPa²’s were reached at 1.5 km distance from the source, whereas these levels were reached at approximately 5 to 7 km for the larger array. For the 470 inch³ airgun array SEL of approximately 140 dB re 1 µPa²’s were reached at distances of approximately 25 km, whereas these levels were exceeded by a few dB at approximately 30 km (the maximum measured distance). The SPLs (peak-to-peak) required for long range avoidance effects ranged between 156.7 dB 1 µPa (35.5 km) and 146.3 dB 1 µPa (45.1 km). Although both surveys took place in relatively shallow water, a direct comparison between the noise levels is complicated by differences in aspect angles, receiver location and environmental conditions.

2.8 Models for predicting propagation of seismic emissions

The produced sound pressure levels and frequency range depend on the type of source or cell, the configuration or clustering of cells and the towing depth. The propagation of the emissions will depend on the bathymetry, the sea state conditions, sediment structure and water depth. To estimate sound levels produced in different environments, propagation loss models were developed, but their validity depends on the availability of acoustic measurements, data quality and distance range acquired of seismic sources operating in representative conditions for the North Sea. Most propagation models for shallow water produce estimates of sound exposure level for impulsive sound sources. Other quantities such as peak sound pressure, or sound pressure are harder to model and to validate due to sensitivity to environmental conditions.

2.8.1 Source models for airgun arrays

A range of source models exist that can predict the far-field source properties of airgun arrays: NUCLEUS (Petroleum Geo Services (PGS)), GUNDALF (Laws, 1980), JASCO airgun model (MacGillivray, 2006), and AGORA (Sertlek & Ainslie, 2015). These models model the dynamics of the oscillating air bubbles released by the airguns (e.g. Ziolkowski et al., 1982), and are validated typically up to frequencies of 2 kHz, but become more uncertain at higher frequencies due to the mechanisms of bubble-bubble interactions, and movement of the air gun sources in the water column (e.g. Sertlek & Ainslie, 2015).

2.8.2 Sound propagation models

The propagation of sound in shallow water environments like the DCS is complex. The absorption of sound in seawater forms part of the total transmission loss of sound from a source to a receiver. It depends on the seawater properties, such as temperature, salinity and acidity and the frequency spectrum of the sound. The details of the underlying physics of absorption are quite complex. Note that the absorption causes only part of the transmission loss. Usually, the major contribution to transmission loss is the spreading of the acoustic wave as it propagates away from the source.
Other than noise developed from stationary sources like windfarm piling, the seismic source is towed and a hydro-dynamic factor is added to the propagation of the emissions, with the bathymetric conditions and towing direction as variables.

Different model approaches exists. Some are based on empirical measurements, and others rely on more complex descriptions of underwater sound propagation mechanisms. Also different models can be adopted depending on the frequency range considered.

A simple propagation estimate was proposed by Thiele (2002), where the sound propagation is approximated by a spherical and cylindrical model and the intermediates per frequency (Figure 5) with 10 and 15 log distance. This model was suggested for use in North Sea & Baltic waters with a water depth up to 100 m and a sandy substrate with a wind speed range ≤ 20 knots.

![Figure 5. Transmission loss models according spherical (20 log R) and cylindrical spreading (10 log R) and the models for 0.1 and 2 kHz according Thiele (2002) in Thomsen et al., 2006.](http://cmst.curtin.edu.au/products/actoolbox.cfm/)

The transmissions losses estimated by Thompson et al (2013) were based on a combination of parabolic (http://cmst.curtin.edu.au/products/actoolbox.cfm/) and ray-trace (http://oalib.hlsresearch.com/Rays/) models for low- and high-frequency components, respectively and assuming the point source being towed 73 m behind the vessel at 6 m depth.

### 2.8.3 Aquarius propagation model

TNO developed a propagation model “Aquarius” (version 1.0) based on the reports of Weston (1971, 1976) in Heinis and de Jong (2015). This model predicts the spreading of the sound, based on the properties of the sound, bathymetry sediment and wind conditions and it outputs underwater sound maps.

The measured acoustic SEL was compared to modelled SEL predicted using the TNO propagation modelling in ARCADIS (2015). The TNO study reported in ARCADIS concludes that "At 10 km distance from the seismic source the SEL based on the model TNO model prediction was 141 dB re 1 µPa²s, against 152 dB re 1 µPa²s measured. The SEL values predicted by the modelling approach were generally shown to agree with measurements (to within modelling uncertainties) at ranges less than 2 km, equivalent to approximately 60 water-depths. At distances exceeding 2 km, the model was shown to predict a fall-off of SEL with range that was significantly more rapid than that observed in the measured data. At a distance of 10 km, the measured SEL values are between 148-155 dB re 1 µPa²s, while the model predictions are typically 10 dB lower than this at the same distance". This shows that sound propagation in shallow water at long distances is still not well understood and may result from
uncertainties in the source model, the sound propagation model, the interface between the source and propagation model, or input parameters to any one of the models.

2.8.4 Sertlek source (AGORA) and sound propagation (SOPRANO)

In a recent study of Sertlek and Ainslie (2015) the complex sound source signature is described for airgun arrays using the AGORA model. Sound maps were generated by combining the source model with a propagation loss, which was calculated by a hybrid method based on normal modes and flux theory (SOPRANO model; Sertlek and Ainslie, 2015). Range dependent propagation equations and results for the Pekeris waveguide (Sertlek et al., 2015). These calculated signatures were used to generate annually averaged seismic survey maps of the Dutch North Sea generated at the center frequencies of 1/3 octave bands (Figure 6). These maps are shown for 3D seismic surveys of 2007, and were based on information for these particular surveys found from the reports on the NLOG web portal. The AGORA source model was validated against measurements of individual airguns, and also used in the comparison of model predictions to measurements of a full airgun array in ARCADIS (2015).

Figure 6. Annually averaged seismic survey sound maps of the North Sea for 2007 at the center frequencies of 1/3 octave band from 30 Hz to 3 kHz. The receiver depth is 1 m. The green lines show the Dutch coastline and the DCS outline (taken from Sertlek & Ainslie, 2015).

2.9 Spatial and temporal use of seismic operation on the DCS

The DNZ 2011 report shows that 2D seismic operations declined in the years beyond the 1990s (Figure 7), while 3D-seismic surveys are the main type of seismic technique applied and that these operations covered the complete DCS (Figure 8), except for the most southern part, which is probably related to shipping intensity.
The reported total airgun volume ranged between 1500-3000 inch$^3$ (DNZ, 2011). Furthermore the DNZ 2011 report indicates that these figures did include personal interviews of TNO experts and that they were not achieved by using data portals only.

The spatial use of seismic surveys on the DCS and the use of areas outside these boundaries raises the question on the temporal distribution and if simultaneous operations in multiple areas on the DCS would occur, as these would increase the complexity of impact on marine animals. Based on information of the annual reports of the "Staatstoezicht op de Mijnen, 2004, Ainslie et al. (2009) concluded that 3D-surveys had the highest contribution to the annual acoustic energy budget.
The average area covered by 3D-surveys between 2000 and 2004 was 1370 km²/y and 1490 km² in the period 2003-2007 ("Staatstoezicht op de Mijnen", 2007). Based on an estimate of 70 airgun shots per square kilometre we find a total of 98,000 shots per year. Based on a peak-to-peak source level of 255 dB re 1 µPa²m², and 1 MJ/strike, the total mean energy estimated was 100 GJ/y (with uncertainties incorporated 30-300 GJ/y).

The final report of TGS surveys conducted between 2003 and 2007 (TGS-Final Report 474, derived from the NLOG web portal) shows that the exposed areas overlapped and varied per year and that they were conducted predominantly in UK and Norwegian waters (Figure 9b). Secondly, these operations concerned 2D-seismics with a relatively large airgun volume of 3100 to 5000 inch³ and are in the upper range of seismic exposure ranges, which is significantly higher than the 3D-range of 1500-3000 inch³ reported in DNZ (2011). A second observation is that some of the 2D-transects could also involve very long single line transects not limited to a particular area (Figure 9a and b).

Another point of concern is that the NLOG web portal does not provide a full coverage of seismic surveys on the DCS. The most recent annual overview 2D and 3D surveys over the period 2000-2012 were distributed by TNO-GND for this purpose (source TNO-Geology, pers. communication. J. Hettelaar, TNO-GDN) and based on documents supplied by the operators; digital information is not available or stored elsewhere. Information on the operational conditions, the applied seismic source and temporal positions as most vital information could not be delivered, not excluding their existence.

Figure 9 a & b. Overview of seismic operations on the DCS between 2000-2012 (9a left) and (9b right) annual 2D-seismic surveys of the TGS-Renaissance survey, conducted between 2003 (yellow), 2004 (purple), 2005 (red), 2006 (green) and 2007 (blue) (NLOG web portal).
2.10 2D-seismic operations between 2004-2011

Other than the DNZ 2011 report suggests (Figure 7) 2D-seismic executed in other fields appeared significant and involved a total distance of 9091 km in the period between 2004 and 2011 (pers.communication TNO-GND, Sytze van Heteren). Surveys executed by TNO-Geology in the Dutch coastal waters in the period between 2000 and 2007 involved single-channel surveys (Figure 10a) and multi-channel surveys (Figure 10b), mainly on near-shore locations, including Westerschelde (2005), Maasvlakte (2007), Betonzand (high res. grid near Maasvlakte – 2001), Hoek van Holland (high res. grid – 2000), Katwijk Zuid (high res. grid 2000), Katwijk Noord (2001), Bergen (high res. grid 2001), Den Helder & Petten (2005), Ameland (2005), Noordelijke Blokken (2002). The total exposed distance was 9180 km.

The only sources on the NLOG web portal for 3D-seismic operation are based on annual reports per year. Detailed information is not directly available other than the acronyms of the surveys listed in the portal. A total of 14 survey lists (3D) were found for 2013 (8) and 2014 (6).

Figure 10 a & b. Single (a) and multi (b) channel surveys conducted by TNO-Geology between 2000 and 2007.

2.11 Temporal use of seismic surveys on the DCS

For the temporal use of survey data from the existing web portals (NLOG) detailed timeline information is required of the positions and timing of seismic sequences. 3D-surveys are operationally more complex, including sophisticated instruments and more detailed reports. Sertlek and Ainslie (2015) used the production log of a 3D-survey (NLOG_SMC_1321_Z3PGS2007A_2007066_ATL_Wintershall) to extract the positions for each single firing (Figure 11) leading to the sound propagation maps of Figure 6.
12.6 Production log

<table>
<thead>
<tr>
<th>Seq</th>
<th>Salt Lims</th>
<th>FGSP</th>
<th>LGSF</th>
<th>Orientation</th>
<th>Mode</th>
<th>Type</th>
<th>Status</th>
<th>Date</th>
<th>SQL UTC</th>
<th>EOL UTC</th>
<th>km</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1896FLP</td>
<td>3590</td>
<td>1375</td>
<td>231.6</td>
<td>3D</td>
<td>Prime</td>
<td>Good</td>
<td>13/12/2007</td>
<td>23:17:13</td>
<td>01:31:08</td>
<td>32.2502</td>
</tr>
<tr>
<td>2</td>
<td>2266FLP</td>
<td>3590</td>
<td>1375</td>
<td>231.6</td>
<td>3D</td>
<td>Prime</td>
<td>Good</td>
<td>13/12/2007</td>
<td>04:03:19</td>
<td>07:42:05</td>
<td>27.6750</td>
</tr>
<tr>
<td>3</td>
<td>1882FLP</td>
<td>1007</td>
<td>3661</td>
<td>231.6</td>
<td>3D</td>
<td>Prime</td>
<td>Good</td>
<td>13/12/2007</td>
<td>10:48:14</td>
<td>14:52:13</td>
<td>32.3275</td>
</tr>
<tr>
<td>4</td>
<td>2164FLP</td>
<td>2590</td>
<td>1357</td>
<td>231.6</td>
<td>3D</td>
<td>Prime</td>
<td>Good</td>
<td>13/12/2007</td>
<td>17:20:43</td>
<td>20:39:59</td>
<td>27.6750</td>
</tr>
<tr>
<td>5</td>
<td>1876FLP</td>
<td>1049</td>
<td>3909</td>
<td>51.6</td>
<td>3D</td>
<td>Prime</td>
<td>Good</td>
<td>13/12/2007</td>
<td>23:49:39</td>
<td>03:40:07</td>
<td>32.6375</td>
</tr>
<tr>
<td>6</td>
<td>2162FLP</td>
<td>3535</td>
<td>1335</td>
<td>231.6</td>
<td>3D</td>
<td>Prime</td>
<td>Good</td>
<td>14/12/2007</td>
<td>06:18:33</td>
<td>09:34:58</td>
<td>27.4750</td>
</tr>
<tr>
<td>7</td>
<td>1858FLP</td>
<td>1031</td>
<td>2667</td>
<td>51.6</td>
<td>3D</td>
<td>Prime</td>
<td>Good</td>
<td>14/12/2007</td>
<td>12:25:14</td>
<td>16:13:46</td>
<td>32.8375</td>
</tr>
<tr>
<td>8</td>
<td>2159FLP</td>
<td>3558</td>
<td>1321</td>
<td>231.6</td>
<td>3D</td>
<td>Prime</td>
<td>Good</td>
<td>15/12/2007</td>
<td>18:41:52</td>
<td>21:51:07</td>
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</tr>
<tr>
<td>9</td>
<td>1868FLP</td>
<td>1013</td>
<td>3005</td>
<td>51.6</td>
<td>3D</td>
<td>Prime</td>
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<td>00:43:30</td>
<td>04:40:05</td>
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</tr>
<tr>
<td>10</td>
<td>2158FLP</td>
<td>3522</td>
<td>1303</td>
<td>231.6</td>
<td>3D</td>
<td>Prime</td>
<td>Good</td>
<td>15/12/2007</td>
<td>07:09:52</td>
<td>10:22:24</td>
<td>27.8750</td>
</tr>
</tbody>
</table>

Figure 11. Example of a part of the production log of a 3D survey acquired for Wintershall

This 3D-survey was conducted in the winter months of 2007 and 2008. The timing of the operation illustrates the opportunities as a function of the sea state conditions, showing that the production was conducted below sea state 4 condition and the survey was interrupted above this condition (Figure 12).

Figure 12. Daily production scheme of the 3D Wintershall survey, showing the down-time was < 50% (NLOG_SMC_1321_Z3PGS2007A_2007066_ATL_Wintershall).

2.12 Measures to improve efficiency and new technologies

In the reports of Weilgart (2010) and Bureau of Ocean Energy Management, BOEM (CSA Ocean Sciences Inc., 2014) alternative techniques were reviewed with potential to reduce the impact of seismic
operations to the marine environment. These techniques involve new airgun designs to reduce emissions in frequency ranges > 200 Hz and measures to reduce inefficient emissions in the horizontal radiated sound field. Lower source levels of seismic equipment could be achieved through system optimization, i.e. an improved pairing of source and receiver performances. New receiver technologies, with fibre optic receivers, were mentioned to improve the overall system noise level and so enabling lower source levels. Re-engineered airguns with "mufflers" can be used to attenuate unwanted high frequency energy without affecting frequencies of interest. Bubble curtains could improve the directivity of the source, but they hamper the operational use and add to noise. The use and development of alternative technologies were presented by the industry on the Okeados workshop of 2009 in Monterey, California, USA (Weilgart, 2010). Controlled sources, such as marine vibrators (e.g., hydraulic, electric generators) offer the opportunity to reduce the overall source level and to tune the frequencies transmitted to exactly the bandwidth required for operations. A broad calculation in the near-field, a one-second oscillatory / vibrator / projector pulse equals the geophysical amount of energy as an airgun, but would be one-hundred times quieter, resulting in a ten-thousand fold reduction in the exposed area (Weilgart, 2010). A number of alternative technologies and sources were reviewed, such as the electromechanical modern marine vibrator, low frequency acoustic projector (driving cylinder, e.g. Low Impact Seismic Array, LISA), a solid state piezo-ceramic Helmholtz resonator (e.g. The U.S. Naval Research Laboratory’s DTAGS, Deep-Towed Acoustics Geophysics System), and other non-impulsive, oscillating sound sources (see also Appendix A, Table 1). By applying a marine vibrator in sweep mode the harmonic energy can be attenuated which enables a reduction of the overall peak power with about 30 dB. The application of Marine Vibrators for 2D-, 3D- and 4D-seismic operations, including deep subsurface imaging was deemed feasible.

Improvement of the present airgun technique are proposed that increase the falling and rising edges of the impulses, which reduces the high-frequency contribution in the 0.5 to 1 kHz range by 10 dB and are likely to be used in future 4D operations (Coste et al., 2014).

The operational aspects of alternative sources producing lower energy sound levels at higher frequency ranges will have to be weighed against the hearing thresholds of harbour porpoise to estimate their potential progress against the conventional technology. Other acquisition techniques using conventional airgun arrays are explored to reduce peak levels. For instance, the use of ‘pop-corn’ shooting methods (Coste et al. 2014), in which multiple airgun shots are distributed over time, and digitally aligned in the post-process. It still needs to be demonstrated that this technique provides the same quality, before becoming accepted by the E&P community. Also this type of shooting would require some adaptation of conventional arrays to control the timing of individual guns.
3 Potential effects on harbour porpoise

3.1 Harbour porpoise

The harbour porpoise (*Phocoena phocoena*) is the most abundant marine mammal species in the North Sea. It is a protected species under European legislation (i.e. the EU’s Habitat Directive). The Netherlands has signed international (North Sea Conservation Plan ASCOBANS) and national agreements on the protection of the harbour porpoise in the Dutch national porpoise conservation plan (Camphuysen & Siemensma, 2012).

The North Sea population is estimated at 386,000 animals in 2005 (Hammond et al., 2002, 2013). Between the first North Sea wide SCANS survey in 1994 and SCANS II in 2005, the harbour porpoise population has undergone a redistribution across its range (Hammond et al., 2002, 2013), resulting in an increase in harbour porpoise abundance in Dutch waters (Camphuysen, 2004). The maximum numbers in Dutch waters were estimated at approximately 86,000 animals in March 2011 (Geelhoed et al., 2013). Numbers in summer and winter are lower, but only a few estimates for these periods are available (Geelhoed et al. 2014; Scheidat et al., 2012).

Harbour porpoises feed mainly on fish. Since they have a high metabolic rate and a relatively thin blubber layer (Lockyer, 2007), they have a limited ability to cope with prolonged starvation (Kastelein et al., 1997) and are highly dependent on a sufficient intake of prey.

Harbour porpoises spend their entire life in the water. They are mammals and have to come to the surface to breathe. Hearing is the primary sense for harbour porpoises, which use sound for communication, navigation, detection of prey and echolocation. Harbour porpoises have extremely sensitive hearing, which makes them vulnerable to noise-induced effects from anthropogenic activities at sea (Kastelein et al., 2010; 2012a-b; 2013a-d; 2014a-b; Lucke et al., 2009). The harbour porpoise audiogram is U-shaped with the range of best hearing from 16 kHz to 140 kHz. Some individuals have a reduced sensitivity around 64 kHz. The maximum occurs between 100 kHz and 140 kHz. This range corresponds to the peak frequency of echolocation pulses produced by harbour porpoises (120-130 kHz). The main part of the energy of the echolocation pulses is around 132 kHz in a narrow band between 120-150 kHz (Au et al., 1999). Hearing sensitivity falls about 10 dB per octave below 16 kHz and shows a sharp decline above 140 kHz. To predict possible effects of seismic activities propagated spectra in the frequency range between 16 – 140 kHz should be also considered. Kastelein et al. (2015) showed that impulsive pile driving sounds with most of their energy in the low frequencies (500-800 HZ) can cause reduced hearing at higher frequencies in harbour porpoises. This means that most airguns should be considered as potentially impacting harbour porpoises, since 90 % of their emitted energy is in the 70 to 140 Hz bands.

3.2 Potential effects of sound exposure

Hearing is the primary sense for harbour porpoises. As a consequence, anthropogenic underwater noise can have significant disrupting effects on harbour porpoises by interfering directly with the animals auditory sense, inducing behavioural changes or indirectly inducing behavioural changes in prey species. Effects can work on individuals but can have long-term effects on population level as well. Potential effects on harbour porpoises can be divided in different categories, summarized by Gordon et al. (2003):
Indirect effects

- Reduced prey availability

Chronic effects

- Stress leading to reduced viability or disease

Behavioural effects

- Disruption of normal behaviour (e.g. avoidance of an area, changes in dive and respiratory pattern, disruption of feeding)

Perceptual effects

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

Physical effects

- Damage to body tissues such as crushing, fracturing, hemorrhages, and rupture of body tissues caused by a blast wave, resulting in immediate or eventual mortality
- Gross damage to ears or ear trauma resulting in a permanent hearing loss (and consequently mortality)
- Permanent threshold shift (PTS: reduction in auditory sensitivity from which there is no recovery)
- Temporary threshold shift (TTS: reduction in auditory sensitivity with eventual recovery).

The main potential effects of the (impulsive) underwater sound of concern are either direct injury to an individual animal, or a behavioural disturbance and stress effects. Any of these effects could have consequences on a population level. The knowledge on potential effects of impulsive sound on marine mammals increased rapidly in recent years. Most studies focused on harbour porpoises, though there is increasing awareness that seals are more sensitive to sound than previously thought. Recently two Dutch studies have reviewed the current knowledge on potential effects of underwater explosions (Von Benda-Beckmann et al, 2015) and of offshore wind farms (especially pile driving, Heinis et al, 2015) on harbour porpoises in the North Sea. This chapter is largely based on the information compiled in these reports, and has been complemented with information regarding studies on effects of seismic sound on porpoises.

3.2.1 Physical effects

Physical effects of sound on marine mammals are scantily studied. Ketten (2004) exposed dead corpses (including harbour porpoises) to underwater explosions in a controlled environment. She found hemorrhage, fractures, lung and ear trauma. Peak overpressure levels at which effects were observed indicate that the inner and middle ear were the most sensitive tissues to the explosion shock wave. It is judged in this study that damage to the porpoise middle ear would likely result in a permanent, acute hearing loss, which could be broad spectrum in the case of middle ear damage or elevated thresholds in only some frequencies depending upon the received acoustics impacting the inner ear. It is not clear how these results translate to physical effects on living porpoises, or how to translate the effects of the experiment with explosions to effects of seismic surveys. The characteristics of airgun sound (peak sound pressure, SEL, rise time etc.) differ from those of explosions, and it is unlikely that seismic surveys in the North Sea will reach levels attained by explosions. Avoidance of seismic vessels by harbour porpoises will decrease their chance of being exposed to sound levels causing physical effects. Therefore, it is deemed unlikely that seismic surveys will cause primary blast injury on harbour porpoises.

3.2.2 Threshold shifts in hearing

Intense underwater sounds may cause hearing loss in harbour porpoises. This can result in threshold shifts in hearing ability that may be temporary (TTS) or permanent (PTS). This threshold shift may
depend on the sound level, spectral content, temporal pattern, and exposure duration. TTS can be caused by metabolic exhaustion or mechanical damage to hair cells in the inner ear. Noise exposure may lead to loss of sensory cilia or changes in their structure and rigidity. PTS occurs when the damage is non-recoverable. Recovery of hearing after a TTS, depends on the sound an animal was exposed to and the amount of threshold shift that occurred. Generally, there is a trade-off between exposure duration and sound level: low level sounds produce TTS only after long-duration exposure. The frequency range that is affected becomes broader with increasing received sound levels. Most studies follow Southall et al. (2007) and define TTS onset, with a TTS = 6 dB measured shortly (1-4 min) after cessation of the sound exposure. TTS in the frequency range of echolocation clicks of porpoises could limit a porpoise’s ability to echolocate and thus reduce an animal’s feeding efficiency and theoretically even cause starvation depending on the health and previous feeding conditions of the animal.

For harbour porpoises information on TTS is limited, and solely based on experiments with captive animals. Several studies have been conducted using continuous sound and impulsive sound, with single or multiple pulses. Von Benda-Beckmann et al. (2015) summarized the available information:

- Lucke et al. (2009) determined a masked TTS-onset level for a porpoise subjected to single airgun transients, measuring auditory evoked potentials. At 4 kHz the predefined TTS criterion was exceeded at received SELs higher than 164 dB re 1 μPa²s.
- In a study by Kastelein et al. (2011b) it was not possible to determine TTS risk thresholds using broadband, pulsed sound spectra, due to the fact that it was not possible to generate sound levels high enough to induce TTS in porpoises. It appeared that no TTS occurred at a broadband SEL of 115 dB re 1 μPa²s (broadband 1/3-oct. noise spectrum with a peak at 630 Hz; transient duration T₉₀ = 124 ms). Hearing was measured at 4 kHz.
- Recently, Kastelein et al. (2015) measured a TTS due to multiple pile driving playbacks. Exposure of 1 hr to these playbacks induced TTS at SEL of 180 dB re 1 μPa²s. Statistically significant TTS occurred at 4 and 8 kHz; no TTS was found at 2, 16, 125 kHz. Hearing was recovered within 48 min after cessation of the sound exposure. This study shows that exposure to multiple impulsive sounds with most of their energy in the low frequencies (500-800 Hz) can cause reduced hearing at higher frequencies in harbour porpoises. The porpoise’s hearing threshold for the frequency in the range of its echolocation signals was not affected by the pile driving playback sounds.

Measurements of PTS onset levels in marine mammals are not conducted. Currently, there is no single rule of thumb for PTS onset based on TTS onset. Southall et al. (2007) proposed thresholds for PTS that were based on studies in human threshold shifts and extrapolation of estimated TTS onset points for marine mammals using growth rates of impulsive sound measured in chinchilla’s. The onset of PTS is proposed to be 15-20 dB above the onset of TTS (Southall et al. 2007). Recent TTS studies by Kastelein et al. (2013c, 2014a,b) resulted in TTS growth curves for harbour porpoises, exposed to 1-2 kHz and 6-7 kHz intermittent and continuous sonar sounds. The differences in SEL thresholds for TTS onset between Kastelein et al. (2015) with Lucke et al. (2009) may be explained by the fact that the intermittency and frequency content of the two studies differed which are both expected to affect the risk of TTS (Kastelein et al. 2014 (sonar), 2015 (pile driving), Tougaard et al. 2015). As the sonar type of sound are in mid-frequency range these tests may not be a representative airgun TTS reference. However, they may gain importance when alternative sources with higher frequency, like boomers, are operated. It must be noted that both studies relied on a single individual, and differences are to be expected between individuals.
Effect distances for PTS and TTS

To estimate effect distances for hearing effects due to seismic sound, knowledge is required on the hearing sensitivity of animals to seismic sound, the sound field generated by the airgun array, the animals diving behaviour and the movement of animals relative to the source (e.g. Gedamke et al. 2011, von Benda-Beckmann et al. 2014, Wensveen et al. 2015). Here we assume that TTS, resp. PTS occurs when the SEL due to a single shot exceeds a threshold for SEL1 > 164 dB re 1 µPa ²s (based on Lucke et al. 2009) or when the cumulative SEL exceeds the SELcum > 180 dB re 1 µPa²s (based on Kastelein et al. 2015).

The effect distance for hearing effects due to a single shot can be estimated by comparing the measured SEL from ARCADIS (2015) to thresholds for a single airgun shot (SEL exceeds the 164 dB re 1 µPa²s). Levels that exceed this threshold were measured at around 5 km at broadside of the array (ARCADIS, 2015), and or 2 km at angles further away from broadside. The corresponding estimated SEL threshold for PTS, which is assumed to be 15 dB above the SEL threshold for TTS onset, would result in a SEL threshold of 179 dB re 1 µPa²s. This threshold was not exceeded in the measurements reported in ARCADIS (2015), where the highest levels were measured at a minimum distance of 668 m.

The risk of hearing effects due to accumulation of SEL over multiple exposures is more challenging to estimate, because of the lack of data on harbour porpoises swimming behaviour in the North Sea and responses to seismic sources. Methods have been proposed to model porpoise movement in the context of pile driving (Nabe-Nielsen et al. 2014; Heinis et al. 2015), however the applicability to seismic sources is unclear. Also it is not clear over what time the sound exposure needs to be accumulated. Commonly, an accumulation time of no more than 24 hours is adopted (e.g. Southall et al. 2007). The TTS study by Kastelein et al. (2015) suggest SEL threshold for TTS (ca 180 dB re 1 µPa²s) for the situation where animals at larger distances are exposed to a repetitive air guns sound over a longer period. As an illustration, consider an animal situated at a constant distance of 10 km at broadside of an array, which is being exposed to one airgun shot every 10 seconds for 60 minutes. The ARCADIS (2015) measurements would suggests that for a typical array a cumulative SEL = 155 dB re 1 µPa²s + 10-Log_{10}(1-60-60-0.1/(1s)) = 180 dB re 1 µPa²s. Therefore, even though a higher threshold is adopted, accumulation due to multiple pulses could lead to larger effect distances. Note that this scenario should be considered as an illustration, and more realistic movement patterns of the animal, as well as movement of the source and source directionality, should be accounted for to estimate the realistic effect distances for PTS.

3.2.3 Behavioural disturbance

Behavioural changes are expected before hearing effects occurs. Levels at which harbour porpoises show behavioural responses to impulsive sound under controlled condition are summarized in von Benda-Beckmann et al. (2015), Tougaard et al. (2015), Heinis et al. (2015). A few studies have been conducted that address the effects of impulsive sounds on captive harbour porpoises. Most studies were conducted in un-masked background noise conditions and used playback of piling sounds (Kastelein et al. 2011b, 2013b) but one study used airgun sound (Lucke et al. 2009). The results of these studies indicate startle responses and avoidance behaviour and will be discussed in section 3.2.3.1. Observations of effects of seismic surveys on harbour porpoises in the field are limited to studies in Scottish waters (Thompson et al., 2013; Pirotta et al., 2014) and in British Columbia (Bain & Williams, 2006). The results of these studies will be discussed in section 3.2.3.2.
3.2.3.1 Observed effects under controlled conditions

Kastelein et al. (2013) found no behavioural response at a level below a SEL of 63 dB re 1 μPa²s, by exposing a harbour porpoise to single pile driving sound playback. A brief startle response was observed at a SEL of 90 dB re 1 μPa²s. Exposure of a harbour porpoise to multiple semi-broadband impulsive sound evoked avoidance behaviour at a SEL = 115 dB re 1 μPa²s, unweighted levels (Kastelein et al. 2011b).

Onset of an avoidance response to a single airgun shot has been reported for a captive porpoise by Lucke et al. (2009). A consistent avoidance reaction for a SEL above 145 dB re 1 μPa²s was observed.

3.2.3.2 Observed effects in the field

Tougaard et al. (2015) proposed an update to the criteria from Southall et al. (2007) for harbour porpoises. They reviewed a series of known studies on thresholds for behavioural reactions caused by pile driving or acoustic deterrent devices showing avoidance of 'low-frequency' pile driving in the order of magnitude of 20 km. Reactions to 'mid-frequency' seal scarers are observed between 1-7.5 km, while 'high-frequency' pingers have a smaller reaction radius of approximately 200 m. Recent studies indicate that the most important factors determining a porpoise’s reaction is the signal loudness (expressed by L_{eq,fast}), which is determined by the stimulus duration and the sound level above the hearing thresholds, the so-called sensation level. Tougaard et al. (2015) propose an exposure limit to be L_{eq,fast} 45 dB above the hearing threshold. This suggests that frequency content, as well as the duration of the pulse need to be considered when predicting the effect distances for disturbance. Note that due to propagation effects in shallow water, both the frequency content and duration are affected by frequency selective propagation, and pulse stretching (see Chapter 2 for more detail). Thompson et al. (2013) showed that there was a drop in harbour porpoise activity (relative density and acoustic activity) at SEL values between 145 and 151 dB re 1 μPa²s. The approach from Tougaard et al. (2015) is similar to that adopted in von Benda-Beckmann et al. (2015) for predicting the effects of explosions on harbour porpoise behaviour. However, the Heinis et al. (2015) study proposed that the unweighted single-strike SEL\_1 = 140 dB re 1 μPa²s to be used for predicting the onset of avoidance for porpoises exposed to impulsive sound. Also note that the occurrence of a behavioural disturbance is likely to also depend on the context of the exposure: distance to the sound source, the animal’s age, sex, status, feeding condition etc. (Ellison et al. 2011, Miller et al. 2012).

Recently, Stone (2015) reviewed the observations from marine mammal observers on board seismic survey vessels in the years 1994-2010. The main conclusions of this review were:

- Median closest distance of harbour porpoises to the airguns changed from ca 650 m to ca 1100 m during firing of large arrays.
- Median closest distance for all small odontocetes is 800 m for source off, and 1400 m during soft-start. For harbour porpoise the observed numbers were too low to show significant differences.
- Avoidance behaviour of harbour porpoises was observed for small and large arrays.
- Sighting rates differed significantly with source activity (not firing versus soft start versus full power) for all small odontocetes combined that were able to be tested. In all cases, sighting rates during the soft start were significantly lower than when the airguns were not firing. For harbour porpoise the observed numbers were too low to show significant differences.
- It appeared that the soft start elicited increased avoidance compared to times during which no firing occurred and a decrease in positive interactions of small odontocetes with the vessel or its
equipment and in some cases also an increase in swimming speed (or fewer slow swimming behaviours).

Bain & Williams (2006) studied the effect of a seismic survey on marine mammals in British Columbia. The seismic survey consisted of generating shots with a towed array of 13 or 16 air guns with a total volume of 4820 or 6712 inch$^3$ (79 or 110 l), respectively. The maximum theoretical source level for the larger array was calculated to be on the order of 260 dB re 1 μPa. The airguns produced energy above ambient levels at all frequencies up to 100 kHz, although the peak frequency was quite low. They found that harbour porpoises were the most sensitive species and affected by the lowest peak to peak levels of airgun noise (155 dB re 1 μPa$^2$), and apparently showed avoidance over 70 km from the airguns. Sample sizes were too small to permit statistical testing.

A more recent study investigated whether a commercial two dimensional seismic survey in the Moray Firth in the North Sea led to changes in the occurrence of harbour porpoises (Thompson et al. 2013, see table 1 for details on noise levels). The 470 inch$^3$ airgun array was fired at intervals of 5 to 6 s on transects of 7 or 15 km long and took respectively 75–150 min to complete, resulting in regular noise exposure over a 200 km$^2$ area over a total period of 10 days. The estimated peak-to-peak source levels of the airgun array were 242-253 dB re 1 μPa m. Sound measurements showed that SPLs at 5-10 km from the source were 165-172 dB re 1 μPa, whereas SELs for a single airgun pulse were 141-151 dB re 1 μPa$^2$s (See chapter 2 for details). The measured sound levels exceed the threshold for a SEL of 145 dB re 1 μPa²s, that invokes avoidance by porpoises (Lucke et al. 2009). Thompson et al. (2013) found evidence for displacement of porpoises. The density of porpoises decreased in a 10 km radius. Analysis of CPOD data from the same seismic survey Pirotta et al. (2014) showed a reduction in buzzing activity by 15% in the remaining porpoises. This reduction could reflect disruption of feeding or social activities. Densities increased again after cessation of seismic activity. Therefore, Thompson et al. (2013) conclude seismic surveys do not lead to long-term displacement. However, their results can also be explained by immigration of new individuals. The initially exposed porpoises might have left the area completely, and could have been replaced by immigration of new animals.

3.3 Pile driving vs seismic surveys

The effects of seismic surveys on harbour porpoises are not directly deductible from the effects of pile driving on harbour porpoises. The sound characteristics of both activities differ in a number of aspects. Seismic surveys produce sound from a moving source, whereas pile driving is a stationary activity. Sound emission is a side-effect of the pile driving activity whereas it is a requirement of the seismic activity. Seismic surveys could potentially affect a larger area, due to movement of the source. On the other hand, the duration of the disturbance is potentially shorter. A comparison made in Heinis et al. (2015) shows that in terms of number of animal disturbance days (roughly the total area affected each day x number of animals present in the area) was comparable for these two activities when activities in the whole North Sea were considered (see next section). The number of animal disturbance days is a good indicator of the population changes as predicted with the Interim PCoD model (Heinis et al. 2015). In the scenario describing the international activities in Dutch North Sea waters as well as surrounding countries, for seismic surveys a reduction of 53,000 porpoises in the North Sea was modelled, the scenario for wind farms predicted a population reduction of 46,000 animals. The comparison was based on the following assumptions:

- annual area of 20,000 km$^2$ of 3D seismic surveys in the Southern North Sea
- 6 weeks of survey time is expected to cover 1000 km$^2$ (incl. 20% down time, the airgun is off), regardless of method, type of airgun and resolution;
- seismic surveys will be conducted from March to October;
• up to 8 surveys will be conducted in the North Sea simultaneously;
In the calculation a typical movement of the seismic vessels is taken into account.
• a duration of 6 weeks for a survey of an area of 1000 km². With 20% downtime that area will
be surveyed in ca 34 days, i.e. approximately 30 km² per day;
• with a track length of ca 25 km, an area width of ca 1.2 km per day shot.
• airguns are assumed to be 3090 inch³ and shoot at 2000 psi at 6 m depth
• threshold for disturbance is set at SEL₁ = 136 dB re 1 µPa²s

Some of these assumptions can be validated using recent measurements. For instance, modelled effect
distances for seismic surveys for a SEL₁ = 140 dB re 1 µPa²s contour in Heinis et al. (2015), ranged
between 20 km and 40 km, depending on the location of the array. This is in reasonable agreement with
the reported levels in ARCADIS (2015), where levels just exceeded the 140 dB re 1 µPa²s threshold by a
few dB at 30 km (the maximum measurement distance, see Chapter 2). An important underlying
assumption was that 2 hours of pile driving were equated to one day of disturbance. To account for
longer disturbance, as shown by some studies, Heinis et al. (20150 assumed an extra so-called residual
day of disturbance in some scenarios. For seismic activity there may be 24 hours of shooting, which
would also count as one day of disturbance, without a residual day of disturbance. However, it is unclear
if a single animal would be continuously disturbed throughout that period. One of the key underlying
questions is how does this disturbance compare between the two different sources, and thus how to
accumulate effects of these sources?

For seismic 2D surveys with 490 inch³ array as used in the Moray Firth (Thompson et al. 2013)
avoidance up to 10 km was measured. Hermannsen et al., 2015 measured the propagation effects of a
single airgun of 10 to 40 inch³ at different air-pressure ratings and concluded that even with small single
airgun systems avoidance is likely to occur at several kilometres and the commonly used shut-down zone
of 500 meters not an appropriate measure. With larger arrays used for 3D surveys in the Dutch part of
the North Sea (e.g. a 3147 inch³ array measured by ARCADIS 2015, see table 1 for details on noise
levels) levels predicted to cause disturbance can occur in a radius of approx. 30 km. In the Dutch part of
the North Sea avoidance behaviour is therefore expected to occur till 30 km from the sound source. It is
unclear what the role of distance to the source, and other contextual variables would influence the
likelihood that an animal would respond at those distances. However, studies at wind farms in German
and Danish waters showed that pile-driving can result in avoidance over a range of 20 km or more
(Brandt et al. 2011, Dähne et al. 2013, Tougaard et al. 2009) ), indicating that porpoises may respond at
such large distance to impulsive sound.

Other differences are the potential for hearing effects to occur. The inter pulse interval and frequency
content may be different between these two sound sources. For pile driving the usage of ADDs is
assumed to be effective enough to avoid the risk of PTS (see chapter 4), because expected effect
distances for PTS are of order of a few hundred meters. However, due to movement of the seismic
source, and lack of methods to estimate risk for a moving seismic source on a moving animal, it is not
yet known how the risk of PTS differs between these two activities.

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4 Note that the examples in Heinis et al. (2014) for seismic surveys were provided for SEL₁ = 136 dB re
1 µPa²s. However, the report proposes a threshold of at SEL₁= 140 dB re 1 µPa²s to be used in upcoming
impact assessments for pile driving.
3.4 Population effects

There is a concern that accumulation of disturbance effects due to sound introduced into the marine environment may lead to population level consequences (NRC, 2005). In order to address this concern the PCoD model (King et al. 20015, Harwood et al. 2013) was developed to assess the impact of renewable energy activities on population levels of different marine mammals species, including the harbour porpoise. The interim PCoD model consists of a population dynamics model that is characterized by demographic variables of the population (Harwood et al. 2013). Quantitative information on effects on vital rates is virtually absent. Therefore, Harwood et al. (2013) relate the duration of disturbance to vital rates of animals in the Interim PCoD model using expert elicitation, where experts were asked to judge the probability (and associated uncertainty in their estimate) of a reduction in vital rates for different species and life categories due to the construction of offshore wind farms.

The Interim PCoD model has recently been applied in the development of guidelines to be used in the licensing of new offshore wind farm construction in the Netherlands (Heinis & de Jong, 2015). The caveats of using these model for assessing the impact on the North Sea harbour porpoise population are discussed in detail in Heinis et al. (2015). One of the challenges encountered when applying this approach to seismic surveys was that the Interim PCoD model relied on a choice of demographic parameters (i.e. mortality rate), which had been based on harbour porpoise density information prior to the start of relatively new activities such as pile driving for wind farm construction (Heinis et al. 2015). Other activities, such as seismic surveying and underwater explosions, have been going on for the past decade. Any potential effect these may have, is already implicitly accounted for in assumed mortality rate in Interim PCoD model. It is therefore not straightforward to interpret the outcome when these effects are explicitly used as an extra pressure of seismic surveys in the Interim PCoD model.

The DEPONS model, an agent-based population consequence model, is currently being developed by the University of Aarhus (Nabe-Nielsen et al. 2014; van Beest et al. 2015) to assess the effect of wind farm construction, and operational noise on the population of harbour porpoises. The model relies on knowledge of movement behaviour of harbour porpoises, prey availability, and response to pile sound source, which have been based on observations of porpoises responses to pile driving activities where possible. However, information regarding onset and duration of responses of individual animals to seismic surveys are scarce (Thompson et al. 2013). Also the model is based on effect ranges around a stationary source, and the approach would need to be extended to incorporate moving sources and would require effect distances for representative seismic surveys. The agent-based approach of DEPONS may currently be the best way to deal with questions on how to accumulate disturbance effects of different sources like pile driving and seismic surveys.

Using the Sound Risk Analysis Tool (SORIAN) (von Benda-Beckmann et al. 2015), the contributions from both pile driving and seismic surveys for the scenario proposed in Heinis et al. (2015) were accumulated into disturbance maps (Figure 13a,b,c &d). The predicted effects of both activities were in the same order of magnitude.

Until PCoD models become capable of handling effects of seismic surveys, such disturbance maps may provide a useful, short term, solution to visualize and compare contributions of different types of sources. These could be used to indicate areas of high pressure, potential blocking of migration routes, etc). In addition the TSG noise working group underlined possible effects of displacement/behaviour (Dekeling et al., 2014 a,b,c).
Figure 13 a,b,c & d. Examples of disturbance maps of pile driving and seismic survey activities generated by SORIANT (von Benda-Beckmann et al., 2015), which is based on an international multi-year pile driving scenario considered by the ‘RWS Werkgroep onderwatergeluid’ (Heinis et al. 2015). The grey scales indicate the number of days per year that each location the single strike SEL1 due to pile driving or seismic surveys exceeds 140 dB re 1 μPa2s, which is adopted as a threshold for behavioural disturbance in Heinis et al. (2015).
4 Mitigation measures

To mitigate the potential effects of seismic surveys, different nations have adopted guidelines for mitigation measures. The purpose of this chapter is to provide an overview of mitigation measures that are typically adopted by different countries, discuss how these relate to the harbour porpoise on the DCS, and to identify knowledge gaps.

The type of guidelines aimed at reducing the impact of seismic sound on marine mammals can be categorized as follows:

- Guidelines for source exclusion zones (EZ)
  - Size of EZ
  - Airgun shut-down for animal within EZ
- Guidelines for detecting animal presence in EZ
  - Visual observer requirements (Marine Mammal Observers)
  - Use of passive acoustics monitoring (PAM)
  - Duration of pre-shoot watch
  - Night-time/poor-weather usage
- Guidelines aimed at deterring animals, to avoid them entering the EZ
  - Soft-starts/ramp-up
  - Soft-start delay for animals within EZ
  - Airgun/ADD usage during line-changes
- Guidelines during planning/consenting process to avoid sensitive times/areas:
  - Time/area closed zones
- Guidelines for data collection

4.1 Guidelines for source exclusion zone (EZ)

**Size of EZ:** Source exclusion zones are typically determined to what can be monitored practically (between 500 m and 3000 m), or based on estimated distances to which certain hearing effects (temporary or permanent hearing threshold shifts, TTS resp. PTS) can be expected\(^5\). The distances at which harbour porpoises sustain TTS and PTS depend on the type of source, duty cycle, propagation conditions, as well as the sensitivity to impulsive sound (see Chapter 3). For a single shot, measurements suggest that PTS is not reached at distances of more than 688 m. Accumulation of energy may increase the effect distance for PTS, but has not yet been quantified, because this depends strongly on assumptions made in the movement and response to the seismic source (see section 3.2.2). Estimated distances for TTS for typical seismic arrays (~ 3000 inch\(^3\)) can be up to several km from the source. However, the effect of low levels of TTS on a harbour porpoises’ fitness is likely to be low. Since avoidance responses occur at much larger distances (several to tens of kilometers, see section 3.1.1) than what can be observed from ship-based monitoring, airgun shut-down linked to monitoring is not effective in reducing large scale behavioural disturbance.

**Airgun shut-down for marine mammals within EZ:** When animals are detected within the EZ, some countries (e.g. AU, CA) prescribe a shut-down of the source. Some countries allow for continuing after ramp-up and while the source is in acquisition phase (e.g. UK). Other countries may prescribe a power-...

\(^5\) Here we make the distinction between impact zone (an area in which animals are exposed to a sound dosage that is high enough to lead to a risk of a pre-determined effect (e.g. TTS or PTS). The source exclusion zone refers to the distance that requires monitoring and a certain action once animals are sighted within the EZ. These zones may differ substantially, depending on the nation considered.
down (in terms of number of airguns used) when animals are sighted. The effectiveness of this procedure depends on how effective marine mammal presence can be monitored (see section 4.2).

4.2 Guidelines for detect animal presence in EZ

**Visual monitoring/ MMO:** All nations that have guidelines prescribe the use of Marine Mammal Observers (MMO) to monitor the exclusion zone. Visual detection performance depends on a number of factors, such as weather conditions, group size, and is best when the observer is well-rested and trained in detecting marine mammals (Palka et al., 1996, Berggren et al., 2008, Herschel et al. 2013). Some countries recognize and recommend official training courses for dedicated Marine Mammal Observers. Typically one or two MMOs are required, more during longer surveys to rotate shifts, because fatigue of observers strongly affects the detection probability of marine mammals. Due to the inconspicuous nature of harbour porpoises, ship-based detection distances for harbour porpoise are in the order of a few hundred meters, but quickly decline with poor weather conditions (e.g. Palka et al. 1996). Therefore, ship-based visual monitoring will only cover a limited part of the EZ.

**Passive acoustic monitoring (PAM):** Use of real-time acoustic detection of marine mammals using hydrophones (or arrays of hydrophones) to detect (and localize) harbour porpoises. Effective use of PAM equipment requires trained personnel (JNCC, 2015b). Also practical issues exist with PAM deployment, especially to avoid risk of entanglement with the seismic streamers (JNCC, 2015b). Detection ranges of harbour porpoise echolocation clicks using a single sensor are in order of magnitude of 300 – 500 m, or even less in noisy weather conditions (Kyhn et al. 2012, Herschel et al. 2013), and therefore will cover only part of a typical EZ. Also detection probabilities are less than 100% for smaller distances, due to the high directionality of porpoise echolocation clicks (e.g. Madsen et al. 2010, Kyhn et al. 2012). Localisation of porpoises using multiple hydrophones is not considered of added value, as the impact distances likely exceed the detection distance (e.g. as soon as an animal is detected, it is likely to be within the impact distance). Studies of harbour porpoise response to airguns show that animals react with a reduced click production rate, which may limit the effectiveness of acoustic detection during shooting even more.

**Duration of pre-shoot watch:** When animals are sighted within the EZ, typically a delay of 20 – 30 minutes is adopted before initiating a soft-start.

**Night-time/poor-weather usage:** Shooting of seismic surveys generally is allowed in conditions of poor vision (night-time/poor weather), but some countries (e.g. CA, AU) require additional monitoring (e.g. night-vision binoculars, infrared, PAM) as a conditions for continue operating seismic sources. In the context of the harbour porpoise, given the limited detectability of these animals during day-time, it seems not logical to have much more stringent restrictions during night-time/poor-weather conditions. Delays due to harbour porpoise presence during night-time are known to occur (Stone, 2015a), mainly due to animals being detected with PAM.
4.3 Guidelines aimed at deterring animals, to avoid them entering the EZ

**Soft-start/ramp-up**: A soft-start or ramp-up, consists of a gradual increase in output energy of the airgun array, prior to the data collection at full power. A soft-start is aimed at providing warning time for animals to move out of the high risk areas (EZ). A soft-start is generally adopted as a common-sense approach, but the effectiveness of it is not well known (Weir & Dolman, 2007; von Benda-Beckmann et al. 2014; Stone, 2015a). The effectiveness of soft-start depends on whether animals respond in time, and whether they swim fast enough to avoid high risk areas (von Benda-Beckmann et al. 2014). Typical soft-start durations vary between 20 min to 40 min (Weir & Dolman, 2007). The rate of increase of output power, array configuration used, and shooting time between shots vary between operators. JNCC requires no soft-start for breaks < 10 min, and when no animals were sighted. Harbour porpoises have been reported to move away from airgun sources shooting at full power (Thompson et al. 2014; Stone, 2015a). An analysis of multi-year observations by MMO’s during seismic surveys concluded that small odontocetes (including harbour porpoises and dolphins) were observed significantly further away from the source during a soft-start period, with altered swimming behaviour (fewer interactions with the equipment, and increased swim speeds), indicating that the soft-start has some effect (Stone, 2015a). However, it remains to be demonstrated how much reduction in risk can be achieved using soft-start procedures.

**Soft-start delay for animals within EZ**: When animals are sighted within the EZ, guidelines generally adopt a waiting period after the last sighting, typically about 30 min, prior to initiating a soft-start.

**Airgun usage during line-changes**: For seismic surveys where line-changes are necessary, some nations recommend cessation of shooting, or reduce the shooting to a single (smallest) airgun to unnecessarily disturb animals. Long pauses (> 20 min) may also require a new soft-start prior to the acquisition phase. Different sources can be used to deter animals from the EZ during change of lines. Some operators use a mitigation gun (a small airgun) or a pinger or acoustic deterrent device (ADD). The latter produce higher frequency sounds to which some animals are more sensitive. Some countries explicitly prohibit the use of mitigation guns. The usage of ADDs is currently prescribed in NL to mitigate the risk of hearing damage prior to pile driving. The effectiveness of ADDs has been studied for porpoises, and shown to make porpoises move away from the ADD at distances up to several km, with a decreasing effect with greater distance, and a lot of differences between types (see Herschel et al. 2013, and references therein). However, these experiments have been performed for stationary sources. Because a seismic source is typically moving, it is therefore not clear whether animals will anticipate the movement and avoid future shot locations.

4.4 Guidelines during planning/consenting process to avoid sensitive times/areas

**Temporal/spatial planning**: Some nations adopt seasonal restrictions of airgun use in some areas, which is aimed to mitigate disturbance of sensitive periods (e.g. breeding areas) or when endangered species are known to be present. The harbour porpoise in general is widely distributed, and it is not well known whether they use special areas for reproduction or foraging on the DCS (Camphuysen & Siemensma, 2011; Geelhoed et al. 2013a). It is therefore not apparent how such spatial and temporal restrictions would apply for seismic surveys on the DCS. Some areas of special importance are discussed, such as the Dogger Bank, which has been proposed as a candidate Special Area of Conservation (cSAC) under the EC Habitats Directive (Natura 2000), and is known to have high animal abundance during summer (Geelhoed et al. 2013a). Harbour porpoises were observed mainly around the edge of the Dogger Bank with fewer sightings on the bank itself, likely due to prey availability (Geelhoed et al. 2013b). Seasonal...
dependent restrictions are currently being considered for regulating pile driving activities on the DCS, because of lower animal abundance in autumn than in spring (Heinis et al. 2014). These restrictions allow for less time of piling, or a relatively larger reduction in radiated noise in seasons with high animal densities. The rationale for a seasonal dependent time-budget would be applicable to seismic surveys too. However, the size of the time budget depends on the ability to translate the duration of the survey into an estimate of the number of animals affected, which requires the ability to use PCoD-type models to be applicable to seismic surveys (see section 3.3.1). It must also be noted that seasons of lower porpoise abundance in summer to early autumn fall in the reproductive season of harbour porpoises, and some animals (pregnant females, or females with young calves) could be more sensitive to disturbance. The reduction in radiated noise achievable with conventional seismic sources will be limited, because any reduction needs to be balanced against the required seismic data quality. Alternatives in techniques are being developed that reduce peak levels and unnecessary high frequency components, which are discussed in section 4.6.

4.5 Guidelines for data collection

Apart from real-time mitigation, UK also uses data collected by operators (visual and acoustic sightings) to do strategic assessment of collected data of effectiveness of mitigation measures (e.g. soft-start, shut-down) and check for compliance of how guidelines are being followed.

4.6 Alternative source quieting technologies

Chapter 2 briefly summarized new approaches that are being explored by the E&P community to reduce the effect of seismic surveys on marine life. These methods can be broadly categorized into three groups: 1) adaptations to existing airgun sources, 2) alternative low-frequency transducers, and 3) methods to shield the sound transmitted into the water column.

For the first category, adapted airguns are being developed that produce less energies at high frequencies (> 200 Hz) than conventional airguns (Coste et al. 2014). Recent studies indicate that both the risk of hearing effects and disturbance is frequency dependent (e.g. Tougaard et al. 2015), which suggests that this may provide a viable way to reduce the effect distances. These systems have been shown to be effective at reducing high frequency content, but are still being tested for their endurance and reliability for repeated use, before these will become operational.

The second category is the development of marine vibrators. Three different prototype marine vibrators are being developed within the JIP Marine Vibrators (Mike Jenkerson, presentation at OCEANOISE 2015), which are being designed for transmitting signals over longer periods at lower SPL (like a sonar), and provide less power output at frequencies above those used for seismic acquisition (> 100-200 Hz). Although this will reduce the peak levels, they are unlikely to be operated at lower energy output, and may potentially increase the masking potential. For harbour porpoises, however, it is not clear what the potential for masking is at these very low frequencies, since it is very far out of the band that they use for echolocation and communication, and they generally have poor hearing ability in this frequency range. Other acquisition techniques using conventional airgun arrays are explored to reduce peak levels. For instance, the use of ‘popcorn’ shooting methods (e.g. Abma & Ross, 2013), in which multiple airgun shots are distributed over time, and later digitally aligned. It still needs to be demonstrated that this technique provides the same quality, before becoming accepted by the E&P community. Also this type of shooting would require some adaptation of conventional arrays to control the timing of individual guns. It is expected that due to the low technological readiness level (TRL) these techniques will not yet become available in the near future.
The third category consists of solutions that shield the sound being transmitted horizontally into the water column. Bubble screens that are commonly used to reduce radiated sound from pile driving are not well suited for moving seismic sources. Some solutions have been proposed that consists of fixed screens filled with Helmholtz resonators that can be tuned to filter out high frequencies, which could be altered to tow beside moving seismic sources (Mark Wochner, presentation at OCEANOISE 2015). It is expected that due to the low technological readiness level (TRL) these techniques will not yet become available in the near future.
5 Conclusions, Knowledge Gaps & Recommendations

The goal of this study is to gather relevant information on the extent of seismic surveys on the DCS, their potential effects on harbour porpoises and possible mitigation measures. In addition the knowledge gaps have to be identified and prioritized.

This information can be used by policy makers for short-term implementation of the most obvious measures in the regulations of seismic surveys. Furthermore, the relevant knowledge gaps which have been identified can be addressed in future research programs for the MSFD and in other relevant programs, e.g. Monitoring and researching ecological effects of Dutch offshore windfarms, Masterplan 2.0.

5.1 Conclusions

First, information on the extent of seismic operations was gathered and the following conclusions were drawn:

- Seismic surveys for hydrocarbon exploration are one of the main sources of man-made (anthropogenic) noise in the North Sea.
- Representative data of the seismic operations on the DCS are required to estimate effect distance and the duration of exposure. The existing data are few and mainly concern 3D operations, such as measured by ARCADIS (2015).
  a) Data for a representative airgun array have been recently measured and reported.
  b) At close distances (< 2 km) measured and modelled sound exposure levels match, but measured levels are higher than predicted by models at large distances (> 5 km). This means that the propagation of seismic sound in shallow water at large distances is not yet well understood.
- Available reports and databases do not provide enough detail in temporal information on the occurrence of seismic operations in multiple areas of the North Sea (DNZ, 2011);
  a) Access to data (NLOG web portal) on spatial and temporal distribution in and outside the DCS is complex and/or incomplete (data concerns mainly 3D seismic);
  b) Knowledge on degree of temporal and spatial overlap of simultaneously execution of surveys is lacking;
- 2D seismic for the Oil & Gas industry may have declined since 2000 (DNZ, 2011). However, additional data retrieved from the TNO-Geology desk showed that operations in other fields (probably coastal projects, like wind farms) were significant. Between 2003 and 2007 a total of 9000 km was monitored mainly in the coastal zone.
- Between 2000 and 2007 2D seismic on the DCS were not always restricted to a particular squared area, but also included some very long single line transects of about 250 km (Figure 9 and 10).

Regarding the effects on harbour porpoises it can be concluded that:

- The most important factors determining a porpoise’s reaction are the sound level above the hearing thresholds, the so-called sensation level, the stimulus duration and repetition rate. The effect these factors have depends on the context of the exposure: distance to the sound source, the animal’s status, feeding condition etc.
- Given the characteristics of sounds emissions it seems unlikely that seismic surveys will cause primary blast injury on harbour porpoises.
- Sound exposure experiments established thresholds for TTS onset and growth to estimate the risk of PTS. This knowledge is attained from impulsive sound sources (either a single airgun, or intermittent playbacks of pile driving noise). However, different exposure stimuli lead to very different SEL onset
thresholds. Therefore the current TTS thresholds cannot directly be translated to seismic surveys, since the sounds characteristics of airguns differ from the studied sound sources.

- Observations in the field showed avoidance i.e. a decrease in the density of harbour porpoises for smaller airgun arrays (490 inch3), as well as a reduction in feeding activity, in a radius of 10 km in the North Sea. For large arrays (4820-6712 inch3) avoidance responses may occur even up to 70 km in deeper water in British Columbia. However, response levels and consequently response ranges vary with the context of the exposure (e.g. distance to source, behavioural state, importance of habitat), which makes it hard to translate these results to larger seismic operations occurring on the DCS. Models are currently being developed for addressing population level consequences of impulsive sound on the harbour porpoise population (King et al. 2015, Nabe-Nielsen et al. 2014, van Beest et al. 2015). These models incorporate the effect of PTS, and disturbance of individual harbour porpoises, and have been applied to pile driving sound (Heinis et al. 2014, van Beest et al. 2015).

- There is a clear need to obtain more knowledge on the potential effects of seismic surveys, and measures to mitigate these effects.

The conclusions of the review of mitigating guidelines and their effectiveness of mitigating the effect of seismic surveys on harbour porpoises can be summarized as follows:

- Various countries adopt guidelines for mitigation during seismic surveys. However there is a large variation between countries in how strict these guidelines are.
- Current visual and acoustic monitoring strategies are likely to be ineffective in detecting porpoises in time to avoid hearing effects, but this will depend on the type of array (and corresponding effect distances) and effect mitigated for (PTS or TTS).
- Methods to deter animals from the source, such as soft start or use of ADDs prior to, are likely to have some effect, but it is unclear whether all animals respond in time to avoid hearing effects.
- Continued use of airguns, or use of ADDs during line changes (when no seismic data is acquired) may act as a deterrent on one side, but have the potential to disturb animals for longer than necessary.
- Most current guidelines are aimed at reducing the risk of hearing effects/injury of animals close to the airguns array, but are not able to mitigate the larger scale behavioural disturbance of harbour porpoises that is expected to occur and potentially could lead to population level effects. Due to limited knowledge about habitat use of harbour porpoises in the North Sea (and on the DCS in particular), it is unclear how effective and useful restrictions of certain areas are.
- Ship-based monitoring of the EZ is not effective for reducing potential behavioural disturbance of harbour porpoises that can occur at distances of tens of kilometers.
- The qualitative effectiveness of different guidelines adopted is summarized in Table 2.
Table 2. Qualitative scaling of effectiveness of mitigation measures to reduce effect of seismic surveys on harbour porpoises in the North Sea (++ very effective, + = low effectiveness, o = not effective, - = negative effect, ? = unknown, n.a. = not applicable).

<table>
<thead>
<tr>
<th>Mitigation measure</th>
<th>Mitigation effectiveness</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monitoring of exclusion zone (EZ) + source shut-down</td>
<td>+ / (o)</td>
<td>If EZ size based on effect distances (i.e. for PTS/TTS)</td>
</tr>
<tr>
<td>Visual observer (Marine Mammal Observers)</td>
<td>+ / (o)</td>
<td>Depends on MMO effectiveness. Depends on experience MMO, weather conditions, and effect mitigated for (PTS or TTS)</td>
</tr>
<tr>
<td>passive acoustics monitoring (PAM)</td>
<td>+ / (o)</td>
<td>Depends on where PAM systems are deployed, and effect mitigated for (PTS or TTS)</td>
</tr>
<tr>
<td>Night-time/poor-weather usage</td>
<td>o</td>
<td>Depends on MMO/PAM effectiveness. Depends on experience MMO, weather conditions, and effect mitigated for (PTS or TTS)</td>
</tr>
<tr>
<td>Visual observer (Marine Mammal Observers)</td>
<td>o</td>
<td>Depends on where PAM systems are deployed, and effect mitigated for (PTS or TTS)</td>
</tr>
<tr>
<td>passive acoustics monitoring (PAM)</td>
<td>+ / (o)</td>
<td>Depends on where PAM systems are deployed, and effect mitigated for (PTS or TTS)</td>
</tr>
<tr>
<td>Soft-start</td>
<td>+ (++?)</td>
<td>Possibly has some benefit. Not clear whether all animals avoid source, and whether they can respond in time.</td>
</tr>
<tr>
<td>Airgun use during line change</td>
<td>+ (++?)</td>
<td>Depends whether animals respond. Has potential downside to disturb animals for longer period than necessary.</td>
</tr>
<tr>
<td>ADD/pinger use during line change</td>
<td>+ (++?)</td>
<td>Has potential downside to disturb animals for longer period than necessary, but potential possible lower than airgun use, due to attenuation of higher frequencies.</td>
</tr>
<tr>
<td>Time/area closed zones</td>
<td>n.a.</td>
<td>Unclear how useful this is for harbour porpoises, due to wide spread distribution throughout the DCS/North Sea. Possible useful for some specific areas with high abundance (e.g. proposed NATURA2000 areas, such as the edges of the Dogger Bank), but unclear how important these sites are for harbour porpoises.</td>
</tr>
</tbody>
</table>
5.2 Knowledge gaps

Several knowledge gaps have been identified during the compilation of this review. These gaps are prioritized according to a three-point scale.

The overall knowledge gap in relation to the extent of seismic surveys is that the quantification of the exposed ranges on the DCS and possible interaction of extensions outside these boundaries is lacking. More specifically:

- Information on parameters of seismic operations required for determining effect on marine mammals is lacking, or not directly available for external use (NLOG web portal). In particular 2D seismic survey information could not be produced. Information required are type of sources (airgun, sparker, etc), geometry of arrays, pressure and volume of airguns used, timing and location of shots, survey adjustments are not well documented over the last decades. (HIGH)
- Knowledge on temporal distribution and simultaneously execution of surveys. (HIGH)
- Better understanding of propagation of seismic sound at large distances, and validated sound prediction models for modelling seismic sound at large distances (several tens of kilometres) are required. (HIGH)
- Acoustic measurement data at 30 km distance concern a single record, data over larger distances is lacking. (HIGH)
- Data of seismic surveys are limited to oil and gas industry surveys up to 2007, seismic surveys for other projects such as windfarm construction not included in NLOG web portal. Data portals lack standardized data formats and are probably incomplete (2D surveys). (HIGH)
- It is not clear if 4D seismic could also involve alternative techniques with HF-sources, like marine vibrators intended for use in all existing seismic dimensions (2,3 and 4D seismic). Such operations with higher frequency emissions require additional impact assessment. (HIGH).
- Annually averaged noise measurements were proposed by TSG noise as a requirement within the MSFD, annual data sets representative for the soundscape of the DCS are lacking and will have to be initiated and compared against short-term averaged results in the same period.

The identified knowledge gaps regarding the effects on harbour porpoises are partly specifically for seismic surveys and partly generic. The latter refers to information on harbour porpoise distribution, and population parameters, and methodology to assess the effects on sound exposure, and is identified as knowledge gaps in the currently developed Monitoring and researching ecological effects of Dutch offshore windfarms, Masterplan 2.0. Combination of resources to address the generic knowledge gaps is paramount.

Knowledge gaps regarding the effects on harbour porpoises are:

- The current distribution and migration behaviour of harbour porpoises in the different seasons:
  - High resolution data on temporal and spatial distribution of harbour porpoise and knowledge on movement patterns required for predicting population level effects. Basic data is required on the dynamics and habitat use of the porpoise populations in space and time in the (southern) North Sea. (HIGH)
  - Identification of areas with special functions: reproduction areas, important feeding areas (HIGH)
  - Migration and turnover (duration of presence) of porpoises through the southern North Sea (MEDIUM)
- Population parameters of harbour porpoises:
  - Basic demographic parameters for North Sea harbour porpoise population: fecundity, mortality etc. (HIGH)
• Sound properties and methodology to assess and mitigate effects:
  o What are appropriate sound metrics to be used to predict behavioural disturbance (SEL_{ss}, L_{eq}-fast)? (HIGH)
  o Methodology for determining risk of TTS and PTS for swimming porpoises exposed to a moving seismic source? (HIGH)
  o What are the behavioural effects on harbour porpoises of simultaneous seismic operations in different areas on the DCS, to what extend would the distance between different seismic areas be crucial? Knowledge on the distribution and density of harbour porpoises and seasonal aspects is required (listed in in the bullets above). (HIGH)
  o Differences between seismic sound and other impulsive sound sources in order to assess their cumulative effects? (HIGH)

• Effects of exposure to seismic sound:
  o studies on potential behavioural responses of harbour porpoises to seismic sound at long distances (MEDIUM)
  o How does avoidance affect the energy budget of species? Is avoidance behaviour significantly changing vital rates and will this lead to a change in reproductive success or mortality rate (HIGH)
  o TTS threshold and growth, recovery in a range of frequencies, for repeated airgun signals with representative inter-shot-interval and exposure durations for seismic surveys (HIGH)
  o What is effect of TTS and PTS on vital rates of harbour porpoise? Ecological consequences of hearing loss on behavioural aspects, e.g. feeding, echolocation. (HIGH)
  o How long does acoustic disturbance last for individual animals? Is there an effect on vital rates, e.g. reproductive success or mortality rate? Stress could also lead to for instance immune suppression or higher chance of disease. Do individual animals habituate to seismic surveys? (HIGH)
  o What is the role of exposure context (e.g. distance to source) in predicting the risk of behavioural disturbance (e.g. sound metrics, distance to source) (MEDIUM)

Knowledge gaps regarding the mitigation of the risk for hearing effects of harbour porpoises that are close to the seismic source:

• What is an appropriate choice for EZ for seismic surveys on the DCS? (HIGH)
• What is the effectiveness of soft-start?
  o How much is the risk of hearing effects reduced by soft-start? (HIGH)
  o Do animals respond well ahead in time to move out of the EZ? (MEDIUM)
  o What are optimal soft-start procedures (e.g. duration, shot interval, increase rate of ramp-up in)? (LOW)
• How can monitoring procedures be improved to obtain high detectability within EZ? (MEDIUM)
• What is the effectiveness of deterrent devices (ADDs, mitigation guns) for moving seismic source?
  o What is effect distance of ADDs compared to impact distances of seismic sources? (HIGH)
  o How can ADDs be effectively deployed (i.e. based from seismic ship, or near start point of new line between deployments?). (MEDIUM)

Knowledge gaps of mitigation measures at larger distances from the source:

• Does continuing shooting between line changes decreases the risk of animal presence at the start of a new line? (HIGH)
• Does it unnecessarily increase the duration of the disturbance? (HIGH)
• Is it more appropriate to use ADDs or soft start at start of each new line? (MEDIUM)
• Are there special areas/times that require closure to seismic surveys (for instance, Dogger Bank)? (MEDIUM)

At last a general knowledge gap is the question if data collection of MMO/PAM can be useful for more strategic assessment of mitigation effectiveness (allow for pooling with other international efforts, by e.g. JNCC)? (MEDIUM)
5.3 Recommendations

Regarding these knowledge gaps a starting point list could involve the following actions. This list does not address all knowledge gaps, but the most essential elements for impact assessment of seismic surveys on harbour porpoises.

1. Improve the availability and quality of seismic survey data, in particular data essential for impact assessment;
2. Determine the occurrence of simultaneous execution of seismic surveys in different areas and develop acoustic and behavioural research on harbour porpoise in the appropriate areas and distance ranges presently lacking. Additionally, perform background noise measurements to compute an annual record of the soundscape on the DSC (TSG noise 2014c). Questions like the applied seismic technique and ISO-normalized acoustic measures, disturbance distance, duration of disturbance should be addressed by this research. In order to follow these guidelines participation of other North Sea countries is recommended;
3. As a reference to harbour porpoise responses to seismic exposure, knowledge on the seasonal distribution, densities and demographic parameters is required, which can be obtained by conducting aerial surveys of harbour porpoises on the Dutch Continental Shelf in different seasons of the year, and by collating current scattered knowledge on basic demographic parameters (e.g. reproduction rate, mortality,) and identify the relevant research needs.
4. To improve and validate sound prediction tools and their inputs to reliably predict seismic sound levels at maximum distances at which behavioural disturbance occurs;
6 Acknowledgements

This project was funded by the Dutch Ministry of Economic Affairs (EZ). René Dekeling and Jeroen Vis provided feedback on the project and commented on a draft report and Meike Scheidat for the internal review.

We thank Sytze van Heteren en Jenny Hettelaar, TNO-GND for contributing data of seismic surveys, and Wintershall, Sterling Resources, NAM, and Hansa Hydrocarbons, for helpful discussions and making available the ARCADIS (2015) report describing the acoustic measurements and model comparisons of the seismic survey.

7 Quality Assurance

IMARES utilises an ISO 9001:2008 certified quality management system (certificate number: 124296-2012-AQ-NLD-RvA). This certificate is valid until 15 December 2015. The organisation has been certified since 27 February 2001. The certification was issued by DNV Certification B.V. Furthermore, the chemical laboratory of the Fish Division has NEN-EN-ISO/IEC 17025:2005 accreditation for test laboratories with number L097. This accreditation is valid until 27 March 2013 and was first issued on 27 March 1997. Accreditation was granted by the Council for Accreditation.
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Computation from near-field measurements including interactions: Geophysics, 47(10), 1413- 1421.
Appendix A. Airguns, theory, operations and configuration

Airguns produce high levels of predominantly low frequency sound by releasing controlled volumes of high pressure air into the water creating an oscillating bubble, which produces 90% of its energy in the band 70 to 140 Hz.

Figure A1. Top: An airgun and a cluster of three airguns. Bottom: Pictures of air bubbles 1 ms, 1.5 ms, and 7 ms after firing a small air gun in a tank.

The amplitude (or loudness) of the seismic signal is a function of the volume and pressure of the air inside the cylinder and the cylinder’s depth under the water surface. As with a balloon, the larger the cylinder volume and the higher the internal air pressure, the louder the “pop”.

Figure A2. Left: An airgun releasing its compressed air. Right: the principle of the sound released.
The firing of an airgun generates an oscillating bubble in the water column. At the time of firing, the pressure of the air inside the cylinder far exceeds the outside pressure in the surrounding water. This difference in pressure causes a bubble to rapidly expand in the water around the airgun. It is this initial bubble expansion that generates the relatively broadband seismic pulse. Because of the momentum of the bubble expansion, the bubble continues to grow until the air pressure inside the bubble becomes less than the surrounding water pressure. At that point the bubble will start to collapse. At some time during this collapse the pressure inside the bubble will again become greater than the pressure outside. The bubble will then start to expand again. This expansion/collapse cycle will continue until the bubble reaches the sea surface and vents to the air.

Depending on the physical scale a towed array can consist of an arrangement of multiple cells positioned in-line in the front section of a "streamer" hose. The total array can exist of multiple streamer elements all towed in parallel at the surface (Figure A3).

It is common to arrange several (2-4) airguns in a cluster, with the guns at short distance from each other so that they behave like a larger single gun. The main advantage of such a configuration is that the bubble motion is reduced, adding to overall signal performance.

Figure A3. Typical composition of an airgun array with the capacity declining towards the end of the array.
Table A4. Overview of seismic sources and acoustic properties and ranges reported by Weilgart (2010), as a product of the workshop on alternative technologies to seismic airgun surveys for oil and gas exploration and their potential for reducing impacts on marine mammals.

Table 1. Characteristics of various technologies used to image the ocean substrate for petroleum deposits.

| Source Type          | Pressure (psi) | Freq Cycle | Peak Freq | Freq Range | Watts (W) | Peak Pressure (psig) | Pulse Duration | Directionality (%) | Source Depth (m) | Tow Rate (mph) |
|----------------------|----------------|------------|-----------|------------|-----------|----------------------|----------------|--------------------|------------------|----------------|----------------|
| Airguns              |                |            |           |            |           |                      |                |                    |                  |                |                |
| Marine Vibrators     |                |            |           |            |           |                      |                |                    |                  |                |                |
| DIAGS                |                |            |           |            |           |                      |                |                    |                  |                |                |
| Paracoustics         |                |            |           |            |           |                      |                |                    |                  |                |                |
| Linea                |                |            |           |            |           |                      |                |                    |                  |                |                |
| Sparkers             |                |            |           |            |           |                      |                |                    |                  |                |                |
| Micro-seismons       |                |            |           |            |           |                      |                |                    |                  |                |                |
| Receivers            |                |            |           |            |           |                      |                |                    |                  |                |                |
| Fibers Optics        |                |            |           |            |           |                      |                |                    |                  |                |                |

*Added by Dawson Bros. ARGOS Inc., a supplier of gravity gravdynamite
**Added by Ryan Arkland, a developer of LACSS
***LACS increases its signal energy by transmitting many pulses at a rapid rate.
† In a marine environment, practically no energy above 100Hz.
‡ Frequent intervals of at least 10,000 Hz, but typically, the duty cycle will record at 2 ms intervals, which means that no frequencies > 250 Hz are recorded, regardless of what is recorded.

Table 1 (cont'd.).

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<td>30</td>
<td>30 m</td>
<td>10 m</td>
<td>20-200 m</td>
<td>variable</td>
<td>medium</td>
<td>available</td>
<td>medium</td>
<td>medium</td>
<td>medium</td>
<td></td>
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<tr>
<td>Marine Vibrators</td>
<td>30</td>
<td>30 m</td>
<td>10 m</td>
<td>20-200 m</td>
<td>variable</td>
<td>medium</td>
<td>available</td>
<td>medium</td>
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<tr>
<td>DIAGS</td>
<td>all</td>
<td>all</td>
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<td>1.5-20 m</td>
<td>medium</td>
<td>1 cm</td>
<td>3-5 yrs</td>
<td>continuous</td>
<td>10 yrs</td>
<td>continuous</td>
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<td>Paracoustics</td>
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<td>1-20 m</td>
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<td>medium</td>
<td>1 cm</td>
<td>3-5 yrs</td>
<td>10 yrs</td>
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<td></td>
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<td>Linea</td>
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<td>all</td>
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<td>1-20 m</td>
<td>variable</td>
<td>medium</td>
<td>1 cm</td>
<td>3-5 yrs</td>
<td>10 yrs</td>
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<td>all</td>
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<td>1-20 m</td>
<td>variable</td>
<td>medium</td>
<td>1 cm</td>
<td>3-5 yrs</td>
<td>10 yrs</td>
<td>continuous</td>
<td></td>
</tr>
<tr>
<td>Receivers</td>
<td>1-14 days</td>
<td>1000 m</td>
<td>1.5-5 m</td>
<td>1-20 m</td>
<td>medium</td>
<td>2 yrs</td>
<td>available</td>
<td>medium</td>
<td>10 meters</td>
<td>continuous</td>
<td></td>
</tr>
<tr>
<td>Micro-seismons</td>
<td>all</td>
<td>all</td>
<td>1.5-5 m</td>
<td>1-20 m</td>
<td>medium</td>
<td>2 yrs</td>
<td>available</td>
<td>medium</td>
<td>10 meters</td>
<td>continuous</td>
<td></td>
</tr>
</tbody>
</table>

*Added by Dawson Bros. ARGOS Inc., a supplier of gravity gravdynamite
**Added by Ryan Arkland, a developer of LACSS
***LACS increases its signal energy by transmitting many pulses at a rapid rate.
† In a marine environment, practically no energy above 100Hz.
‡ Frequent intervals of at least 10,000 Hz, but typically, the duty cycle will record at 2 ms intervals, which means that no frequencies > 250 Hz are recorded, regardless of what is recorded.
The scientific quality of this report has been peer reviewed by the a colleague scientist and the head of the department of IMARES.

Approved: Melke Scheidat
Researcher

Signature: 

Date: 26 November 2015

Approved: Jakob Asjes
Department Head

Signature: 

Date: 26 November 2015