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TNO report

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Assessment of natural and anthropogenic sound sources and acoustic propagation in the North Sea

Date	February 2009
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Summary

Title	:	Assessment of natural and anthropogenic sound sources and acoustic propagation in the North Sea
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(Photograph by P.A. van Walree)

Background and scope

For a proper (national) implementation of the European Union’s ambitious Marine Strategy Framework Directive, it is required that the impact of anthropogenic activities on the North Sea environment is assessed thoroughly. One of the effects of the use of the North Sea by humans is the generation of underwater sound. Sound propagates over longer distances in water than in air. The impact of anthropogenic underwater sound sources could therefore be serious. At this time, there is insufficient information on the underwater sound environment in the North Sea to make an impact assessment. The information on anthropogenic sources of underwater sound, i.e. the sound characteristics and source levels, is by no means complete. Once this information becomes available, the next challenge is to predict correctly how the sound propagates in the shallow water of the North Sea, i.e. to find out the sound footprint of individual anthropogenic or natural sources of sound. The research reported on in this document aims at making an inventory of the existing knowledge on the underwater sound environment and identifying the gaps.

In the next steps towards an impact assessment, there is insufficient information on the physiology and behaviour of the marine fauna of the North Sea. There is also a lack of knowledge on the effects of the various anthropogenic sources of sound on the ecosystem of the North Sea, both individually and cumulatively.

Methodology

The subject of sound is introduced with special attention to the difference between underwater and above water sound, and the proposed sound measures are defined.
The first step is an inventory of all relevant natural and anthropogenic sources of sound, with specific information on source levels, frequency bands, etc. The anthropogenic sources are divided in two categories: intentional sound sources, e.g. sonar equipment, and unintentional ones, e.g. shipping.

A simple and robust underwater sound propagation model has been implemented in a computer code. As an example, sound propagation results for a selection of cases are computed and presented in the form of North Sea sound maps. It should be emphasized that these maps are mainly indicative, due to the uncertainties involved in the computation (measured source levels, modelling of environment).

Results

Ubiquitous natural underwater sound sources are rain and wind. Lightning is also subject to scrutiny because of the large amount of energy available in each individual strike. Compared to the sound levels due to these causes, the levels due to underwater fauna – marine mammals, fish, etc. – are small. As such the animals do not substantially contribute to the total (time-averaged) sound levels in the North Sea. Important anthropogenic sources include shipping, seismic airguns, pile driving activities and underwater explosives. Looking at the impact of sound sources at larger distances, the influence of the local water depth and bottom material is clearly present.

Theoretically, once the doses are known (in this case the sound pressure levels), their effect on the underwater fauna could be predicted using the appropriate dose-response relationship and then proper mitigation measures could be put in place. However, in practice, this is very complex. Factors that contribute to the complexity include: the involved frequency range, the character of the sound (prey or enemy), the duration of the sound, and the difficulties of studying underwater animals in their natural environment. In addition: once the effects are known, it is not clear what effects would be acceptable. Also, little is known about the effects of mitigation measures.

Recommendations

Based on the identified knowledge gaps and the results presented in this report, the following recommendations are made:

- Clear generic guidelines / procedures should be established for the measurement, processing and quantification of underwater sound, such that future studies and measurement campaigns will lead to comparable results. This involves both hardware aspects, i.e. how to measure, and software aspects, i.e. how to process the measured data. It also involves taking into consideration international work in this field.
- There is a large demand for proper measuring protocols and measurements of natural and anthropogenic underwater sound in the North Sea (i.e. measurements that comply with the mentioned guidelines) for further development of the propagation modelling and validation of the resulting sound maps. Both the spatial distribution over the NCP (Netherlands Continental Shelf) and the variation with time on a short (minutes, hours) or long time scale (seasons, years) should be sampled with sufficient resolution.

- The main contributions to anthropogenic sound energy in the North Sea are found to come from shipping, seismic surveys (airguns), underwater explosions and pile driving. Underwater sound maps (including frequency spectra) should become available for these sources, and ideally including the effects of variations of bottom type across the NCP region.
- The available and the still-to-be-acquired data should be stored in a central database (e.g. as has been done for groundwater levels) with well-defined and annotated data of sources, mitigation measures, propagation and background noise. This database could be filled via mandatory monitoring for all MER (environmental impact assessment, Dutch: milieu-effect-rapportage) liable off-shore projects.
- It should be investigated whether the method used for the calculation of propagation losses and the generation of underwater sound maps can (in the long term) be further developed to a generally applicable legal basis for underwater sound ('rekenvoorschrift'), as exists for sound in air (industrial and traffic noise).
- There is a large demand for research on the possible impact of underwater sound on diverse species (both individually and for populations, in short and long term). This refers to the individual physiology and the short term dose-response relationship as well as to the long term impact on the population. It is therefore recommended that experts from various disciplines (acousticians, ecologists, biologists) establish some sort of platform with the aim of improving the collaboration.

TNO Defence, Security and Safety

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To
Readers of TNO report TNO-DV 2009 C085

From
M.A. Ainslie, C.A.F. de Jong, H.S. Dol, G. Blacquière

Subject
Errata TNO-DV 2009 C085

Section 1 of this document contains errata for TNO report TNO-DV 2009 C085 "Assessment of natural and anthropogenic sound sources and acoustic propagation in the North Sea", by M.A. Ainslie, C.A.F. de Jong, H.S. Dol, G. Blacquière and C. Marasini (February 2009). None of the errata affect the conclusions of the report.

We take the opportunity to also make some minor (textual) changes and add some clarifying information in Section 2.

1. Errata

Page 28, Equation 2.15

Replace Eq. (2.15) with

$$\int_{f_1}^{f_2} K_{\mathrm{rain}} \mathrm{d}f = 10^{4.16} R_{\mathrm{rain}}^{2.5} \frac{24000}{1.3} \left[\left(\frac{24}{F_1} \right)^{1.3} - \left(\frac{24}{F_2} \right)^{1.3} \right] \quad \mu\mathrm{Pa}^2$$

Page 29, §2.4.1

Replace "30 MJ" with "30 kJ" (twice).

Page 30, §2.4.2

Replace the last two sentences with

"Taking Hill's estimated source level (with 30 μs duration and 2 strikes per square kilometre) gives 114,000×30 kJ/y ≈ 3.4 GJ/y. This figure would require a 0.006 % efficiency for conversion from electrical energy of the discharge to acoustic energy in the water.".

Page 54, line 2

Replace the words "per year" with "present".

Page 57

Remove the sentence

"However, the data at two distances from the same UK test pile (Robinson *et al.*, 2007) in Table 4.2 demonstrate that the proposed scaling of (4.4) leads to a difference of only 3 dB in the estimation of the scaled SEL at a distance of 500 m.".

Page 58, Table 4.2

Replace Table 4.2 with the following (the values in highlighted cells are corrected).

Table 4.2. Summary of measurement results for different pile driving operations, based on Table 2-1 from Nehls *et al.* (2007), with the lower three rows added, based on data from Robinson *et al.* (2007) and De Jong & Ainslie (2008). Hammer blow energy and Sound Exposure Level (SEL) are given per single stroke (or blow). Normalized values in the last columns are scaled to a distance of 500 m and a water depth of 20 m, using (4.4). The question marks indicate uncertainty about the correct values.

Project	Pile diameter [m]	Water depth [m]	Measuring depth [m]	Measuring Distance [m]	Blow energy [kJ]	Peak Level [dB re 1 μPa²]	SEL [dB re 1 μPa²s]	Normalized Peak Level [dB re 1 μPa²]	Normalized SEL [dB re 1 μPa²s]
Jade port construction, Germany, 2005	0.9	11	5	200	70-200	188	162	181	155
Jade port construction, Germany, 2005	1.0	11	5	340	70-200	190	164	186	160
FINO 1, Germany, 2001	1.6	30	10	750	80-200	192	162	196	166
SKY 2000, Germany, 2002	3.0	21	5	260	200	n/a	170	n/a	166
FINO 2, Germany, 2006	3.3	24	5	530	300	190	170	191	171
Amrunbank West, Germany, 2005	3.5	23	10	850	550	196	174	200	178
North Hoyle, UK, 2003	4.0	7-11	5	955	450	192	155?	194	157?
Scroby Sands, UK, 2003	4.2	1-8	<5	500	n/a	194	n/a	191	n/a
Kentish Flats, UK, 2005	4.3	3	2	243	400	189	n/a	180	n/a
Barrow, UK, 2006	4.7	15-20	5?	500	n/a	198	n/a	198	n/a
Burbo Bank, UK, 2006	4.7	<10	5?	500	n/a	190	n/a	188	n/a
Test Pile, UK, 2006	2.0	8-15	?	57	800	208	178	193	163
Test Pile, UK, 2006	2.0	8-15	4-7	1850	800	188	164	195	171
Q7 site, NL, 2006	4.0	20-25	8-15	890-1200	800	195	172	200	177

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2. Minor changes

Page 12, line 8
Replace "small" with "weak".

Page 14, line 2
Replace "*infrasonic*" with "*infrasound*".

Page 15, last line of §1.1.1
Replace "0 dB re 20 μPa" with "0 dB re (20 μPa)^2".

Page 15, 2nd paragraph from below
Replace the sentence
"The difference corresponds to a factor of almost 3700."
with
"The precise values depend on the conditions (e.g. temperature and salinity), but the ratio is usually between 3500 and 3700.".

Page 16, Figure 1.2
Replace "dB re 1 μPa" with "dB re 1 μPa^2" on the y-axis of the figure.

Page 17, last line of §1.1.2
Replace "0 dB re 1 μPa" with "0 dB re 1 μPa^2".

Page 24, last line of 2nd paragraph
Add after "expressed in m/s":
"(the 'hat' symbol is used throughout to denote a dimensionless value, scaled by dividing by the appropriate SI unit, in this case 1 m/s)".

Page 25, line 2 of §2.2.2
Replace "all frequencies" with "frequency".

Page 25, 2nd line from below
Replace "$\hat{v}_{10} = 5$ m/s" with "$v_{10} = 5$ m/s", and "$\hat{v}_{10} = 10$ m/s" with "$v_{10} = 10$ m/s".

Page 29, line 9
Replace "lighting" with "lightning".

Page 29, 3rd paragraph
Replace "on June 2008" with "on 2 June 2008".

Page 34, caption to Figure 3.2
Replace "normalized" with "weighted".

Page 35, line 1

Replace "noise source levels" with "source levels of seismic survey sources".

Page 46-53, captions to Figures 4.1-4.7

In these figures, the term "source level" is used sometimes to mean a monopole source level (i.e. the source level of a point source representing the ship) and sometimes a dipole source level (i.e. the source level of a point source combined with its surface image, which together make a dipole at low frequency – hence the name). The text explains which of the two definitions is applicable in each case. The following supplementary information is provided for the captions to Figures 4.2 to 4.7, to make it easier to interpret these figures without needing to read the relevant text.

- The Wales & Heitmeyer (2002) data are monopole source levels (Figs. 4.2, 4.6).
- The RANDI model data are assumed to be monopole source levels (Figs. 4.2, 4.3, 4.7).
- The Arveson & Vendittis (2000) data for the *Overseas Harriette* are dipole source levels (Figs. 4.3, 4.4).
- The cruise ship data of Kipple (2002) are dipole source levels (Figs. 4.4, 4.5).
- The data from Richardson (1995) are assumed to be dipole source levels (Fig. 4.6).
- No information is available concerning the type of source level measurements from the Sakhalin web site (Fig. 4.6).
- The ICES requirement is assumed to be for a dipole source level (Fig. 4.7).

Page 52, caption to Figure 4.6

Replace the caption with

"1/3-octave band source level spectra of underwater noise for marine dredging and offshore drilling, compared with the average source level of transiting merchant ships (Wales & Heitmeyer, 2002). Dredging and drilling source levels are measured in shallow water and are therefore subject to low frequency cut-off. The data for the *JFJ de Nul* Cutter Suction Dredger and the *Gerardus Mercator* Trailing Suction Hopper Dredger are taken from the Sakhalin data and the other spectra from Richardson *et al.* (1995). The levels between brackets in the legend give the broadband integrated source level in dB re 1 $\mu Pa^2 m^2$.".

Page 59, Figure 4.11

Replace "dB re 1 μPa" with "dB re 1 μPa^2 s" on the y-axis of the figure.

Page 63, Table 5.1

Replace "0.2" with "< 0.2" in the row for military search sonar.

Page 68, 1st bullet

Replace "$\hat{v}_{10} = 6.5$ m/s" with "$v_{10} = 6.5$ m/s".

Page 76 and 77

Replace "*Princes Amalia windpark*" with "*Prinses Amaliawindpark*" (twice).

Contents

List of abbreviations

CPA	Closest point of approach
CW	Continuous wave
DDG	Duik- en demonteergroep
EC	European Commission
EEZ	Exclusieve economische zone
EPWI	Equivalent plane wave intensity
FM	Frequency modulation
FOM	Figure of merit
h	Hour
HF	High frequency
HFM	High frequency modulation
HMS	Hull-mounted sonar
ICES	International Council for the Exploration of the Sea
JIP	Joint industry programme
kn	Knot
LAT	Lowest astronomical tide
LCF	Luchtverdediging- en commandofregat
LF	Low frequency
LLWS	Low low water spring tide
MER	Milieu-effect rapportage
MSL	Mean sea level
MV-2	Maasvlakte 2
nmi	Nautical mile
NCP	Nederlands continentaal plat
NL	Noise level
p-p	Peak-to-peak
PL	Propagation loss
rms	Root-mean-square
RANDI	Research ambient noise directionality
RI	Riemann integral
RNLN	Royal Netherlands Navy
RX	Receiver
SEL	Sound exposure level
SL	Source level
SPL	Sound pressure level
SSP	Sound speed profile
TNT	Trinitrotoluene
TRDT	Triple rotating directional transmission
TX	Transmitter
y	Year
z-p	Zero-to-peak

1 Introduction

For a proper (national) implementation of the European Union's ambitious Marine Strategy Framework Directive, it is required that the impact of anthropogenic activities on the North Sea environment is assessed thoroughly. One of the effects of the use of the North Sea by humans is the generation of underwater sound. At this time, the information on anthropogenic sources of underwater sound in the North Sea, i.e. the sound characteristics and source levels, is by no means complete. The next challenge is to predict correctly how the sound propagates in the shallow water of the North Sea, i.e. what is the sound footprint of individual natural or anthropogenic sources of sound? Also, there is insufficient information on the hearing parameters of the marine fauna of the North Sea. Finally, there is no inventory of existing knowledge on the effects of the various anthropogenic sources of sound on the ecosystem of the North Sea, neither in relation to each other in a cumulative way, nor in relation to natural sources of sound.

Table 1.1. Inventory of relevant acoustic noise sources in the North Sea.

Natural noise sources	Anthropogenic noise sources	
	Intentional	**Unintentional**
• Wind • Rain • Precipitation other than rain • Lightning • Mammals • Fish • Crustaceans • Biota other than mammals, fish and crustaceans • Breaking gravity (surf) waves • Wave-wave interactions • Flow noise • Gravel noise • Thermal noise[1]	• Seismic explorations • Normal-incidence echo sounder • Fish-finding sonar • Sub-bottom profiler • Military search sonar • Obstacle avoidance sonar • Sidescan sonar • Minesweeping equipment • Multibeam echo sounder • Doppler current profiler • Research sonar • Acoustic communications equipment • Acoustic transponders • Acoustic deterrent devices • Acoustic cameras	• Shipping: merchant, ferries, tankers (incl. supertankers), leisure craft • Fishing vessels • Dredging, pipelaying, cable laying • Explosives: mine & bomb clearance • Offshore industry – Platform construction (pile driving, alternative methods) – Platform operation (e.g. wind turbines) – Platform maintenance (supply, tugs) – Oil & gas platforms: pumping, drilling, associated supply & maintenance) – Flow noise (pipelines) – Wind farm decommissioning • Industrial/harbour noise • Ship shock trials

[1] Thermal noise is not sound; it contributes to the background noise of any measurement system based on the detection of pressure fluctuations.

The research reported on in this document aims at making an inventory of the existing knowledge and revealing the gaps. The study was started by making an inventory of all relevant natural and anthropogenic sources of sound in the water column, see Table 1.1. For the anthropogenic sources, a further distinction was made between intentional sources, for which the production of sound is a key feature (e.g. sonar equipment), and unintentional sources, for which the production of sound is merely an undesirable by-product (e.g. shipping). Sound sources in the air (e.g. aircraft) have been excluded from the study, as the acoustic propagation from air into water is very small.
Separate chapters are dedicated to discussion of the sound sources: Chapter 2 treats the natural noise sources, Chapter 3 focuses on intentional anthropogenic noise sources, while unintentional anthropogenic noise sources are the subject of Chapter 4.
Where available, source levels, frequency bands, and other characteristic information are collected in these chapters, see also the tables in Appendix A. Based on the information collected in Chapters 2-4, an acoustic energy budget comparison is made in Chapter 5, putting the different natural and anthropogenic noise sources into perspective. For a limited number of cases, noise maps are presented in Chapter 6. Due to the uncertainties involved in the computation of these maps (measured source levels, modelling of environment), these maps are mainly indicative. Also, some attention will be given to the subject of mitigation in Chapter 7, giving possible measures to reduce the risk of harmful effects of the noise sources on sea life.
Finally, in Chapter 8, some recommendations for future study are made.

Before starting the discussion on the (noise) sources of sound in the North Sea, an introduction on the subject of sound, its measures and some of the differences between underwater and above-water sound definitions will be presented in two parts. The first part is an introduction to the world of sound and its measures for readers without a background in acoustics. Those who are familiar with the subject may skip this part. The second part is more formal and provides the definitions and equations with respect to some important measures of sound.

1.1 Part I: Introduction to the world of sound

1.1.1 Sound: what is it?

In all materials vibrations can propagate. Air is an example of a medium that supports the propagation of vibrations quite well. The vibrations are actually variations in the air pressure due to the motion of the air particles. Air only supports so-called longitudinal waves, where the direction of particle motion is parallel to the direction of wave propagation. The same is true for water. Seabed material, and all other solids, in addition also support so-called transverse waves, where the direction of particle motion is perpendicular to the direction of wave propagation. See Figure 1.1. The propagation speed in air is approximately 340 m/s (approx. 1200 km/h). Vibrations in air are called sound if they are audible. As a start, some remarks will be made on sound in air in relation to human beings, because this is closer to the human experience than *underwater* sound.

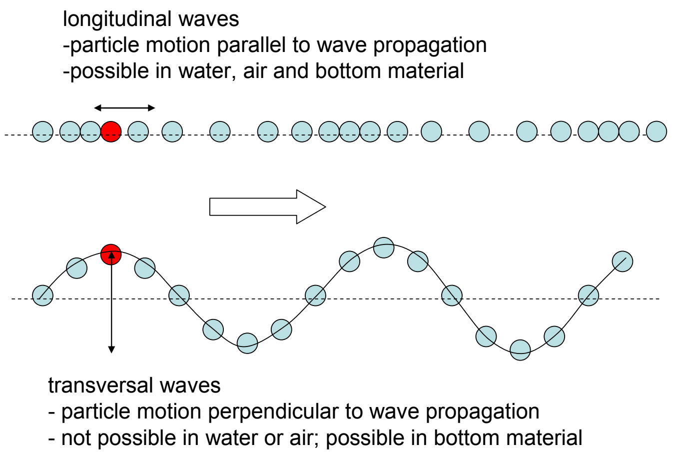


Figure 1.1. Longitudinal and transverse waves illustrated. The wave propagation is from left to right, whereas the particle motion is indicated by the arrow near the particle-in-red.

Sound in air is considered to be audible to humans if it is in the frequency range from 20 Hz to 20 kHz. The hertz (symbol Hz) is the unit of frequency, indicating the number of cycles per second of the vibrations. A pure tone is characterized by one frequency only, but in general sound is a mixture of many frequencies. Depending on the character of this mixture, humans experience the sound as music, speech or noise, etc.

Frequencies higher than 20 kHz cannot be heard by humans. In fact, the highest frequency to be observed is a function of age. For example, at the age of 25 the upper limit has lowered to somewhere below 15 kHz. However, this does not mean that higher frequencies do not exist. In fact, bats use such *ultrasonic* frequencies for navigation and hunting. Their hearing system is capable of detecting a much wider range of frequencies than the human hearing system. In general, every species has its own hearing sensitivity and frequency range, which becomes smaller as it grows older.

Frequencies lower than 20 Hz also exist. The changes in air pressure due to the weather for instance can be characterized by extremely low frequencies that could better be expressed in cycles per month than in cycles per second! Also, the impact of a meteoroid somewhere high in the atmosphere gives rise to very low frequencies well below 1 Hz. They can be detected with special *infrasonic* detection systems.

It is clear now that in most practical applications related to human hearing, neither the infrasonic frequencies, nor the ultrasonic frequencies are relevant. Therefore, in audio applications for humans, normally a frequency filter is applied when measuring sound. This filter only passes the relevant frequencies, e.g. in the range from 20 Hz to 20 kHz, and it removes the frequencies outside this range. Note that the frequencies outside the range from 20 Hz to 20 kHz may have amplitudes that are much higher than those of the frequencies within this range. This means that the total unfiltered sound pressure may be very different from the audible sound pressure. As will be discussed later, the human hearing sensitivity over the frequency range from 20 Hz to 20 kHz is far from uniform and sometimes a filter is applied to correct for this.

Depending on the strength of the vibrations, i.e. their amplitude, we experience a different loudness. Sound may be so loud that it even becomes annoying. A well-known phenomenon is that humans experience a temporary reduction of hearing sensitivity after having been exposed to very loud sounds, like after a night out at the discotheque. In the case of extremely large amplitudes, we may even start to experience pain in our ears. The ultimate effect of a too long exposure to too much sound is a permanent loss of hearing sensitivity (deafness).

At the low end, humans may be capable of detecting very small pressure variations of order 20 μPa. The pascal (symbol Pa) is the unit of pressure which equals 1 N/m^2 (one newton per square metre). At the high end, very large pressure variations may occur. There is no upper limit in principle, but as an example we consider a variation with an amplitude equal to the static ambient pressure in air, which is 10^5 Pa. This means that there is a factor of at least 5,000,000,000 between these large pressure variations and those of the lowest audible sounds. Such huge factors have led to the decibel (symbol dB) as the unit of sound pressure level. Definitions will be provided later. For now, it is sufficient to know that the dB is a logarithmic measure, that an increase in acoustic energy by a factor of 10 leads to an increase by 10 dB, an increase of a factor of 2 leads to an increase by approximately 3 dB, and the factor 1 is equal to 0 dB. Once expressed in dB, sound levels get values in the order of tens or hundreds of decibels, which is much more convenient than the huge numbers that would be required otherwise.
This logarithmic definition implies that the addition of two sound powers does not correspond to the addition of numerical values of sound pressure level (see later) expressed in decibels. Furthermore, it is good to realize that a dB is like a percentage: one must always ask the question "relative to what?" By definition, the reference pressure for reporting sound pressure levels in air is 20 μPa, i.e. this corresponds to 0 dB. Although this definition answers the question "relative to what?", it still is a good practice to explicitly mention this in the notation, e.g. 10 dB re 20 μPa.

As will be discussed later, energy measures are related to the *square* of the pressure. For this report, we adopt the practice of making this explicit in the notation.
For instance, in the case of sound pressure level, which is an energy measure, we would express this in dB re $(20\ \mu Pa)^2$, or equivalently dB re 400 μPa^2. Note however, that this is not an internationally accepted standard. So, in literature one is likely to encounter dB re 20 μPa in the case of sound pressure level.

Before going to the underwater situation, one effect has still to be discussed: the hearing sensitivity. For humans, the hearing sensitivity is not the same for all audible frequencies. In general, each species has hearing adaptation for its own vocalizations, those of its prey, and sometimes those of its predators. For example, humans are most

sensitive to frequencies around 2500 Hz, i.e. around the frequency range of speech, but not very sensitive to frequencies below 200 Hz or above 10 kHz. As a consequence, a tone of 2500 Hz will be experienced to be much louder than a tone of 200 Hz, even if the amplitudes of both tones are equal in terms of pressure variation. For that reason, various frequency-weighting functions have been designed to take this effect into account. The A-weighting is the most commonly encountered example. This weighting is applied to the measured signal, before sound related measures are computed.
The sound levels that are obtained in this way are expressed in dB(A) to indicate that the A-weighting has been applied. In Dutch law, all levels related to traffic noise, or industrial noise are expressed in dB(A).

Summarizing, when talking about a sound level in air, one must always remember the following properties:

- There is a corresponding range of frequencies
- A frequency-weighting may have been applied
- It is expressed in dB:
    - 10 dB acoustic energy increase corresponds to a factor of 10
    - 3 dB acoustic energy increase corresponds to a factor of 2
    - 0 dB acoustic energy increase corresponds to a factor of 1
- A dB is like a percentage: one must always ask “relative to what?” By definition, the reference pressure of sound in air is 20 μPa, i.e. 20 μPa corresponds to 0 dB. Nevertheless, it is preferred to explicitly mention it in the notation: 0 dB re 20 μPa.

1.1.2 Sound underwater

The situation of sound in the underwater environment is very similar to the situation of sound in air. The medium ‘water’ supports the propagation of sound even better than the medium ‘air’. In water, the attenuation is less than in air. This means that sound propagates over longer distances underwater than in air. It also propagates much faster: the speed of sound in water is approximately 1500 m/s (versus 340 m/s in air).
There are many different underwater sound sources. To mention a few: ships, breaking waves, animals, underwater construction activities, wind energy farms, wind, rain and lightning.

A major difference between underwater and above-water sound measures is that the amplitude of the reference pressure variation in the case of underwater sound is by definition 1 μPa (versus 20 μPa in air). This difference is an important cause of misunderstandings, e.g. when comparing above-water sound levels with underwater sound levels. Both are expressed in dB, but with respect to a different reference level!

A second important difference is the difference in characteristic impedance between water and air. The characteristic impedance Z is the product of density ρ and speed-of-sound c. Thus, $Z = \rho c$. In water it is approximately 1000×1500 kg/(m^{2}s), whereas in air it is approximately 1.2×340 kg/(m^{2}s). The difference corresponds to a factor of almost 3700. The meaning of this is that a particular pressure variation in water represents much less power than the same pressure variation in air.

The matter of frequency filtering in the underwater situation is closely comparable to the situation in air. In fact, it may even be more important, which can be made clear with the following example. Imagine that a hydrophone (i.e. an underwater microphone) is located at the sea floor in relatively shallow water. Depending on the weather conditions, the hydrophone may experience pressure variations due to waves at the surface. In the case of long wavelengths, these cause a changing hydrostatic depth. Likewise, a hydrophone deployed from a moving ship (heave) may also sense such low frequencies. Such variations may have large amplitudes and they would lead to large sound measures if they were not removed from the measurements. Fortunately, they are characterized by low frequencies, usually below 1 Hz, which means that they can be filtered out. This example demonstrates the importance of frequency filtering in the case of underwater measurements.

Although the emphasis in this report is on sound sources (including underwater animals), it is interesting to provide some information on animals as the recipients of underwater sound. The various animal species that live underwater, like fish and marine mammals, each have their own specific hearing sensitivity and frequency range. Sound is particularly important for those animals that rely on sound for navigation and hunting, like porpoises, dolphins and whales. Some of these animals have sophisticated echo-location capabilities. The frequency range relevant to them may easily be ten times larger than the range that is relevant to humans. For example, they may produce and hear frequencies up to 160 kHz. To take this species-dependent sensitivity into account, a frequency weighting function can be applied to the measured sound. Such a function is based on the so-called audiogram. An example of audiograms of the harbour seal, the harbour porpoise and the cod is given in Figure 1.2. The lower the curve, the more sensitive a species is. Note the large differences between these audiograms. Regularly, updated audiograms are published in literature, reflecting the latest, improved knowledge. The example in Figure 1.2 is meant for illustration purposes only, and motivates our choice of relevant frequency range.

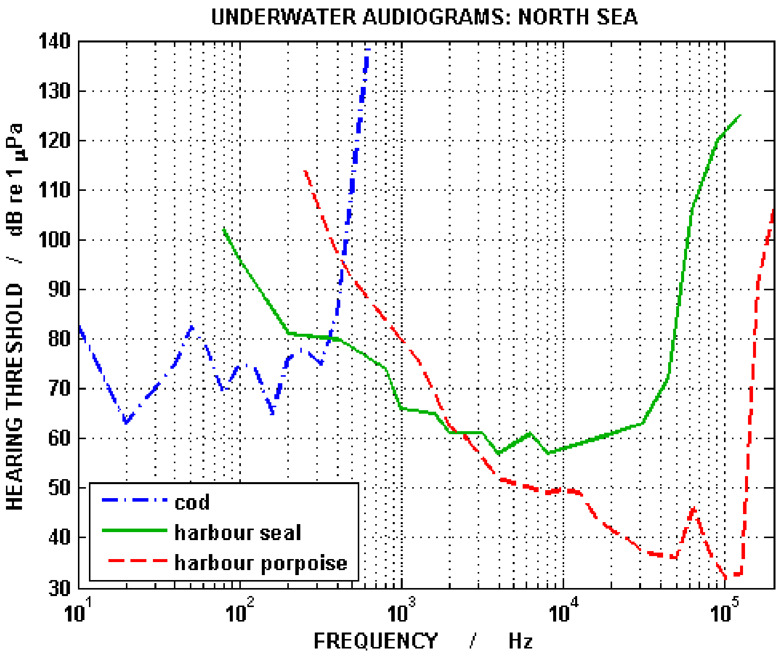


Figure 1.2. An example of audiograms of the harbour seal, the harbour porpoise and the cod.

It should be noted that some amphibious animals, mainly pinnipeds, can hear in water as well as in air and for these animals, the hearing difference needs to be taken into account, i.e. they have two audiograms: an air-audiogram and an underwater-audiogram.

High levels of underwater sound may not only be disturbing but also harmful to the underwater fauna. There is a relation between strandings of certain species of whales and high-level military sonar. There may be effects on fish and fish larvae. However, much is still to be known in this area.

Summarizing, when talking about underwater sound, one must always remember the following properties:

- There is a corresponding range of frequencies
- A species-dependent frequency weighting may have been applied, based on the species' audiogram
- It is expressed in dB:
  - 10 dB acoustic energy increase corresponds to a factor of 10
  - 3 dB acoustic energy increase corresponds to a factor of 2
  - 0 dB acoustic energy increase corresponds to a factor of 1
- A dB is like a percentage: one must always ask “relative to what?” By definition, the reference pressure of sound in water is 1 μPa, i.e. 1 μPa corresponds to 0 dB. Nevertheless, it is preferred to explicitly mention it in the notation: 0 dB re 1 μPa.

1.1.3 Different types of sound

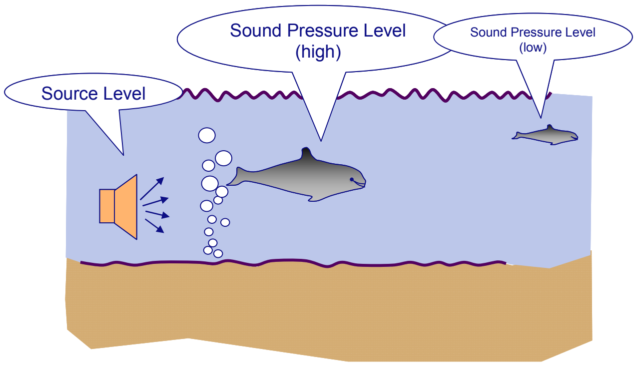
As mentioned before, in many cases sound is a mixture of frequencies. Depending on this mixture, it may appear as music, speech, noise, etc. This is why sound is characterized in different categories:

– Tonal. Tonal sound is characterized by the presence of one or a few single frequencies. An example of tonal noise is the noise generated by rotating machinery (e.g. engines, gearboxes) on board ships. The same applies to operational wind energy farms, where the tonals are also produced by rotating parts.
– Transient. Transients are events of a limited duration. Some typical whale sounds like whistles / sweeps belong to this category. Examples include pile driving, whereby a heavy weight is dropped once about every second, and dolphin clicks.
– Noise. Noise has an irregular character, with many frequencies interfering in an unstructured way. Examples are wind noise and rain noise.

Note that this classification is based on physical properties. As such, a computer is capable of carrying out the classification. However, the impact of sound on animals strongly depends on further, more complex properties. For instance, the sound of their predator may have a very strong impact, while a sound that has similar physical properties may have very little impact if it is produced by a non-predator.

1.1.4 Measures of sound

In Part II, several important measures of sound will be discussed, such as the source level and the sound pressure level. The source level is a property of the source that produces the sound. The higher the source level the higher its power, and hence, the louder the sound that the source produces. However, a recipient at a large distance may experience only a low level, even though the source level is high: the larger the distance from the source, the lower the level that is experienced. Therefore, a second measure is relevant, one that is related to the actually experienced level at a particular location. This measure is called the sound pressure level. It is indicative for an average level of sound that is present at a certain location and as such it is indicative for a *received* level.



A third measure would refer to the total, accumulative amount of sound that is received during a particular time interval; it is called sound exposure level. Finally, the peak level is indicative for the maximum absolute pressure within a particular time interval.

Summarizing, we have:

- Source level, indicative for the strength of an acoustic source
- Sound pressure level, indicative for the average amount of sound energy at one location, during some period of time
- Sound exposure level, indicative for the total amount of sound at one location, during some period of time
- Peak level, indicative for the maximum acoustic pressure at one location, during some period of time

As mentioned, a weighting factor is sometimes applied that takes into account the sensitivity of a particular animal. In such cases, this should be mentioned explicitly. Also the kind of weighting function should be stated. This is because there are no standards yet. Furthermore, due to increasing knowledge, the weighting curves are regularly updated, according to the latest research results.

Finally, as has been mentioned before, the involved frequency range should be stated to avoid confusion. A special case is where the total frequency range is split in frequency bands each of size one-third of an octave (known as third-octave bands). For each of those, the source level, sound pressure level and sound exposure level can be computed. In this way, a frequency dependence can be incorporated. In many cases, an even finer sampling of the frequency axis is required. In the case that the values have been computed for 1 Hz frequency bands, this is called the power spectral density.

Note that all levels as mentioned above are expressed in dB. One can imagine that this may again be confusing. An example: some journalist may compare the source level of underwater pile-driving with the sound pressure level due to a jet-engine of a Boeing 747, where the first number is considerably higher than the last. However, this does not necessarily mean that the experienced sound is louder. One should then remember the following properties:

- The reference pressure in air is 20 μPa (jet engine case) versus 1 μPa underwater (pile-driving case)
- Source level is a source property (pile-driving case) whereas sound pressure level is a level experienced by a receiver at some distance (jet-engine case)
- The recipient is different: the jet-engine is supposed to be heard by humans with their specific hearing properties, whereas the pile-driving is supposed to be heard by animal species that live underwater like fish and marine mammals, with their specific hearing sensitivity and frequency range

Consequently, comparing such quantities, although both are represented by a number expressed in decibels, is far less obvious than it seems to be at first sight. It also demonstrates the importance of explicitly mentioning “relative to what?” as this would be [dB re $(20\ \mu\text{Pa})^2$] in the case of the sound pressure level of the jet-engine and [dB re $1\ \mu\text{Pa}^2\text{m}^2$] in the case of the source level of the pile-driving, see the definitions that now follow in Part II. Furthermore, it illustrates the importance of stating the related frequency contents of the signals. In Part II, some attention will be paid to the rule-of-thumb “to go from water to air, simply subtract 62 dB (or 61.5 dB) from the number of decibels in water”, which turns out to be not simple at all, and which is another source of confusion for comparisons between levels underwater and above water.

1.2 Part II: Measures and definitions

1.2.1 Measures

The measures introduced in Part I will now be defined. They are the sound pressure level, the sound exposure level, the peak level and the source level, respectively.

The Sound Pressure Level (SPL), indicative for the average amount of sound at one location, is defined as

$$\mathrm{SPL} = 10\log_{10}\left(\frac{1}{T}\int_0^T \frac{p^2(t)}{p_{\mathrm{ref}}^2}\,\mathrm{d}t\right) \qquad [\mathrm{dB\ re\ 1\ \mu Pa^2}], \qquad (1.1)$$

where T is the integration time (which for transients must be stated), $p(t)$ is the sound pressure at that location as a function of time t, and p_{ref} is the reference pressure in water of 1 μPa. The sound pressure is the difference between the instantaneous pressure in the sound field and the quasi-static 'background' pressure (atmospheric and hydrostatic), i.e. the pressure with the sound absent; its unit being Pa.

Substituting the following expression for the rms (root-mean-square) pressure

$$p_{\mathrm{rms}} = \sqrt{\frac{1}{T}\int_0^T p^2(t)\,\mathrm{d}t} \qquad (1.2)$$

in equation (1.1) yields an alternative, well-known expression for the SPL:

$$\mathrm{SPL} = 10\log_{10}\left(\frac{p_{\mathrm{rms}}^2}{p_{\mathrm{ref}}^2}\right) \qquad [\mathrm{dB\ re\ 1\ \mu Pa^2}]. \qquad (1.3)$$

Note that $10\log_{10}(x^2)$ is equal to $20\log_{10}(x)$, where x is some positive quantity.
This property could be used to reformulate (1.3) as SPL = $20\log_{10}(p_{\mathrm{rms}}/p_{\mathrm{ref}})$.
In this report, however, we stick to the '$10\log_{10}(x^2)$ notation'.

Note that it is not easy to measure the sound pressure $p(t)$ in practice, since it is usually impossible to measure twice, once with and once without the sound being present. Instead, a low-cut filter is applied to the measurements of the instantaneous pressure in the sound field. The assumption is that the quasi-static background pressure is contained in the low frequencies that have been removed by the low-cut filter, and that the remaining frequencies contain the desired sound pressure. Furthermore, at the high-frequency end a high-cut filter is always applied. This has to do with modern digital recording equipment and the maximum number of samples per second that can be digitized. This limits the maximum frequency to be recorded. In this study, a maximum frequency of 200 kHz has been chosen. This is high enough to capture the frequencies produced by the harbour porpoise (up to 160 kHz).

The Sound Exposure Level (SEL), indicative for the total amount of sound energy at one location over a certain time duration (T), is defined as

$$\mathrm{SEL} = 10\log_{10}\left(\int_0^T \frac{p^2(t)}{p_{\mathrm{ref}}^2 t_{\mathrm{ref}}}\,\mathrm{d}t\right) \quad [\mathrm{dB\ re\ 1\ \mu Pa^2 s}], \tag{1.4}$$

where t_{ref} is the reference time of 1 s. An alternative way of expressing SEL is

$$\mathrm{SEL} = 10\log_{10}\left(\frac{p_{\mathrm{rms}}^2}{p_{\mathrm{ref}}^2}\right) + 10\log_{10}\left(\frac{T}{t_{\mathrm{ref}}}\right) \quad [\mathrm{dB\ re\ 1\ \mu Pa^2 s}], \tag{1.5}$$

In this formula, we recognize the first term on the right hand side as the SPL of (1.3).

The peak level, indicative for the maximum pressure at one location, is defined as

$$p_{\mathrm{peak}} = \max(|\,p(t)\,|)_{t=0}^{T} \quad [\mathrm{Pa}]. \tag{1.6}$$

For a directional sound source, in underwater acoustics, the Source Level (SL) is defined by Morfey (2001) as “the SPL measured in a given radiation direction, corrected for absorption and scaled to a reference distance $r_{\mathrm{ref}} = 1$ m. In equation form, the source level is given by

$$\mathrm{SL} = 10\log_{10}\left(\frac{1}{T}\int_0^T \frac{r^2 p^2(r,t)}{r_{\mathrm{ref}}^2 p_{\mathrm{ref}}^2}\mathrm{d}t\right) \quad [\mathrm{dB\ re\ 1\ \mu Pa^2 m^2}], \tag{1.7}$$

where $p(r,t)$ is the sound pressure radiated to the far field (in the relevant direction) at distance r from the source.” We would like to add that in our view the source level is a source property, which should be independent of the environment (water depth, bottom type, etc.). Equation (1.7) is not unambiguous in this respect. We therefore add the condition that the medium is loss-less, iso-velocity water and that the boundaries (water bottom, water surface) have no influence (i.e., they are far enough from the source location), such that spherical spreading is justified.

Often people remember that the source level is defined as the sound pressure level of the source, measured at a distance of 1 m. However, it is not desired to measure at such a close distance to a source, because this would often be in the near-field. Therefore, the definition allows for measurements at a larger distance (in the far field), and includes a correction term (r/r_{ref}) for this distance. An alternative formulation is

$$\mathrm{SL} = 10\log_{10}\left(\frac{p_{\mathrm{rms}}^2}{p_{\mathrm{ref}}^2}\right) + 10\log_{10}\left(\frac{r^2}{r_{\mathrm{ref}}^2}\right) \quad [\mathrm{dB\ re\ 1\ \mu Pa^2 m^2}]. \tag{1.8}$$

About the difference between a source level in water and a source level in air, one may encounter the following statement: “to convert from water to air, simply subtract 62 dB (or 61.5 dB) from the number of decibels in water”. The term −62 dB here refers to the sum of −26 dB and −36 dB, being $10\log_{10}(p^2_{\mathrm{ref,water}}/p^2_{\mathrm{ref,air}})$ and $10\log_{10}[(\rho_{\mathrm{air}}c_{\mathrm{air}}/\rho_{\mathrm{water}}c_{\mathrm{water}})]$, respectively. Here, $p_{\mathrm{ref,water}} = 1$ µPa is the reference pressure in water, $p_{\mathrm{ref,air}} = 20$ µPa is the reference pressure in air, $\rho_{\mathrm{water}} = 1000$ kg/m^3 is the density of water, $c_{\mathrm{water}} = 1500$ m/s is the speed of sound in water, $\rho_{\mathrm{air}} = 1.2$ kg/m^3 is the density of air, and $c_{\mathrm{air}} = 340$ m/s is the speed of sound in air. The correction is an appropriate one if the physical quantity one wishes to compare is equivalent plane wave intensity (EPWI), defined as mean square acoustic pressure divided by the characteristic impedance of the medium (ρc). For any measure of sound other than EPWI, the conversion is at best misleading. For example, SPL is defined as a ratio of (squared) pressures, not intensities, which makes it inappropriate to include a correction for the impedance ratio for this quantity (Ainslie, 2008b, 2008c). Another example is sound level, which is a weighted version of SPL, for the animal's hearing sensitivity (for humans in air, usually A-weighted). For this quantity, one would need an additional correction to allow for different hearing sensitivities in air and water. Our suggestion is to keep the underwater and above-water worlds separate as far as sound is concerned, and not to try to make comparisons. In the remainder of this document, the source level and the sound pressure level are the two most often used measures.

Finally, to give the reader an impression of the dB numbers involved in underwater acoustics, we give an example of the sound pressure level underwater due to wind.
In this case, the wind speed is 10 m/s, corresponding to 5 beaufort and sea state 4-5. The SPL is 100 dB re 1 μPa^2 for frequencies larger than 1 kHz. This sound pressure level is more or less independent of the location and depth. Another example is the sound pressure level underwater due to typical dolphin clicks. This number is 180 dB re 1 μPa^2 for 25 μs clicks at a distance of 30 m from the animal. Note that a difference of 80 dB corresponds to a power ratio of $10^8 \approx 100$ million, a huge number. Of course, the clicks have a short duration (and therefore not so much total energy), while the wind noise is continuous. Furthermore, the spectra are also totally different. Still, it is interesting to realize that a dolphin is capable of producing very loud sounds.

2 Natural noise sources

2.1 Introduction

The main sources of natural sound, due to their ubiquitous nature, are expected to be wind and rain. These are given the greatest emphasis. Lightning is also subject to scrutiny because of the large amount of energy available in each individual strike. The potential natural sources were listed in the previous chapter (Table 1.1). Information collected on source level and frequency content of some of these sources can be found in Table A.1 (Appendix A).

The primary natural sources of ocean ambient sound from 1 to 50 kHz are wind-generated breaking waves and the splashes from raindrops. Lightning makes an intermittent contribution, producing very intense sounds of very short duration. These three sound sources are therefore given the most attention. It is assumed that underwater animals make a relatively small contribution to the ambient noise by comparison. An overview of natural sources is provided by Wenz (1962) and Urick (1983). The Wenz curves are shown in Figure 2.1.

Individual sound sources are discussed in turn below. Where available, the source level is presented in preference to received levels.

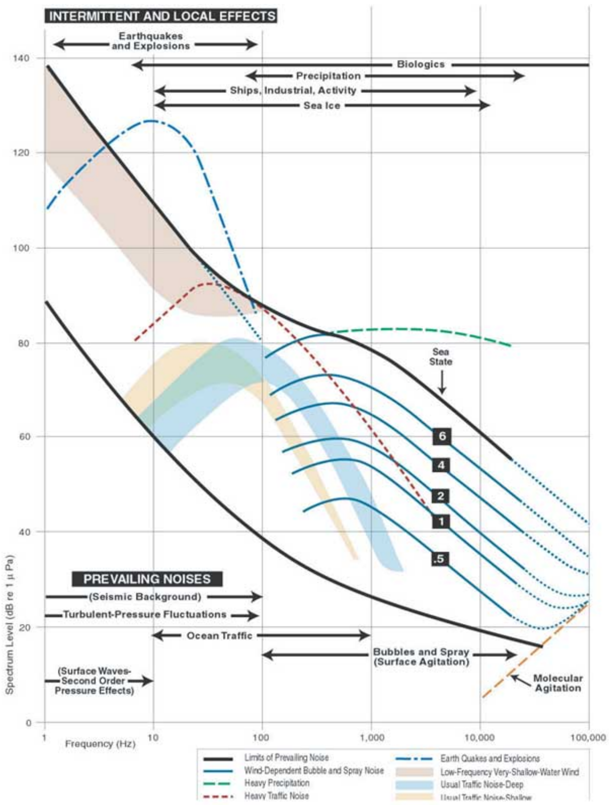


Figure 2.1. Wenz curves showing typical noise spectra, including wind and rain. The vertical axis shows noise spectral density in dB re 1 µPa^2/Hz (from 0 to 140 dB); the horizontal axis shows frequency from 1 Hz to 100 kHz (Wenz, 1962).

2.2 Wind

2.2.1 *Source characterisation*

The wind noise source level is in general associated with the natural pulsations of gas bubbles created by sea surface activities as, for instance, breaking waves. Basically, the source spectral density of wind noise varies with frequency, having a flat behaviour at low frequency, in the range 50 to 400 Hz (Kuperman & Ferla, 1985), see Figure 2.2, and decreasing monotonically with increasing frequency in the range of 10 kHz to 100 kHz (APL-UW handbook, 1994).

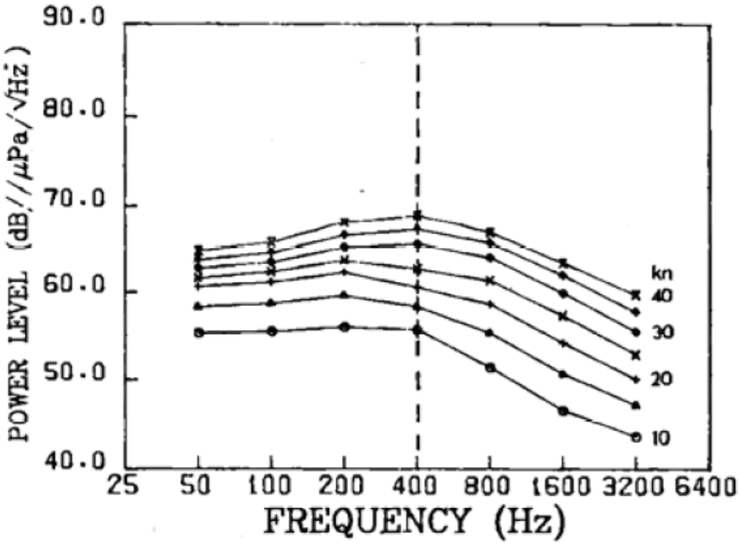


Figure 2.2. Spectral density of wind noise (dipole source level $10\log_{10}K$), in dB re 1 µPa^2/Hz, measured by Kuperman & Ferla (1985) for wind speeds of 10-40 knots (ca. 5-20 m/s).

For high frequencies (10-100 kHz), a useful parameterisation for the spectral density of dipole source strength, denoted K, from the APL-UW handbook (1994) is:

$$K_{\mathrm{HF}}^{\mathrm{wind}} = \frac{10^{4.12}\hat{v}_{10}^{2.24}}{F^{1.59}}\,\mu\mathrm{Pa}^2\ \mathrm{Hz}^{-1}, \qquad (2.1)$$

where F is the frequency in kilohertz and $\hat{v}_{10}$ is the wind speed at 10 m height, expressed in m/s.

For lower frequencies, the measurement of wind noise source level is more problematic, as explained by Kuperman & Ferla (1985), since the wind noise can be masked by shipping noise. The measurements done by Kuperman & Ferla (1985) exhibit a similar dependence to the previous formula (2.1) with a spectrum that flattens off at frequencies less than 400 Hz (see Figure 2.2). This behaviour can be approximated by an asymptotic formula for low frequency (Ch. 8 of Ainslie, 2008):

$$K_{\mathrm{LF}}^{\mathrm{wind}} = \frac{10^{4.12}}{1.5}\hat{v}_{10}^{2.24}\mu\mathrm{Pa}^2\ \mathrm{Hz}^{-1}, \qquad (2.2)$$

where the value in the denominator is chosen to match the measured source level at 400 Hz in Figure 2.2. Typically, values of wind noise source level vary with the wind speed. For example, in a frequency range up to 1 kHz for a wind speed of 10 m/s, dipole source spectrum levels are between 60 and 62 dB re 1 μPa^2 Hz^{-1} (APL-UW handbook, 1994). Combining LF and HF behaviour into a single approximate formula gives (Ch. 8 of Ainslie, 2008):

$$K_{\mathrm{wind}} = \frac{10^{4.12}\hat{v}_{10}^{2.24}}{1.5 + F^{1.59}} \ \mu\mathrm{Pa}^2\ \mathrm{Hz}^{-1}\,. \tag{2.3}$$

See Figure 2.1 for an overview of (received) wind noise levels for different sea states.

2.2.2 *Acoustic energy*

We proceed to provide a first order estimate for the total acoustic energy produced by wind noise on an annual basis. To do this, we integrate over all frequencies and consider the sensitivity to wind speed. If A is the area and W_{Af} the spectral density of power per unit area, the total radiated acoustic power W is:

$$W = A\int_{f_1}^{f_2} W_{Af}\,\mathrm{d}f \ . \tag{2.4}$$

The power per unit area is related to the dipole strength K according to:

$$W_{Af} = \frac{2\pi}{3\rho c}K \tag{2.5}$$

$$\therefore W = \frac{2\pi}{3\rho c}A\int_{f_1}^{f_2} K_{\mathrm{wind}}\,\mathrm{d}f \ , \tag{2.6}$$

where the integral is

$$\int_{f_1}^{f_2} K_{\mathrm{wind}}\,\mathrm{d}f = 10^{4.12}\hat{v}_{10}^{2.24}\,\frac{1000}{0.59}\left(F_1^{-0.59} - F_2^{-0.59}\right)\mu\mathrm{Pa}^2 \tag{2.7}$$

Putting limits of 1 kHz to infinity with A = 57,000 km^2 (NCP area, see nl.wikipedia.org/wiki/Nederlandse_Exclusieve_Economische_Zone) gives W = 60 W ($\hat{v}_{10}$ = 5 m/s) and 300 W ($\hat{v}_{10}$ = 10 m/s). This translates to between 2 and 9 gigajoules per year (2-9 GJ/y).

2.3 Rain

2.3.1 *Source characterisation*

The sound generated from the splashes (or tiny air bubbles) from raindrops falling in the water can be a relevant natural source of noise in the ocean, especially in the frequency band between 1 and 50 kHz. Rain noise is sensitive to the rainfall rate, drop-size distribution and wind speed. An ideal predictive model would take all these parameters into account. A simple model in the APL-UW handbook (1994) includes dependence on wind speed but not on drop size. This model, valid from 1 to 100 kHz, can be expressed by the following equation:

$$10\log_{10}\left(K^{\mathrm{rain}}\right)=10\log_{10}\left(K_{20}^{\mathrm{rain}}\left(R_{\mathrm{rain}},\hat{v}_{10}\right)\right)+\begin{cases}-10\log_{10}F & 1\le F\le 10\\ 49\log_{10}F-59 & 10<F\le 16\\ 0 & 16<F\le 24\\ -23\log_{10}F+31.7 & 24<F\le 100\end{cases} \quad (2.8)$$

where F is the frequency in kilohertz and

$$10\log_{10}\left[K_{20}^{\mathrm{rain}}\left(R_{\mathrm{rain}},\hat{v}_{10}\right)\right]=b\left(\hat{v}_{10}\right)+a\left(\hat{v}_{10}\right)\log_{10}\left[\min\left(R_{\mathrm{rain}},10\right)\right]. \quad (2.9)$$

In (2.9), R_{rain} is the rain rate in millimetres per hour and $\hat{v}_{10}$ is the wind speed in metres per second. The functions $a(\hat{v}_{10})$ and $b(\hat{v}_{10})$ are:

$$a\left(\hat{v}_{10}\right)=\begin{cases}25 & \hat{v}_{10}\le 1.5\\ 5+5.7\left(5-\hat{v}_{10}\right) & 1.5<\hat{v}_{10}<5\\ 5 & \hat{v}_{10}\ge 5\end{cases}, \quad (2.10)$$

$$b\left(\hat{v}_{10}\right)=\begin{cases}41.6 & \hat{v}_{10}\le 1.5\\ 50-2.4\left(5-\hat{v}_{10}\right) & 1.5<\hat{v}_{10}<5\\ 50 & \hat{v}_{10}\ge 5\end{cases}. \quad (2.11)$$

See Figure 2.3 for an evaluation of the model equations. Ma *et al.* (2005) describes the dependence of rain noise on the drop-size distribution. Typically, a dependence on wind speed is present for light rain, while this is not present for heavy rain, i.e. large raindrops.

As described by Ma *et al.* (2005), only large raindrops contribute to the high frequency range (i.e. up to 50 kHz). In this case, the sound is independent of the wind speed. Moreover, the rainfall sound from 1 to 10 kHz is mainly generated by large raindrops of about 2-3.5 mm of diameter. The sound pressure level is almost independent of the wind speed and increases linearly with the logarithmic rainfall rate (Ma *et al.*, 2005). The sound pressure level produced by light rain (drizzle), having small drop size (i.e. 0.8-1.2 mm), is influenced by wind. Ma *et al.* (2005) give equations for the spectral density due to rain noise for different conditions (rain rate up to 10 mm/h, wind speed up to 10 m/s and acoustic frequency up to 50 kHz). Results are shown in Figure 2.4.

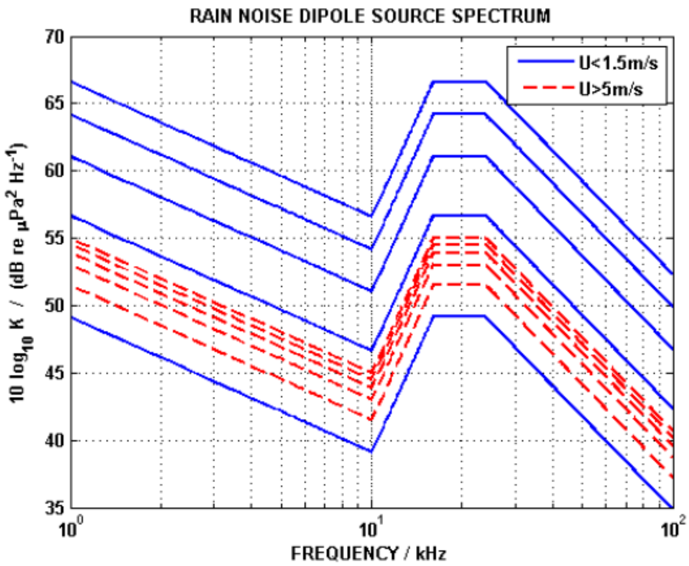


Figure 2.3. Spectral density of rain noise (dipole source level = $10\log_{10}K$), in dB re 1 μPa²/Hz, following the APL-UW handbook (1994), evaluated with (2.8). The multiple blue lines are (from bottom to top) for rainfall rates of 2 to 10 mm/h, in steps of 2 mm/h, and wind speed less than 1.5 m/s. The dashed lines are for the same rain rates, and wind speed above 5 m/s [© Ainslie 2008].

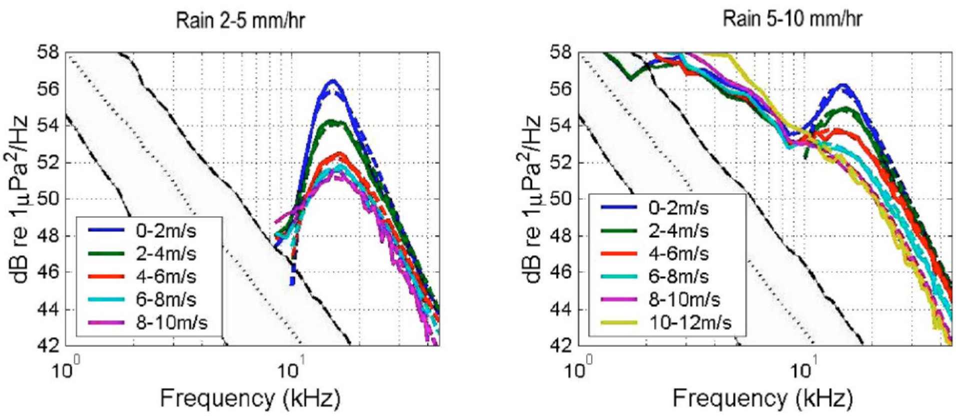


Figure 2.4. Spectral density of rain noise (received omni-directional level), in dB re 1 μPa²/Hz, measured by Ma *et al.* (2005) for rainfall 2-5 mm/h (left graph) and 5-10 mm/h (right) at various wind speeds. The frequency axis runs from 1 to 40 kHz. The white shaded area represents wind-only spectra of Ma *et al.* (2005).

2.3.2 *Acoustic energy*

Eq. (2.5) can be used to calculate the total radiated power:

$$W = \frac{2\pi}{3\rho c} A \int_{f_1}^{f_2} K_{\text{rain}} \mathrm{d}f \ . \tag{2.12}$$

For low wind speed ($\hat{v}_{10}$ < 1.5), the APL-UW handbook (1994) gives for the dipole source strength:

$$K_{\text{rain}} = 10^{4.16} R_{\text{rain}}^{2.5} \times \begin{cases} 1 & 16 < F < 24 \\ \left(\dfrac{24}{F}\right)^{2.3} & F > 24 \end{cases} \quad \mu\text{Pa}^2/\text{Hz} \tag{2.13}$$

For the low frequency contribution (16-24 kHz), this gives:

$$\int_{f_1}^{f_2} K_{\text{rain}} \mathrm{d}f = 10^{4.16} R_{\text{rain}}^{2.5} 1000 (F_2 - F_1) \quad \mu\text{Pa}^2 \tag{2.14}$$

Using a typical rainfall rate of 5 mm/h (KNMI, 2008), the result is 1 μW/(km^{2}Hz), amounting to 500 W for the entire NCP in this frequency band. Given that the annual rainfall is 800 mm (0.09 mm/h on average), this can be converted to a mean power of 9 W, averaged over a year, giving 0.3 GJ/y in the 16-24 kHz frequency range.

The high-frequency contribution (> 24 kHz) can be calculated using:

$$\int_{f_1}^{f_2} K_{\text{rain}} \mathrm{d}f = 10^{4.16} R_{\text{rain}}^{2.5} \frac{24000}{1.3} \left[\left(\frac{24}{F_1}\right)^{-1.3} - \left(\frac{24}{F_2}\right)^{-1.3} \right] \quad \mu\text{Pa}^2 \tag{2.15}$$

and the total is (integrating to infinite frequency):

$$\int_{16\ \text{kHz}}^{\infty} K_{\text{rain}} \mathrm{d}f = 10^{4.16} R_{\text{rain}}^{2.5} \left[8000 + \frac{24000}{1.3} \right] = 3.8 \times 10^8 R_{\text{rain}}^{2.5} \quad \mu\text{Pa}^2 \tag{2.16}$$

Adding this high frequency contribution (a further 0.7 GJ/y for F > 24) gives a total of 1 GJ/y for all frequencies above 16 kHz.

The above calculation can be repeated for high wind speed ($\hat{v}_{10}$ > 5), for which

$$K_{\text{rain}} = 10^{5} \sqrt{R_{\text{rain}}} \times \begin{cases} 1 & 16 < F < 24 \\ \left(\dfrac{24}{F}\right)^{2.3} & F > 24 \end{cases} \quad \mu\text{Pa}^2/\text{Hz}\ . \tag{2.17}$$

The total energy from rain noise, assuming this higher wind speed, becomes 0.3 GJ/y. Frequencies below 16 kHz make a relatively small contribution to the total energy (assuming the spectrum of Figure 2.3) and are neglected. We conclude that the annual energy is between 0.3 and 1 GJ per year.

2.4 Lightning

Lightning strikes are rare but powerful events. Compared to the relatively mature literature for wind and rain noise, little is known about the acoustic signature of lightning, so it is appropriate to analyse the available publications (Arnold *et al.*, 1984; Hill, 1985) in some detail.

Electric discharges in the atmosphere over water can produce strong underwater sound pulses. The physics of this type of discharges and the question of how much energy a lightning strike in air might convert into acoustic energy in water has been addressed by Hill (1985). The underwater pulses are identified with the cloud-to-water strikes on the basis of information of lightning sound pulses in air. The sound measurements reported by Hill (1985) are done by Arnold *et al.* (1984) at a range of 46 km from a lightning flash. The depth of the seawater is about 20 m and the depth of the recording hydrophone is 6 m.

The average number of vertical discharges (strikes) on land in the Netherlands is between one and three per square kilometre per year. This number is between 10-30% of the total number of lighting events, including cloud-to-cloud strikes (Wessels, 1990; see also www.lightningwizard.com/KNMI-av). Lightning strikes are stronger and less frequent in winter (October-March) than in summer. Moreover, in the winter time, they are more concentrated near the west coast, while during summers lightning strikes occur more often in the east region of the Netherlands. Although discharges are more frequent in summer than in winter, in the latter case there is a higher percentage of vertical strikes, giving therefore about the same number of cloud-to-ground strikes both in winter and summer time, typically 2 strikes per square kilometre per year (KNMI, 2008).

In summer, there can be tens of thousands of strikes on a single day. For instance, on June 2008, about 40 thousand discharges were recorded by the Royal Netherlands Meteorological Institute (KNMI). Even though the number of strikes is of order 100-1000 for most of the days, such exceptional days have a large influence on the statistics, increasing significantly the average lightning activity (KNMI, 2008).

2.4.1 *Source characterisation*

Compared to other natural noise sources such as wind or rain, lightning is a relatively rare but very loud event. Hill (1985) estimates a source level of 260.5 dB re 1 $\mu Pa^2 m^2$ (Hill treats the lightning strike on the sea surface as if it were a source of sound in water). If the duration is 30 μs, then this converts to a source energy of 30 MJ.
The upper limit of the source energy is given by the (theoretical) case of a 100% conversion of electrical to acoustic energy. An estimation of this upper limit is 500 MJ per strike (KNMI, 2008; see also en.wikipedia.org/wiki/Lightning). The lower bound is 4 kJ, calculated from the acoustic measurements of Arnold *et al.* (1984) as follows.
The received sound (see Figure 2.5 below) has an amplitude of approximately 10 Pa (corresponding to an rms pressure of 7 Pa) and a duration of approximately 1 s.
The received energy (in the sense of §1.2.1) is therefore 50 $Pa^2 s$, or 137 dB re 1 $\mu Pa^2 s$.
The propagation loss is estimated to be not less than 70 dB re 1 m^2 (Hill's estimate is significantly higher than this, between 114 and 152 dB re m^2). Therefore, the source energy is not less than 207 dB re 1 $\mu Pa^2 m^2 s$, which, converted to SI units, amounts to 4 kJ. Thus, 30 MJ is between the two limits (4 kJ to 500 MJ), but the uncertainty is huge.

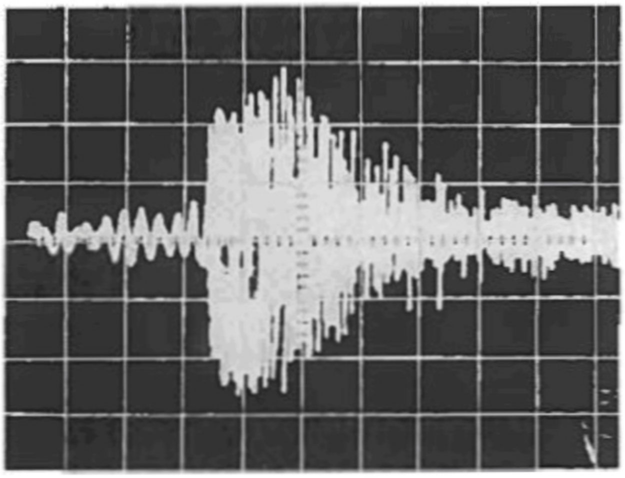


Figure 2.5. Oscilloscope display of underwater acoustic signal density due to lightning strike, from Arnold *et al.* (1984). The major divisions are 5 pascals per division (vertical axis, pressure) and 0.5 seconds per division (horizontal axis, time).

2.4.2 Acoustic energy

The number of strikes is estimated by KNMI (2008) to be approximately 1-3 per km^2y, so the total number of strikes in the NCP area (approximately 57,000 km^2) is between 60,000 and 170,000 per year. The total energy per year is therefore between 60,000 × 4 kJ = 0.24 GJ and 170,000 × 500 MJ = 85,000 GJ, indicating a large uncertainty (more than five orders of magnitude!). Taking Hill's estimated source level (with 30 μs duration and 2 strikes per square kilometre) gives 114,000×30 MJ/y ≈ 3,400 GJ/y. This figure would require a 4% efficiency for conversion from electrical energy of the discharge to acoustic energy in the water.

2.5 Marine mammal species

The most frequent species of mammals present in the Dutch North Sea are:

1. Harbour porpoises (*Phocoena phocoena*)
2. White-beaked dolphin (*Lagenorhynchus albirostris*)
3. Bottlenose dolphin (*Tursiops truncatus*)
4. Harbour seal (*Phoca vitulina*)
5. Grey seal (*Halicoerus grypus*)

From a study conducted during the years 1970-2005, it has been observed that harbour porpoises and white-beaked dolphins are resident species in the Dutch Waters (Van der Meij & Camphuysen, 2008). The bottlenose dolphin is listed as a regular visitor or passage migrant and has been recorded for over 23 years.

Moreover, other species are listed in order of frequency of apparition with respect to sighting (Van der Meij & Camphuysen, 2008):

6. Minke whale (*Balaenoptera acutorostrata*)
7. Sperm whale (*Physeter macrocephalus*)
8. Long-finned pilot whale (*Globicephala melas*)
9. Common dolphin (*Delphinus delphis*)

Also observed, with a lower frequency of occurrence, are fin whales, northern bottle-nose whales, striped dolphins, and (recently) humpback whales (Van der Meij & Camphuysen, 2008; see also home.planet.nl/~camphuys/Cetacea.html).

2.5.1 *Echo-location clicks*

Echolocation means producing directional forward-projecting pulsed sounds of high intensity and frequency. In general, each pulse is very brief (e.g. 50-200 μs) in duration and in most of the cases pulses are spaced so an echo from the target is received before the next pulse is emitted (Richardson *et al.*, 1995; pp. 181-184). The properties of the produced sound (frequency, click interval, source level, pulse duration, etc.) are adjusted by the animal to obtain an optimal performance depending on the conditions of ambient noise, distance to the target and characteristics of the target. The high-frequency components and the maximum levels can be detected only when the beam is directed to the hydrophone, although the position and orientation of the animal with respect to the hydrophone (receiver) is usually unknown.

Three types of echolocations are typically emitted by odontocetes:

1. Orientation clicks: long interclick intervals are used to scan the environment;
2. Discrimination clicks: shorter interclick intervals are used to obtain detailed information about a target;
3. Clicks of which the function is not clear.

Harbour porpoises produce directional echolocation beams (Richardson *et al.*, 1995; p. 184), where high-frequency energy is strongly concentrated in the centre of the beam and lower frequency components are distributed more broadly. See also Busnel & Dziedzic (1967), Teilmann *et al.* (2002), Verboom & Kastelein (2003), Verfuß *et al.* (2005), Villadsgaard *et al.* (2007) and Møhl & Andersen (1973).

2.5.2 *Other vocalisations*

Apart from echolocation clicks, other sounds are produced by mammals, typically these are tonal whistles and less distinct pulsed sounds (compared with echolocations) such as cries, grunts or barks. These types of sounds are produced at a lower frequency than echolocations and they have a lower power. Published information is available about the vocalisations of the harbour porpoise (Hansen *et al.*, 2008), white beaked dolphins (Rasmussen *et al.*, 2006), grey seal (Schusterman *et al.*, 1970) and harbour seal (Schusterman *et al.*, 1970; Van Parijs & Kovacs, 2002).

See Appendix A for a table of source levels and frequency ranges.

2.6 Fish

Many fish are known to produce sounds (Hawkins, 1986; Amorim *et al.*, 2004). However, little information has been found concerning measurements of fish sounds of relevance to the North Sea. Spawning sounds of cod (Nordeide & Kjellsby, 1999), feeding sounds of the grey gurnard (Amorim *et al.*, 2004) and mating sounds of the haddock (Bremner *et al.*, 2002) are reported at frequencies up to about 500 Hz to 1 kHz. The only quantitative information found relating to sound level is from Nordeide & Kjellsby (1999) (their Figure 3, reproduced here as Figure 2.6), who attribute differences in ambient noise of 7-18 dB to spawning Arctic cod.

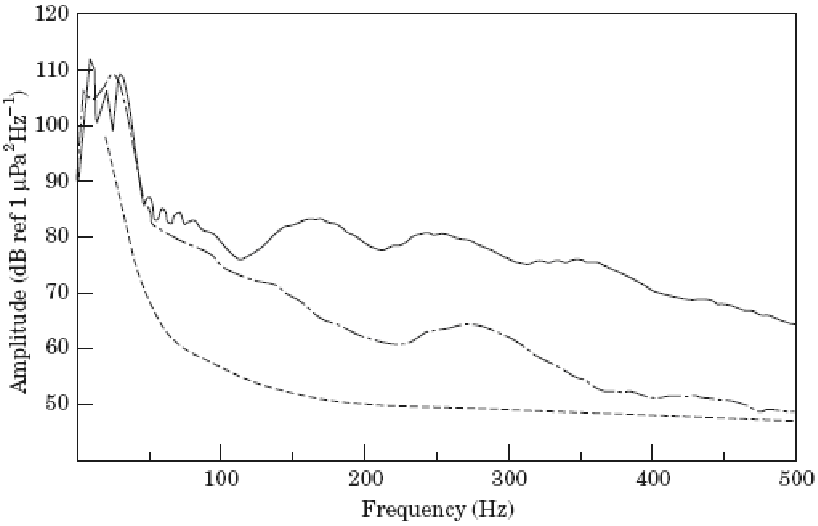


Figure 2.6. Spectral density of ambient noise close to cod spawning ground in Lofoten Islands, Norway. Received omni-directional level, in dB re 1 μPa^2/Hz, measured by Nordeide & Kjellsby (1999).

3 Intentional anthropogenic noise sources

3.1 Introduction

From the list of acoustic noise sources given in Chapter 1 (Table 1.1), this chapter focuses on the intentional anthropogenic noise sources. Source levels and related information are given in Appendix A. The unintentional sources are subject of the next chapter.

Most emphasis is placed on seismic survey sources, as these are known to be important sources of low frequency sound.

3.2 Seismic explorations

Seismic explorations are especially used to search for commercially economic subsurface deposits of crude oil, natural gas and minerals by the recording, processing, and interpretation of artificially induced shock waves in the earth. Artificial seismic energy is generated in marine environments typically by airgun fire. These devices generate sounds by rapidly releasing compressed air from an airgun cylinder, creating oscillating air bubble pulses that act as a source of loud, broadband impulsive sound. Seismic waves reflect and refract off subsurface rock formations and travel back to acoustic receivers such as hydrophones (see Figure 3.1). The hydrophones are contained in long cables, called streamers, that are towed behind the seismic vessel.

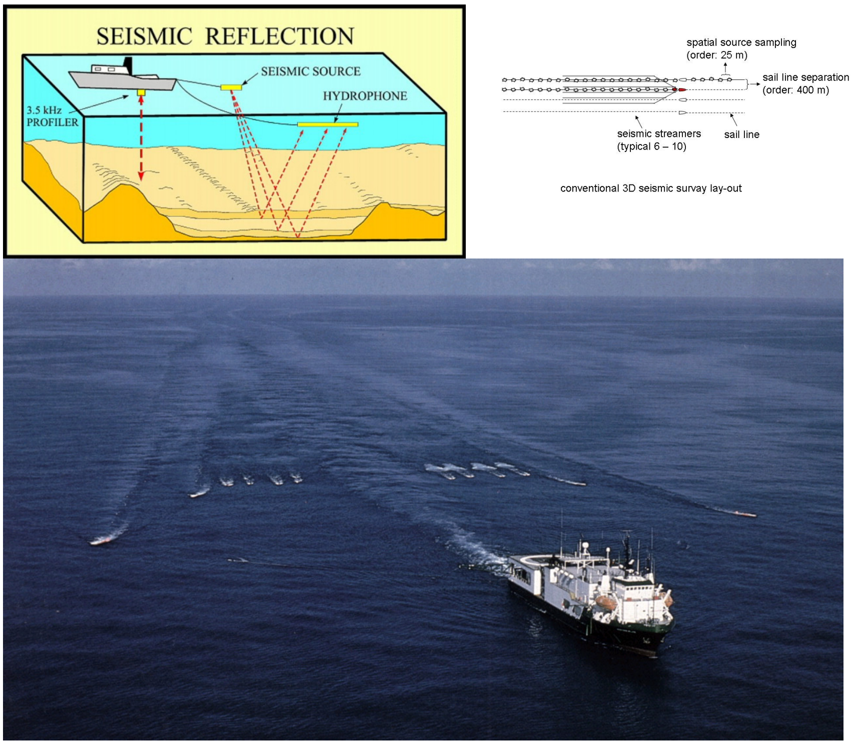


Figure 3.1. Seismic exploration.

To obtain the required high amount of energy, several airguns are usually deployed simultaneously. A configuration of several airguns is called an airgun array.
The frequency range that is used in the processing of seismic data depends on the required image resolution and on the depth of interest. In high-resolution surveys, the usable bandwidth ranges from 10 Hz at the low end to 1000 Hz at the high end. However, if the depth of interest is large, say more than 2 km, then the usable bandwidth is considerably smaller, because the higher frequencies are attenuated in the earth. It typically ranges from 10 Hz to 200 Hz, where in the deeper parts of the earth, i.e. deeper than 3 km, the usable bandwidth is up to order 25 Hz only.

However, this does not mean that an airgun array only generates the 'usable' frequencies. In practice, it also produces much higher frequencies, albeit at lower source levels. E.g., if the source level of a single airgun is expressed in third-octave bands and its maximum value is 210 dB re 1 μPa^2m^2 at 40 Hz, then it may still be 190 dB re 1 μPa^2m^2 at 1000 Hz and 160 dB re 1 μPa^2m^2 at 10 kHz (Goold & Fish, 1988). See also Figure 3.2, where the power spectral density is shown for an airgun source for increasing distance.

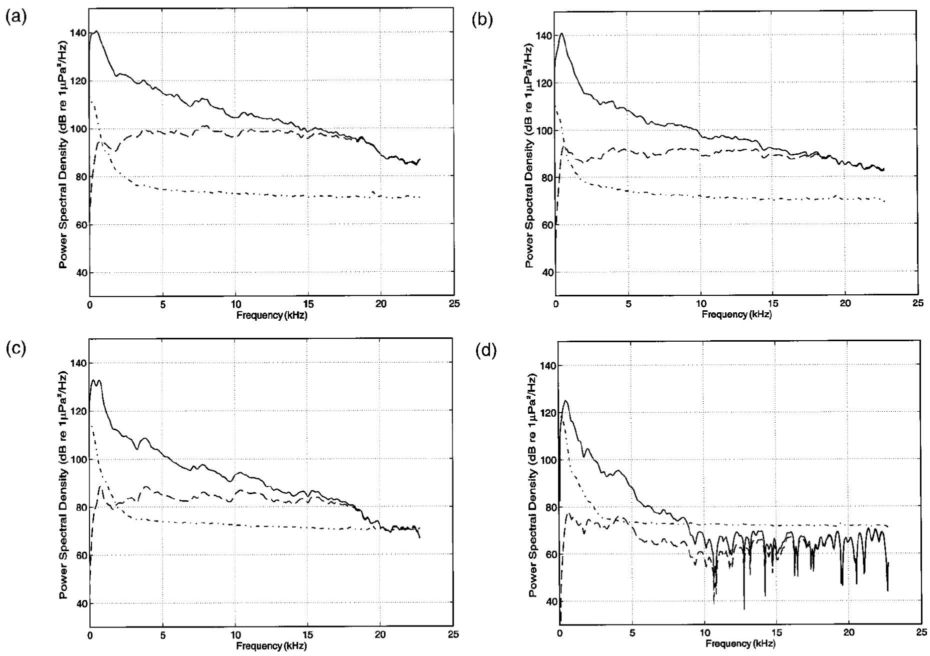


Figure 3.2. Plots of maximum seismic power spectral density (solid line), spectral density normalized using dolphin threshold curve (dashed line), and average background noise, including high ship noise (dot-dash line) at four different source-receiver ranges: (a) 750 m; (b) 1 km; (c) 2.2 km; and (d) 8 km. Plots are shown on a logarithmic scale of power spectral density in dB re 1 $\mu Pa^2/Hz$. The frequency axis runs from 0 to 25 kHz. Figure taken from Goold & Fish (1988).

Seismic sources are designed to transmit energy into a wide range of angles. Current streamers may have lengths up to 10 km. Only energy that propagates into directions close to horizontal reaches the hydrophones that are at the far-end of such streamers. A wide range of angles is required for a high spatial resolution. Nevertheless, there is often a null close to the horizontal direction due to the dipole formed by the source and its image, especially at low frequency.

In the literature, noise source levels are often reported as peak-to-peak (p-p) pressures in bar-metres (bar m). The bar is a unit of pressure equal to 100 kPa. Thus, a bar metre can be converted to the pascal metre unit by means of:

1 bar m = 10^5 Pa m = 10^{11} μPa m.

Or, equivalently:

1 bar^2 m^2 = 10^{22} μPa^2 m^2.

Moreover, it is difficult to compare any of these values with levels from continuous sources, which are normally expressed by a root-mean-square (rms) pressure.

In general, large airgun arrays generate sound pulses with peak energy in the range 10-200 Hz, and far-field measurements yield typical peak-to-peak source levels in the range 222-261 dB re 1 $\mu\text{Pa}^2\text{m}^2$ (De Ruiter *et al.*, 2006). The following graphs show example signatures for a single airgun (Figure 3.3) and an airgun array (Figure 3.4).

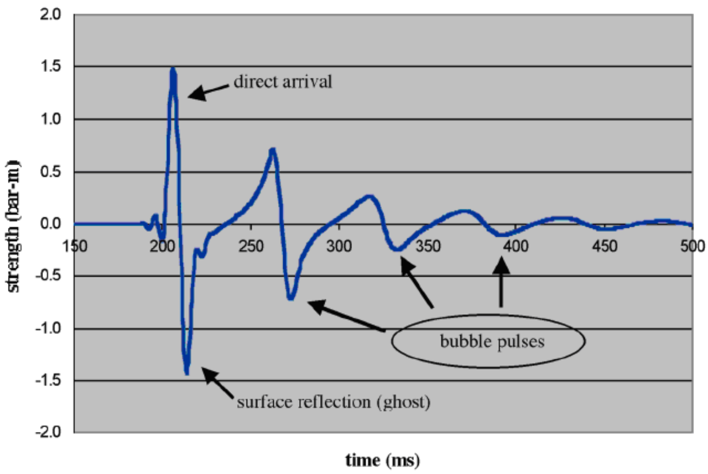


Figure 3.3. Time series for a single airgun (volume 40 in^3 = 0.7 L), recorded directly beneath the airgun (Caldwell & Dragoset, 2000).

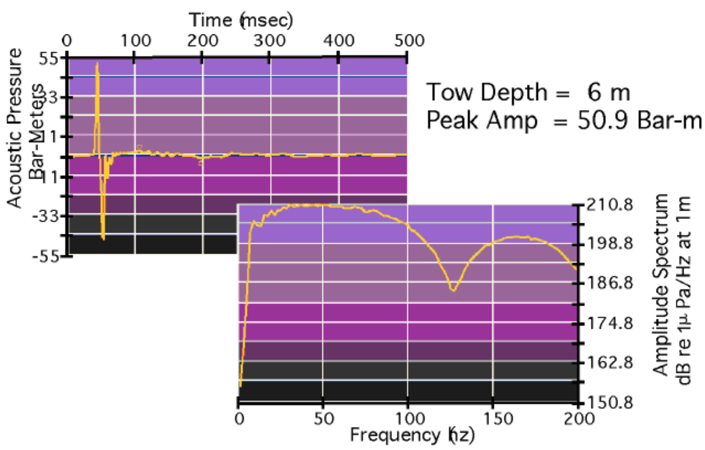


Figure 3.4. Back-calculated time series and amplitude spectrum for an array of airguns (total volume 3397 in^3 = 56 L) (Caldwell & Dragoset, 2000).

Apart from airguns there are many other sound sources for seismic applications. Examples are waterguns, sparkers, boomers and chirps. They have been designed for shallow water, high-resolution surveys and their purpose is to transmit acoustic energy up to a few kilohertz. Their source levels are lower than those of airguns.

More detailed information about selected seismic survey sources is presented in Appendix A.

3.2.1.1 Total energy

In the context of seismic surveys, the most important contribution to the annual acoustic energy budget comes from 3D surveys (Jaarverslag Staatstoezicht op de Mijnen 2004). The average area covered by 3D surveys between 2000 and 2004 is 1370 km^2/y (in the period 2003-2007 the average was 1490 km^2; Jaarverslag 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. Using a peak-to-peak source level of 255 dB re 1 $\mu Pa^2 m^2$, we estimate the energy per shot to be 1 MJ, giving a total energy used of 100 GJ/y (say 30-300 GJ/y, bearing in mind the uncertainties in many of these numbers).

3.3 Normal-incidence echo sounder

One of the most widely used man-made sonars is the basic single-beam echo sounder designed to measure the distance to the seabed beneath the vessel carrying the sonar. In fact, this type of echo sounder looks in a vertical direction, directly towards the seabed. In general, the actual source level depends on the pulse duration and beamwidth of the acoustic signal transmitted typically between 30 and 400 kHz (although there are commercialized single-beam echo sounders working up to 700 kHz).

More detailed information about selected single-beam echo sounders is presented in Appendix A.

3.3.1.1 Total energy

The total energy output of echo sounders is estimated as follows. Assuming a source level of 208 dB re 1 $\mu Pa^2 m^2$ combined with a beam solid angle of $4\pi/10$, results in an output power (during transmission) of 27 dB re 1 W (i.e. 500 W). Taking typical values for pulse duration of 0.5 ms and for repetition rate of 5 s^{-1} gives a duty cycle of 0.25%, so the mean power averaged over many pings works out as a little over one watt. Given the uncertainty in the above calculations (in both directions), we estimate the mean power to be between 0.3 and 3W, about a factor of 4 less than the estimate from Chapter 4 of the total acoustic power per ship. Given that the total contribution to sound energy in the North Sea from shipping is estimated to be 80-800 GJ/y, this translates to 20-200 GJ/y for the echo sounders.

3.4 Fish-finding sonar

Working frequencies of fish-finding sonars and echo locators are between 12 kHz and 200 kHz. As of 2007, the Dutch fishing fleet comprises 344 cutters, 13 freezer trawlers and 60 mussel fishing vessels (Bartelings *et al.*, 2007). Maps showing activity of fishing trawlers are shown in Figure 3.5 and Figure 3.6. In addition to this fleet, there is some fishing activity in the NCP from non-Dutch vessels.

The Dutch fleet is fitted with echo sounders. More information about these is available from Alphatron Marine Zuid (Middelburg) (Seip, 2009).

The trawlers are also fitted with specialised fisheries sonar such as the Simrad SX90. This sonar is used in the upper North Sea (ICES quadrant IVa), which is outside the NCP. They fish for herring between May and October and for mackerel between October and February. More information about this type of sonar is available from WNL Marine Electronics (IJmuiden) (Seip, 2009).

More detailed information about selected fish-finding sonar transmitters is presented in Appendix A.

3.4.1.1 Total energy

Assuming the same (average) source power as an echo sounder used for navigation purposes (i.e. one watt), the fleet of 344 ships translates to up to 344 W (about 10 GJ/y). Allowing for some uncertainty, this becomes (say) 3-30 GJ/y.

3.5 Sub-bottom profiler

Depth or sub-bottom profilers are used less frequently than echo sounders even though they are similar to them, except a lower frequency (i.e. between 2 kHz and 13 kHz) is used in order to probe the seabed. In general, these systems (e.g. GeoChirpII, SIS-3000) use the ‘chirp’ concept, which means a frequency modulation together with digital signal processing techniques to attain good penetration of the sub-bottom layers whilst achieving higher resolution records than previously possible.

More detailed information about selected sub-bottom profilers is presented in Appendix A.

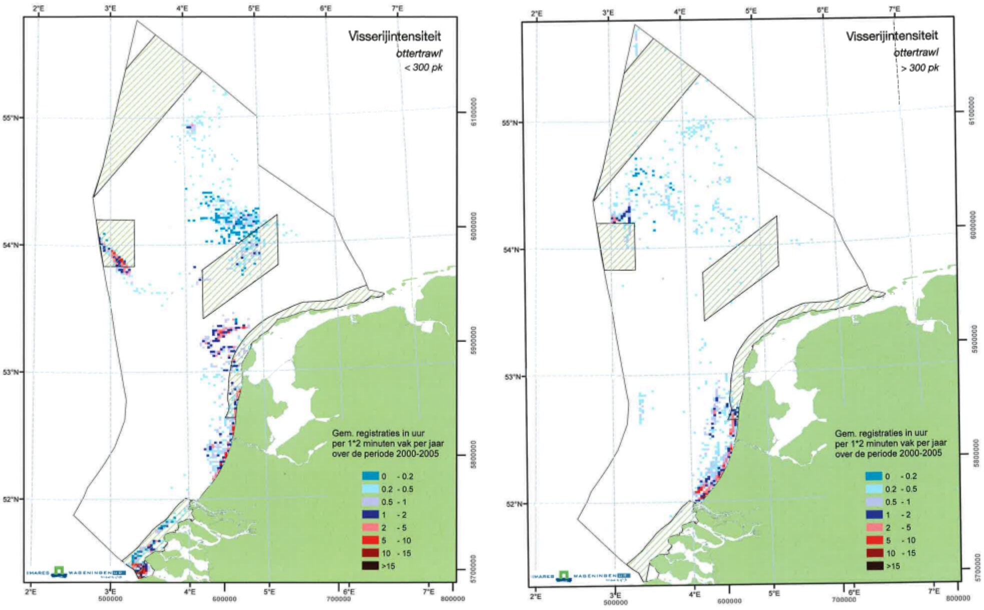


Figure 3.5. Fishing intensity in the period 2000-2005 (average registered fishing activity per hour per 1×2 arc-minute box per year) for Otter trawlers with engine power less (left) and more (right) than 300 horsepower. Magenta = 0.5-1 h/(nmi^{2}y), scarlet = 5-10 h/(nmi^{2}y). (© Lindeboom *et al.*, 2008)

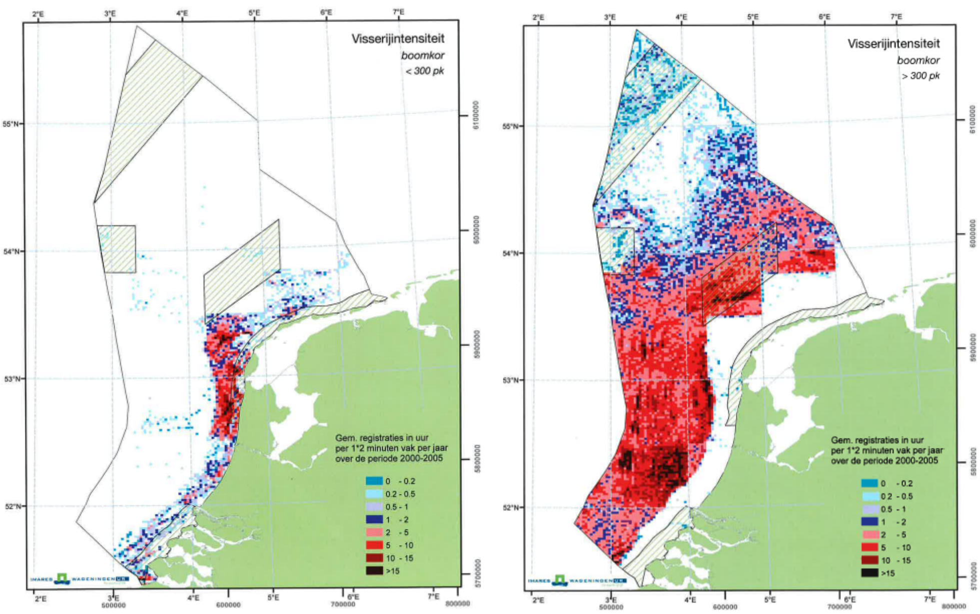


Figure 3.6. Fishing intensity in the period 2000-2005 (average registered fishing activity per hour per 1×2 arc-minute box per year) for beam trawlers with engine power less (left) and more (right) than 300 horsepower. Magenta = 0.5-1 h/(nmi^{2}y), scarlet = 5-10 h/(nmi^{2}y). (© Lindeboom *et al.*, 2008)

3.6 Military search sonar

3.6.1 Hull-mounted sonar

Two types of hull-mounted sonars are in use by the Royal Netherlands Navy (RNLN). These are the DSQS24 sonar (STN Atlas), used on LCF frigates[2] and the PHS-36 sonar (Thales), used on M-frigates[3].

3.6.1.1 Source characteristics

No unclassified information is available on the PHS-36 and DSQS24 sonars. For the purpose of acoustical power, and approximate frequency range, the characteristics are estimated by taking public domain data of the DE1167, a similar hull-mounted sonar system. The source characteristics of this sonar are (Jane's UW Warfare Systems, 2005-2006; p. 161):

- Frequency: 7.5 and 12 kHz
- Source level: 227 dB (triple rotating directional transmission, TRDT), 217 dB (omni) re 1 $\mu Pa^2 m^2$
- Pulse length up to 200 ms
- Bandwidth up to 2 kHz
- The electrical power is 20 kV A, which provides an upper limit of the possible acoustic power of 20 kW; Assuming a 10% duty cycle gives 2 kW average power

3.6.1.2 Sonar use

It is estimated that sonar use by the RNLN in the North Sea is not more than five hours per ship per year, calculated as follows. Hull-mounted sonars are used by RNLN not more than 2% of sailing time. Sailing time is not more than 200 days per year. Of these 200 days, typically 10 days might be spent in the North Sea. Therefore the use is not more than 240 hours per ship per year (< 5 hours per ship sonar usage in the North Sea).

3.6.1.3 Total energy

Assuming that the hull-mounted sonars of 6 ships produce an average power of 2 kW, each for 5 hours per year in the North Sea, the total for all ships amounts to 0.2 GJ/y for RNLN use of hull mounted sonar. This total excludes possible use of military sonar in the NCP by non-Dutch navies.

3.6.2 Dipping sonar

The DUAV-4 sonar, deployed from Lynx helicopters, is the only dipping sonar currently in use by the RNLN. Starting 2010, the Lynx helicopter will be replaced by the NH90 helicopter, equipped with a HELRAS dipping sonar. Characteristics of the DUAV-4 and HELRAS sources follow below.

3.6.2.1 Source characteristics DUAV-4

Reference DUAV-4: MLD 01-520LXD-1 (Air Crew Manual).

- Active mode sonar frequencies: 19 to 24 kHz
- Power (during transmission): up to 500 W

[2] The RNLN operates 4 LCFs (*Luchtverdediging en Commando Fregatten*) fitted with DSQS24 sonar.
[3] The RNLN operates 2 M-frigates (Multi-purpose frigates) fitted with PHS-36 sonar.

3.6.2.2 *Source characteristics HELRAS*

Reference HELRAS DS-100: L-3 Oceans Group flyer (internet source).

- FOM “sufficient to achieve second convergence zone detection in deep water”
- FM pulses up to 5 s duration
- Projector: 7 sonar elements, array length 5.2 m
- Frequencies 1.311, 1.38, 1.449 kHz (CW 0.039 s to 10 s)
- HFM: 0.156 s to 5 s
- FM triplet 0.625 s to 1.25 s
- FM bandwidth 300 Hz, centre frequency 1.38 kHz
- Beamwidth −15 to +15 degrees (assumed to be the vertical beamwidth, omni in horizontal)
- Source level: 217 dB re 1 $\mu Pa^2 m^2$

3.6.2.3 *Sonar use DUAV-4*

RNLN exercises with dipping sonar take place in an area to the north and west of Texel. Usage is estimated as (Dekeling, 2009):

- Pilot training: 12 hours dipping, 3 times per year (36 hours sonar use per year)
- Tactical coordinator training: 12 hours dipping, 3 times per year (36 hours sonar use per year)
- Sensor operator training: no additional hours
- Qualification renewal: 40 hours per year
- Double jumpex (2 helicopters): 10 hours × 3 periods × 2 helicopters = 60 h/y
- The total amounts to 36 + 36 + 40 + 60 = 172 h/y

3.6.2.4 *Sonar use HELRAS*

Considering the HELRAS characteristics, usage of this sonar (number of hours in use per year) in the North Sea by the RNLN is expected to be much less than the usage of DUAV-4 (Dekeling, 2009).

3.6.2.5 *Total energy DUAV-4*

Assuming a 10% duty cycle gives 17 h/y of continuous use = 61 ks/y. For a power of 500 W, this amounts to 31 MJ/y.

3.6.2.6 *Total energy HELRAS*

The acoustic power (calculated from the source level, with a directivity index of 6 dB) is 10 kW, which is 20 times higher than for the DUAV-4. Making a worst case assumption that the usage of HELRAS in the North Sea is the same as that of the DUAV-4 gives a total (forecast) annual energy of 0.6 GJ/y for HELRAS.

3.6.3 *Minehunting sonar*

The RNLN uses the TSM 2022 minehunting sonar on 10 minehunting vessels, of which 8 are operational. The acoustic frequency (for search mode) is 165 kHz (Friedman, 2006; pp. 796-). This high frequency means that the impact of these sonars is limited to the immediate vicinity of the minehunting vessels. They are not considered further.

3.7 Side-scan sonar

Side-scan sonar is a category of sonar systems that is used to create efficiently an image of large areas of the sea floor. A side-scan sonar works on a similar principle to an echo sounder. The main difference is that side-scan sonar emits sound sideways as well as downwards. Moreover, in conjunction with seafloor samples, it is able to provide an understanding of differences in material and texture of the seabed. Side-scan sonar imagery is also a commonly used tool to detect debris items and other obstructions on the seafloor that may be hazardous to shipping or to offshore installations. In addition, the status of pipelines and cables on the seafloor can be investigated using side-scan sonar. Side-scan uses a sonar device that emits fan-shaped pulses down towards the seafloor across a wide angle perpendicular to the path of the sensor through the water, which may be towed from a surface vessel or submarine, or mounted on the ship's hull. To obtain a high resolution image of the sub-bottom and surroundings, subsequent echoes are recorded and processed. Typical source level values are about 225 dB re 1 μPa^2m^2 at a frequency of about 100 kHz.

3.8 Acoustic deterrents

An acoustic deterrent is a device that transmits sounds to deter animals from approaching an area such as a fish farm (to protect the farm from predation) or pile-driving operation (to protect the approaching animal). Sometimes a distinction is made between an 'acoustic deterrent device' and an 'acoustic harassment device'. The latter term is typically used for pingers with high source levels, sometimes called a "scrammer" (190 to 200 dB re 1 μPa^2m^2 compared with ca. 160 dB re 1 μPa^2m^2 for low amplitude deterrents). We do not make this distinction here, referring to all such devices as 'acoustic deterrents', irrespective of their source level and application.

The use of acoustic deterrents in Europe is now widely enforced under the European Commission (EC) (EU COUNCIL REGULATION No 812/2004). Large-scale trials in the Bay of Fundy and in Denmark in 1996 and 1997 showed a reduction in by-catch on nets fitted with acoustic deterrents. In the North Sea, they have been in use since 2005. Two models of acoustic deterrents have been specified by the EC, with a digital and analogue signal synthesis, respectively (see Annex I in Franse, 2005). Acoustic deterrents specially designed for harbour porpoises are AQUAmark 100 and Endurance Savers (Franse, 2005).

More detailed information about selected acoustic deterrents is presented in Appendix A.

4 Unintentional anthropogenic noise sources

4.1 Introduction

Although it is known for a long time that human activities at and near the sea produce underwater noise, the effect that this noise may have on the marine ecosystem has not drawn attention until the last few decades. For many of these activities, the sound is an unintentional by-product. Traditionally, the main interest in anthropogenic underwater noise was driven by the impact that it has on naval sonar performance (Ross, 1976; Urick, 1983). Much of the concern and research about effects of man-made noise on marine life has resulted, directly or indirectly, from the U.S. *Marine Mammal Protection Act* of 1972 (Richardson *et al.*, 1995). In spite of an increased research effort, the effects of anthropogenic sound on marine mammals remain uncertain and, as yet, the significance of sound as a risk factor cannot be assessed reliably (U.S. Marine Mammal Commission, 2007; Southall *et al.*, 2007). This is equally valid for the effects on other species (fish at all life stages, benthos) which have received even less attention.

Although there has been progress in the last decades, much important work remains to be done. The lack of reliable acoustic source data is emphasized in various recent overview studies (Richardson *et al.*, 1995; U.S. Marine Mammal Commission, 2007; Southall *et al.*, 2007, Frisk, 2003). There is a critical need of comprehensive, calibrated measurements of the properties of human-generated sound sources, including frequency-dependent propagation characteristics in different environments (Southall *et al.*, 2007). This is especially true for the unintentional sources, because the concern about the environment is the only driver for carrying out such measurements.

The lack of data is partly due to the inherent difficulty to determine the source level of anthropogenic noise sources. Source levels are always inferred from measurements at greater distances. The general definition of source level, given in §1.2.1, does only account for a distance scaling to a reference distance of 1 m, based on spherical spreading. However, measurements at larger distance are influenced by a situation specific propagation. Assessment of the appropriate loss is usually complex, due to the effects of reflections at the sea bed and water surface and variations of the sound speed across the water depth (Urick, 1983; U.S. Marine Mammal Commission, 2008).
In comparing published source levels, readers must therefore be alert for inconsistencies in reference distances, units and bandwidths, which are all given in various ways in the literature (Richardson *et al.*, 1995) and also of the propagation correction that has been applied.

Of special concern for sources near the water surface is the free surface image interference effect, also referred to as the 'Lloyd Mirror effect'. Quoting Ross (1976): "*The surface of the ocean is a nearly perfect reflector of sound. The radiation from a source near the surface can be analyzed in terms of direct radiation from the source itself and from a negative image source located above the surface. In theory, image interference can be calculated and measured pressures corrected to free-field values. However, the effect is very sensitive to exact values of the geometrical parameters. One seldom knows depths or distances with the precision required. If the monopole source strength is to be calculated, then the effective source depth must be ascertained. This is feasible for small sources, but quite difficult for large, distributed sources such as surface ships*."

As a consequence, many publications (e.g. Arveson & Vendittis, 2000) quote an equivalent 'source level' that is based on a correction that assumes spherical spreading loss [$20\log_{10}$(Distance/1 m)] only, without taking the free-surface and bottom interference effects into account. This assumption may lead to large differences with published source levels (e.g. Wales & Heitmeyer, 2002) that have been corrected for these propagation effects.

4.2 Shipping noise

Vessels, ranging from the smallest boat to the largest supertanker, are major contributors to the overall background noise in the sea, given their large numbers, wide distribution and mobility (Richardson *et al.*, 1995). Especially at low frequencies between 5 and 500 Hz, vessel traffic is a major contributor to noise in the world's oceans (Frisk, 2003). Distant traffic contributes to the general acoustic environment in this frequency range; very large geographic areas are affected. During the past 15 years there has been a virtual revolution in the sizes and speeds of merchant ships, resulting in significant increases in the noise radiated by the average ship (Ross, 2005). This trend is expected to continue.

Noise characteristics of individual vessels can be roughly related to ship size and speed, but there is a significant variation among vessels of similar classes. Particular vessels produce unique sound spectra, known as acoustic signatures, usually composed of a broadband component and a set of tonals (Frisk, 2003). Surface ships radiate underwater noise due to machinery noise, due to the noise generated by the propulsor (propeller, water jet, etc) and due to hydrodynamic noise from the flow around the ship hull and appendages. In addition, incidental activities, like anchoring or on board hammering, may cause underwater noise. The noise depends on a large range of parameters, related with the ship design, the current state of maintenance, the operational settings (the selection of operational machines and their speed setting) and environmental conditions like for example wave height and direction, see e.g. Ross (1976) or Urick (1983). Recently, Trevorrow *et al.* (2008) have shown that manoeuvring a vessel may lead to an increase of up to 18 dB in one-third octave source levels.

Two different environmental effects of shipping noise have to be considered: the general environmental underwater noise due to shipping lanes and the direct impact in the vicinity of individual vessels. The former should be addressed in a statistical approach, similar to highway noise, where models ('*Reken- en meetvoorschrift verkeerslawaai*') have been developed based on generic source level definitions (Kinsler & Frey, 1967). The latter requires more detailed information about the individual vessel and its activities.

The Standard Working Group 47 of the S12 Committee on Noise Standards of the Acoustical Society of America (www.noise-control.com/wg47) has been organized to develop a commercial standard for the measurement of underwater noise from ships, which is currently lacking.

4.2.1 Generic ship source level spectra

Urick (1983) gives some typical radiated source levels that were measured on various classes of ships current during World War II. The underwater noise for these ships is predominated by propeller cavitation noise. The source levels were summarized in an empirical formula in terms of the propeller tip speed U_t (in m/s), the displacement tonnage T and the frequency f in Hz. Ross (1976) has remarked that the dependence on the displacement tonnage does not enter the equation for propeller cavitation noise. Therefore, he suggests using an expression based on the propeller tip speed U_t and number of blades B:

$$\mathrm{SL}_f = 175 + 60\log_{10}\left(U_t/25\ \mathrm{m/s}\right) + 10\log_{10}\left(B/4\right) - 20\log_{10}\left(f/1\ \mathrm{Hz}\right). \quad (4.1)$$

Here, SL_f is the source spectral density level, given in dB re 1 $\mu\mathrm{Pa}^2\mathrm{m}^2/\mathrm{Hz}$.

Measurements of 50 merchant ships of opportunity carried out in 1985 in the area near Genova (Scrimger & Heitmeyer, 1991) show that this formula gives a good estimation of the mean source level spectrum (in the frequency range between 70 and 700 Hz). Source level histograms of these measurements are approximately Gaussian, with a standard deviation of 5 to 7 dB. A separation of the data in three identifiable ship classes (passenger/ferries, cargo ships and tankers) lead to the conjecture that the source levels are not sensitive to ship class.

The most widely used source model is based on a more convenient formula by Ross & Alvarez (1964) in which the source level is expressed in terms of the ship speed V and length L, e.g. in Wales & Heitmeyer (2002):

$$\mathrm{SL}_f = 190.5 + 50\log_{10}\left(V/10\ \mathrm{kn}\right) + 20\log_{10}\left(L/150\ \mathrm{m}\right) - 20\log_{10}\left(f/1\ \mathrm{Hz}\right). \quad (4.2)$$

Researchers of the US Naval Undersea Center have implemented a similar, but more elaborate model for surface ship source spectral densities for five generic classes of surface ships in their RANDI ("Research Ambient Noise Directionality") ocean ambient noise model (Frisk, 2003), see Table 4.1. This type of modelling in combination with limited experimental data lies at the basis of many published tables of source levels per ship class (Richardson *et al.*, 1995; U.S. Marine Mammal Commission, 2004).

Table 4.1. Source spectral densities for commercial vessels underway, adapted from the RANDI model (taken from Frisk, 2003). The indicated levels are for the mean values of ship length and ship speed in each class. Note that there is scientific controversy about the validity of this classification, see below.

			Source spectral density (dB re 1 $\mu\mathrm{Pa}^2\mathrm{m}^2/\mathrm{Hz}$)				
Ship type	**Length [m]**	**Speed [m/s]**	**10 Hz**	**25 Hz**	**50 Hz**	**100 Hz**	**300 Hz**
Supertanker	244-366	7.7-11.3	185	189	185	175	157
Large tanker	153-214	7.7-9.3	175	179	176	166	149
Tanker	122-153	6.2-8.2	167	171	169	159	143
Merchant	84-122	5.1-7.7	161	165	163	154	137
Fishing	15-46	3.6-5.1	139	143	141	132	117

Wales & Heitmeyer (2002) have reviewed this type of modelling on the basis of underwater noise measurements on 272 merchant ships, in the Mediterranean Sea and Eastern Atlantic Ocean, in the years between 1986 and 1992. The data have been acquired in deep water on two sonobuoys deployed on either side of the ship at a depth of 300 m and at a closest-point-of-approach (CPA) that varied from about 360 m to about 1800 m. The source spectra were obtained from the measured time series after dividing by a calculated propagation function, in which special attention has been given to a correct representation of the source depth, and correction for the time dependent Doppler shift. Hence these data are for the equivalent monopole source strength of the vessels. Figure 4.1 gives an overview of the source spectral densities from Wales & Heitmeyer (2002).

All measurements have been taken in the far field of the ship. The authors have determined the proper monopole source level of the ship, using an advanced propagation model and representing the ship by an assumed vertical distribution of incoherent point sources with a Gaussian amplitude weighting. The authors suggest that many of the earlier ship size dependent power law models are based on an incorrect source description.

The results of this study are rather astonishing. The authors observe:

- ***no significant speed or length dependence*** of the source level of transiting merchant vessels;
- ***no other clear parameter dependencies*** (displacement, horsepower, etc.);
- not much change in levels relative to the data presented by Urick (1983).

The mean spectrum level of their measurements can be approximated by the formula (Wales & Heitmeyer, 2002):

$$\mathrm{SL}_f = 230.0 - 35.94\log_{10}(f/1\,\mathrm{Hz}) + 9.17\log_{10}\left(1+[f/340\,\mathrm{Hz}]^2\right) . \qquad (4.3)$$

This formula for the mean spectrum is accurate within 0.6 dB over the 30-1200 Hz frequency band. The individual source spectra have an approximately Gaussian distribution with a standard deviation of about 5 dB at frequencies below 400 Hz and about 3 dB above 400 Hz.

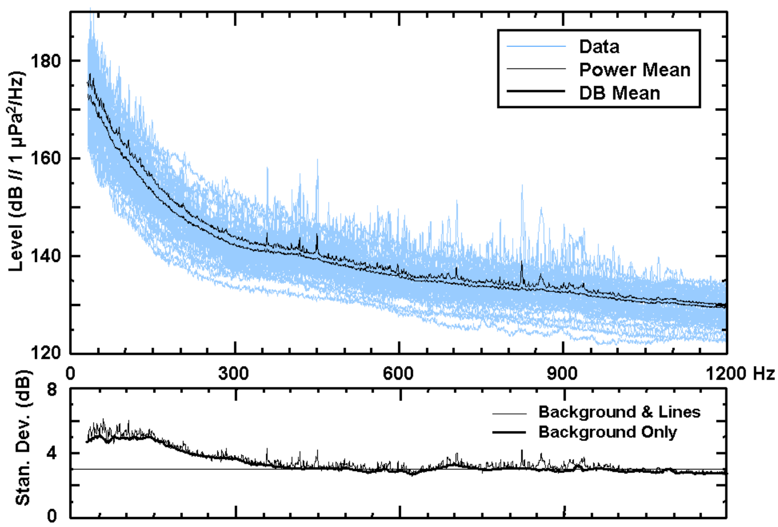


Figure 4.1. Measured underwater noise source spectra of merchant ships (blue curves) and the ensemble average spectra (black curves: ‘Power mean’ refers to the energetic average, while ‘DB mean’ presents the average of the dB-values), with an estimation of the ensemble standard deviation (lower figure), from Wales & Heitmeyer (2002).

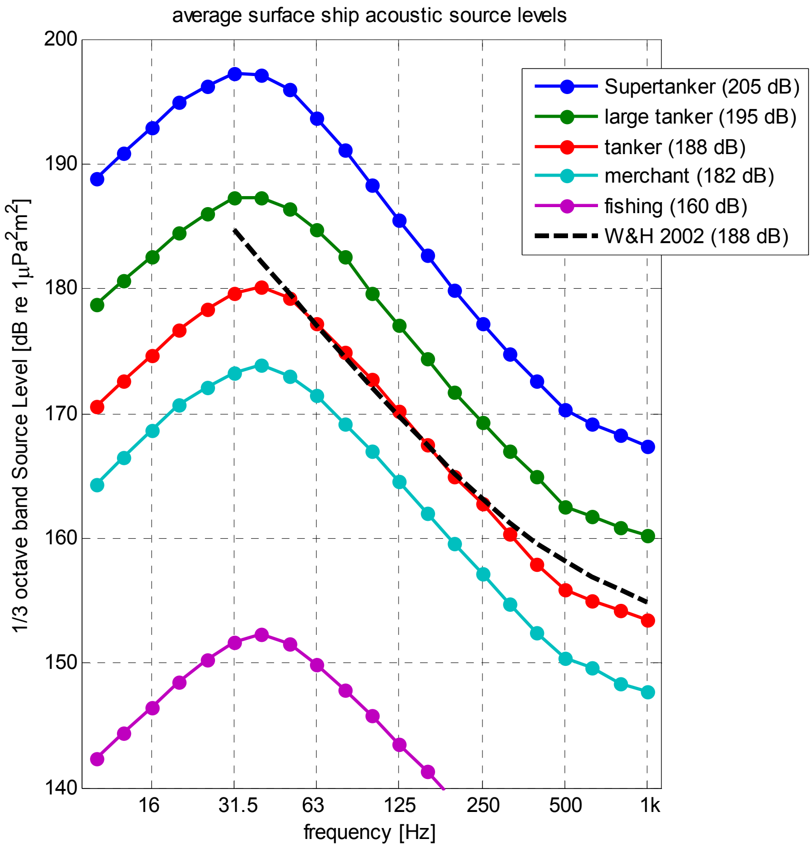


Figure 4.2. Comparison of the average merchant ship source level (Wales & Heitmeyer, 2002) with the RANDI classes (Table 4.1), converted to one-third octave band levels. The levels between brackets in the legend give the broadband integrated source level in dB re 1 μPa^{2}m^2.[4] Note that the integration for the W&H spectrum does not include the frequency bands below 31.5 Hz.

We compare this mean spectrum for merchant ships with the RANDI source levels in Figure 4.2. At frequencies above 50 Hz, the source level agrees closely with that of the RANDI 'tanker' class. The deviation towards lower frequencies is probably related with the difficulty to determine the monopole source level, due to the free surface interference effects (see §4.1). It is not clear whether the RANDI class source levels should be treated as a monopole source strength and if so, which source depth should be assumed.

Wales & Heitmeyer (2002) admit that the surface ship source levels found by Scrimger & Heitmeyer (1991) in the 70-700 Hz band are 7-10 dB higher than predicted by (4.3). They could not give an explanation for this difference.

Hatch *et al.* (2008) have analysed the underwater noise of 541 large commercial vessels transiting the Gerry E. Studds Stellwagen Bank National Marine Sanctuary in 2006. The main analysis was focused on the frequency range between 71 to 141 Hz, which is considered relevant for the large whales in the sanctuary. The average source level estimates in this limited frequency band for individual vessels ranged from 158 ± 2 dB

[4] Hildebrand (2004) quotes ship source levels ranging from 150 dB re 1 μPa^{2}m^2 for a 12 m fishing vessel at 7 knots to 198 dB re 1 μPa^{2}m^2 for a 270 m supertanker.

re 1 μPa^{2}m^2 (research vessel) to 186 ± 2 dB re 1 μPa^{2}m^2 (oil tanker).[5] Hatch *et al.* (2008) are working on a further analysis of the data in a wider frequency range, which will be more relevant for the North Sea.

4.2.2 *Individual ship (M/V Overseas Harriette)*

The only extensive and consistent set of underwater acoustic data of a surface ship in the public domain is given by Arveson & Vendittis (2000). *M/V Overseas Harriette* is a bulk cargo ship (length 173 m, displacement 25,515 tons) powered by a direct-drive low-speed diesel engine, a design representative of many modern merchant ships.
Its underwater noise has been measured according to standard naval procedures at the AUTEC noise range. That means that the source level is estimated on the basis of a correction for spherical spreading only, not for surface or bottom interference effects.
It can be seen from Figure 4.3 that the variations in source level with ship speed of this single ship are substantial and of the same order of magnitude as the class differences in the RANDI model. At frequencies above 400 Hz, the source level is generally higher than the Wales & Heitmeyer (2002) spectrum of (4.3).

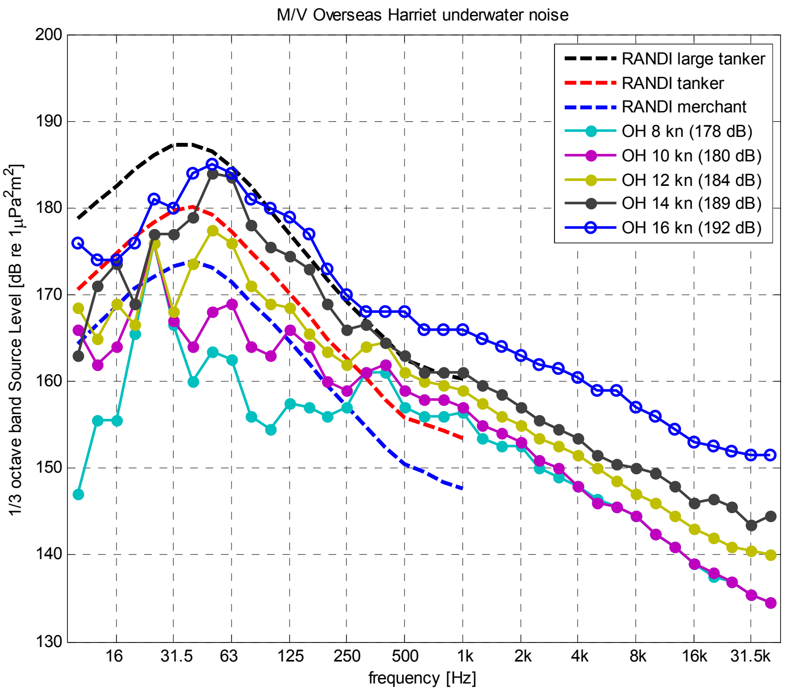


Figure 4.3. The underwater noise source strength of *M/V Overseas Harriette* (OH) at five speeds (in knots: 1 knot = 0.51444 m/s), compared with three RANDI class-average source levels. Note that these data have not been corrected for free-surface interference effects. The levels between brackets in the legend give the broadband integrated source level in dB re 1 μPa^{2}m^2.

[5] Note that the values of acoustic power quoted by Hatch *et al.* (2008) in their Table 4 are incorrectly converted from the decibel values. The error does not appear to affect their assessment of the relative annual contribution of the various classes of ships though.

In contrast with the generic source level spectra (§4.2.1), which have a frequency range up to 1 kHz, these spectra contain data up to 40 kHz. It can be seen that the source level (in 1/3-octave bands) decreases with approximately $-10\log_{10}$(frequency) at frequencies above 1 kHz. This trend is typical for propeller cavitation noise (Ross, 1976).

4.2.3 *Directionality*

The *M/V Overseas Harriette* measurements (Arveson & Vendittis, 2000) also give information on the directionality of the radiated sound. In the 340-360 Hz band, where propeller cavitation is the dominant noise source, the noise is 8-10 dB decreased in the fore and aft directions relative to broadside. Trevorrow *et al.* (2008) find a similar 8-12 dB directionality for a much wider frequency range (160 Hz to 4 kHz bands). It is suggested that this is a general phenomenon, caused by the blocking of the sound radiation by the hull in forward direction and to the aft by sound absorption in the bubble wake.

It is suggested that the reduced noise in forward direction has a disadvantage for whales and manatees (Dutch: ‘zeekoeien’), because it reduced their possibilities to detect approaching ships and boats, which may result in fatal collisions (www.americanscientist.org/issues/feature/manatees-bioacoustics-and-boats). To solve this problem, the vessels may be provided with a bow-mounted alerting device, optimized to the hearing sensitivity of the endangered species and with a narrow beam, to reduce the environmental impact.

4.3 Specific ship types

4.3.1 *Cruise ships*

Between September 2000 and June 2001, the underwater radiated noise levels for six cruise ships were measured at the U.S. Navy’s Southeast Alaska Acoustic Measurement Facility near Ketchikan, Alaska. The goal was to quantify the underwater noise levels associated with cruise ships of the type that typically operate in the waters of Glacier Bay National Park and Preserve. The same measurement and analysis procedure is applied as for *M/V Overseas Harriette* (§4.2.2).

The envelope of the underwater noise source levels for the vessels, sailing at 10 knots, is compared with those of the *M/V Overseas Harriette* in Figure 4.4. The results are very similar. Also the cruise ship levels are generally higher than the Wales & Heitmeyer (2002) spectrum of (4.3), for frequencies above ca. 400 Hz.

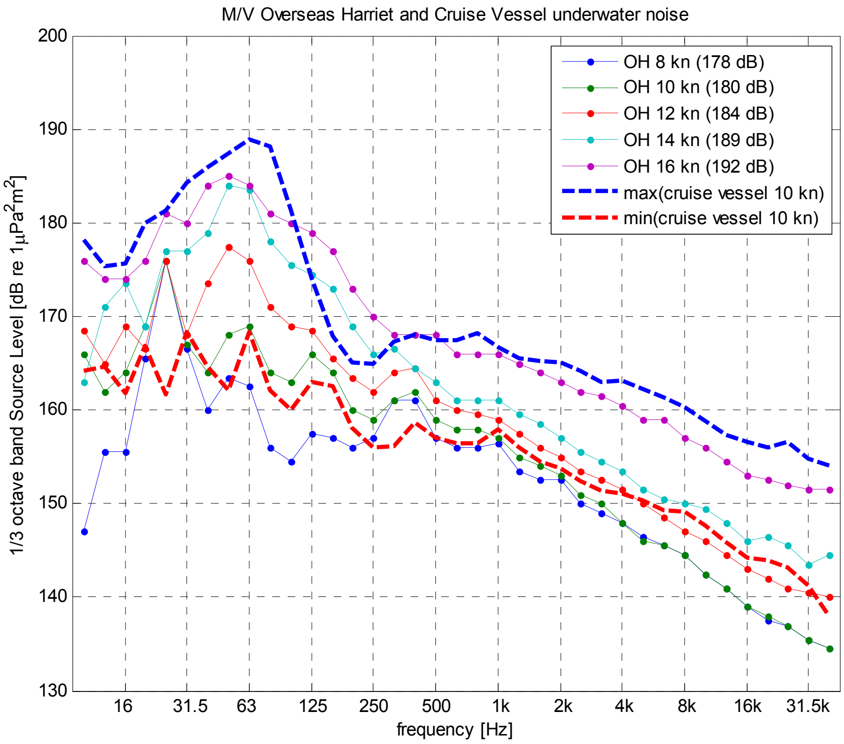


Figure 4.4. Envelope of one-third octave band source level spectra of six Southeast Alaska cruise ships at 10 knots (Kipple, 2002) compared with the underwater noise source levels of *M/V Overseas Harriette* (OH) at five speeds (Arveson & Vendittis, 2000). The levels between brackets in the legend give the broadband integrated source level in dB re 1 µPa^{2}m^2. The broadband integrated source levels for the cruise vessels range from 176 to 195 dB re 1 µPa^{2}m^2.

4.3.2 Advanced propulsion systems

Recent trends in ship design lead to larger and faster vessels (Ross, 2005), but also to new propulsion concepts, which may have an impact on the underwater sound generation. In addition to the range of cruise vessels, Kipple (2002) provides the measured underwater radiated noise levels of the (70367 ton / 260 m) cruise ship *MS Elation*, equipped with an ABB *Azipod* propulsion system, at speeds of 10 and 20 knots, see Figure 4.5. The underwater noise at 10 knots appears to be fully dominated by tonal noise from the underwater electric motors in the 315 Hz 1/3-octave band. The average shipping noise spectra do not account for these new developments. Similarly, underwater noise data are lacking for large high-speed vessels with waterjet propulsion.

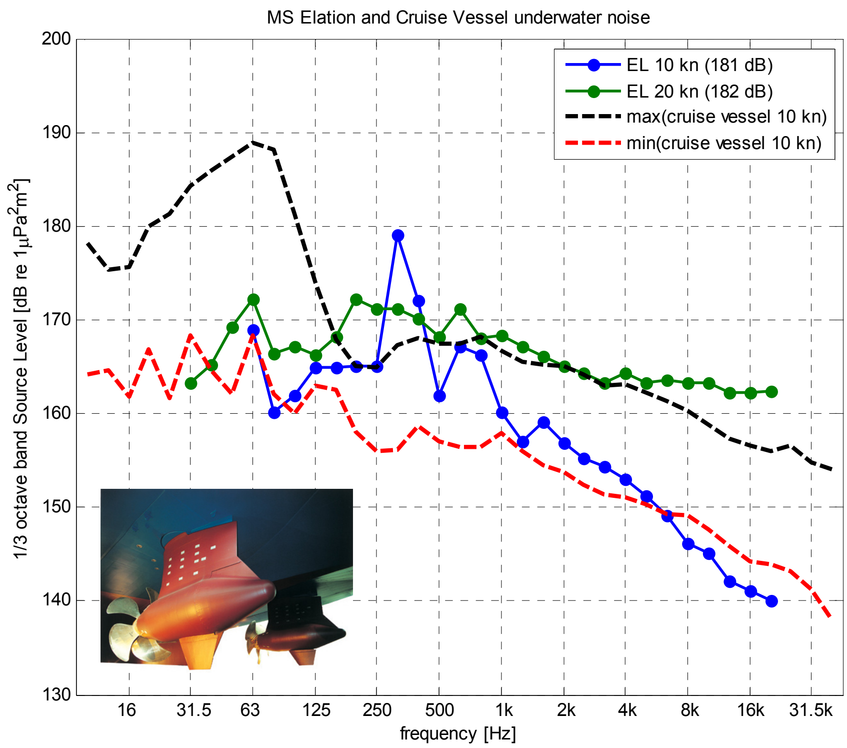


Figure 4.5. Envelope of one-third octave band source level spectra of six Southeast Alaska cruise ships at 10 knots (Kipple, 2002) compared with the underwater noise source level of *MS Elation* (EL), a cruise ship propelled by podded electric drive (shown in the photo), at two speeds. The levels between brackets in the legend give the broadband integrated source level in dB re 1 µPa^{2}m^2.

4.3.3 *Dredgers, drillships*

Dredges can be strong sources of continuous noise in near shore regions (Richardson *et al.*, 1995). Dredging often continues in one area for days or weeks, so that the noise impact may be stronger than that of passing vessels. The limited data of dredging noise in Richardson *et al.* (1995) illustrates that there are large differences in dredging noise. Additional information of dredging noise is available from publication of studies for the Sakhalin Energy Project (www.sakhalinenergy.com/en/documents/doc_33_cea_tbl4-7.pdf).

The various source spectra are compared in Figure 4.6. Broadband source levels range from 172 to 188 dB re 1 µPa^{2}m^2. Note, however, that the same broadband source level can be obtained from very different spectral distributions, see the difference between the spectra for the *Gerardus Mercator* dredger and the average merchant ship.
The decrease of the spectra towards the lowest frequencies (below 63 Hz) suggests that the data are not corrected for the surface image interference, but this is not specified in the publications.

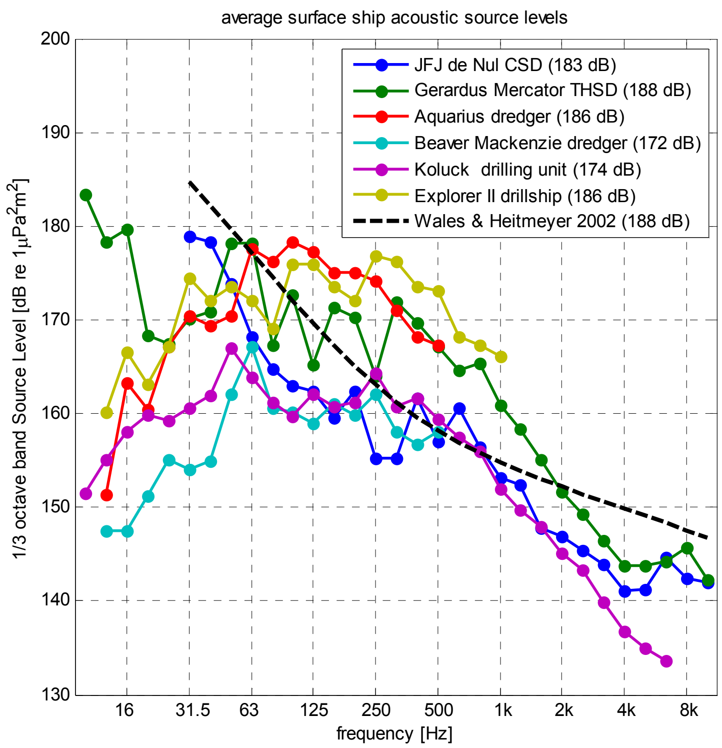


Figure 4.6. 1/3-octave band source level spectra of underwater noise for marine dredging and offshore drilling, compared with the average source level of transiting merchant ships (Wales & Heitmeyer, 2002). The data for the *JFJ de Nul* Cutter Suction Dredger and the *Gerardus Mercator* Trailing Suction Hopper Dredger are taken from the Sakhalin data and the other spectra from Richardson *et al.* (1995). The levels between brackets in the legend give the broadband integrated source level in dB re 1 $\mu Pa^2 m^2$.

4.3.4 *Fishery research vessels (ICES)*

In 1995, the Study Group on Research Vessel Noise of the International Council for the Exploration of the Sea (ICES) came up with an underwater noise specification for fishery research vessels sailing at 11 knots (Mitson, 1995). The noise is limited by potential fish reactions in the region below 1 kHz and by acoustic survey capabilities at frequencies above 10 kHz. The ICES noise specification is compared with the source levels of the five RANDI classes in Figure 4.7. It can be seen that even the class of small fishery vessels does not fulfil the spectral requirement, though the broadband level is lower than that of the ICES requirement.

The fact that there are several fishery research vessels built that fulfil these requirements (see e.g. Fisher, 2007; Otis & Bradley, 2007), illustrates that much can be gained by applying available noise control technology in ship design! Also naval vessels built to acoustic requirements confirm this conclusion.

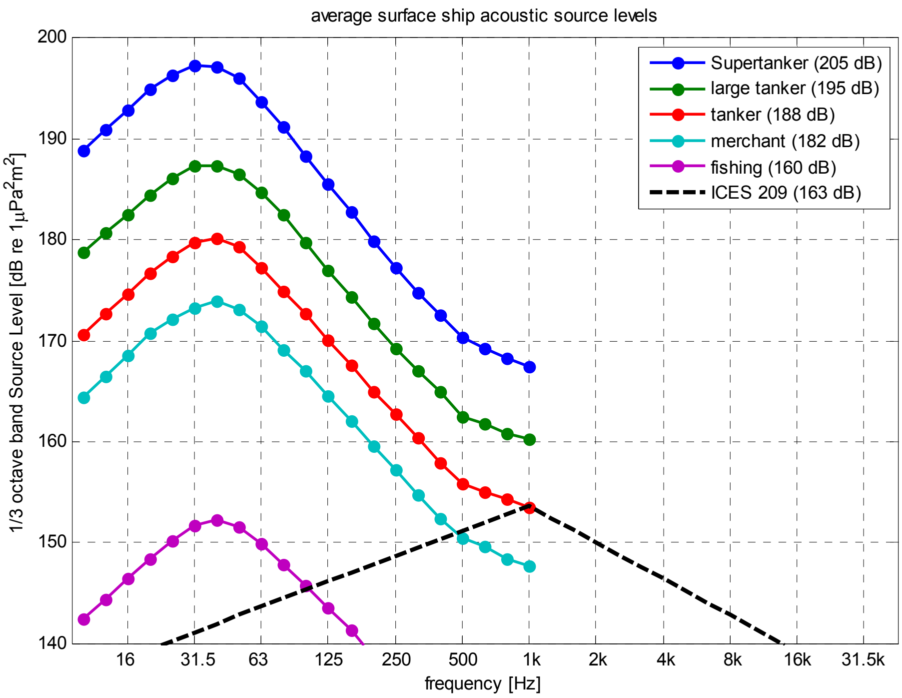


Figure 4.7. The underwater noise source strength of the five RANDI classes (Table 4.1) compared with the ICES requirement for the underwater noise of fishery research vessels. The levels between brackets in the legend give the broadband integrated source level in dB re 1 μPa^{2}m^2.

4.3.5 *Other boats and small ships (supply, tugs, leisure craft)*

Richardson *et al.* (1995) give several references to underwater noise measurements of small vessels. Some data are provided by Hatch *et al.* (2008), but the most extensive coherent set of data of small vessel underwater noise is available from measurements in the Glacier Bay National Park (Kipple & Gabriele, 2003, 2004). Overall broadband source levels of small vessels range from 153 to 181 dB re 1 μPa^{2}m^2. There is a slight trend that the overall levels increase with ship size, but the increase of noise level with speed appears to be greater. Off-design conditions, e.g. due to pulling load or manoeuvring, also leads to increased propeller cavitation and hence to increased source levels. In comparison with noise levels from large cruise ships, the small craft one-third octave noise levels were generally lower at lower frequencies. However, in some bands at frequencies above 1 kHz, the small craft noise levels were comparable to, or in some cases greater than, cruise ship noise levels (Kipple & Gabriele, 2003).

4.3.6 *Acoustic energy and conversion efficiency*

The overall source level of an average merchant vessel is, according to the Wales & Heitmeyer (2002) model of (4.3), approximately 188 (±5) dB re 1 μPa^{2}m^2. This source level implies about 8-80 W acoustic power radiated over a hemisphere (Ross, 1976). If we assume that the average ship has a typical installed propulsive power of about 5-10 MW (www.manbw.com/files/news/filesof5149/P402_tankers_screen.pdf), acoustic power is radiated with an order of magnitude of 0.8-16 W per MW of propulsive power. That means that the acoustic conversion efficiency (Ross, 1976) is of the order of 10^{-6}!

Figure 4.8 gives an overview of the shipping density on the North Sea. According to the information in this figure, the average number of ships per year in the Netherlands Exclusive Economic Zone (EEZ) in the years 1999 to 2001 was 336. If each ship produces about 8-80 W of acoustic power, the total produced sound power is about 3-27 kW. That is equivalent to an acoustic energy of about 230-2300 MJ per day, or a total of 85-850 GJ per year.

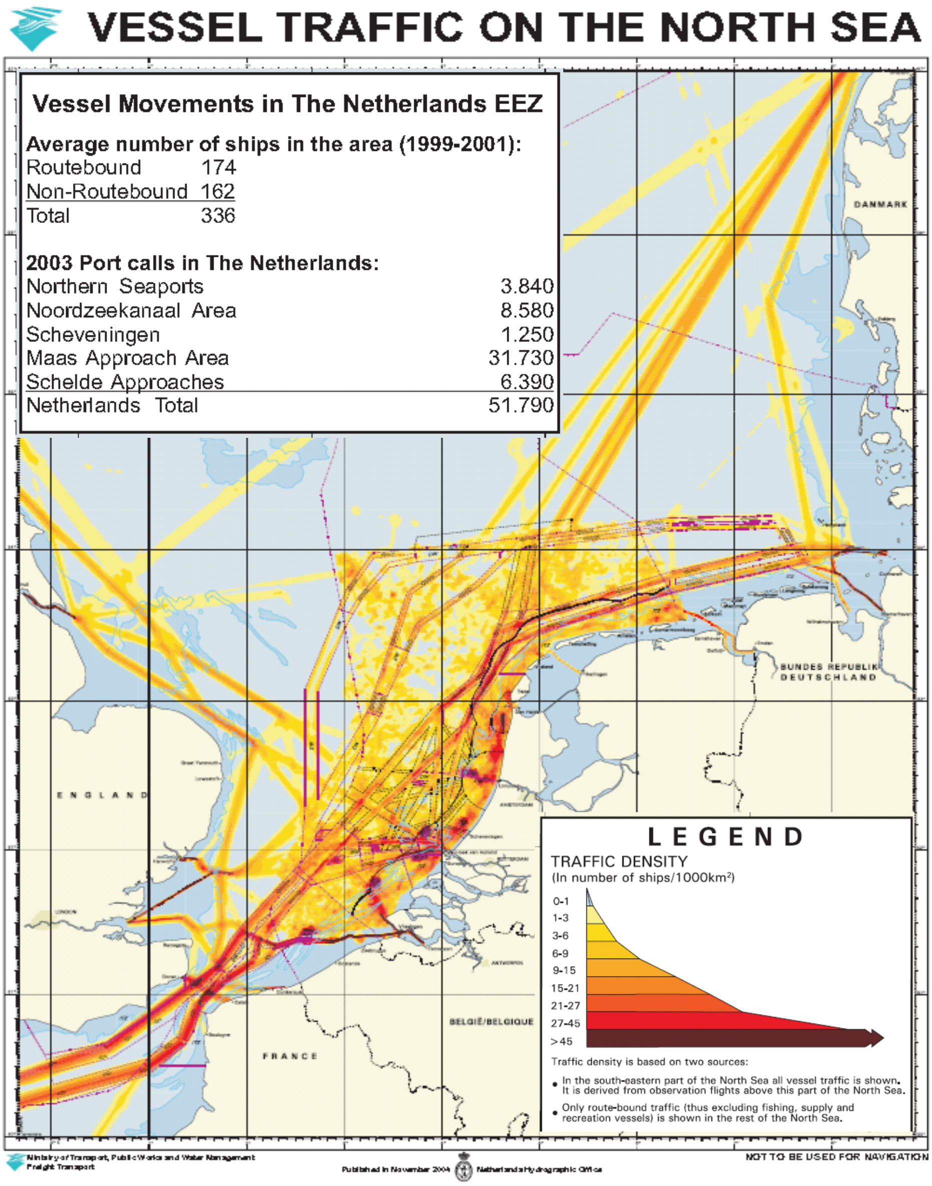


Figure 4.8. Overview of the vessel traffic on the North Sea. Map published by the Netherlands Hydrographic Office in 2004.

4.4 Oil & gas platforms

Figure 4.9 shows the current oil and gas platforms on the North Sea. Several activities (e.g. machinery noise; pumping, drilling, supply & maintenance) may be responsible for underwater noise around these platforms. Common processes are offshore drilling and production, but also platform construction and destruction and traffic to and from the platform will contribute. Richardson *et al.* (1995) give an overview of the available data. These are mainly obtained from studies in the Canadian and Alaskan Beaufort Sea. It appears that drilling noise is mainly due to the drilling machinery. The underwater noise depends strongly on the design of the structure that connects the machinery with the water. Hence, the noise levels of drillships, with their hull coupled to the water, are usually higher than those of platforms standing on legs with a much smaller contact area with the water. The same is true for production noise, which is also mainly machinery noise. Of special concern are impulsive hammering sounds that may be required during the process. Hildebrand (2004) quotes Richardson *et al.* (1995): "*Production activities can generate sound levels as high as 135 dB re 1 μPa at 1 km from the source which suggests source levels as much as 195 dB re 1 μPa^{2}m^2, with peak levels at 40 to 100 Hz*", but the noise levels are highly variable and it is not possible to give general numbers or scaling laws for the underwater noise due to oil and gas platforms.

A group of oil and gas exploration and production companies runs the 'E&P Sound and Marine Life Joint Industry Programme (JIP)' (www.soundandmarinelife.org) since 2005. This programme funds research to describe industry sources, the known or potential effects of these sources on animals, and ways to mitigate these effects. Within this programme, a report was produced that provides an extensive 'review of existing and future potential treatments for reducing underwater sound from oil and gas industry activities' (www.soundandmarinelife.org/Site/Products/NCE07-001_TreatmentsForUnderwaterSoundFromOil.pdf), which presents a lot of additional information that has not been covered here.

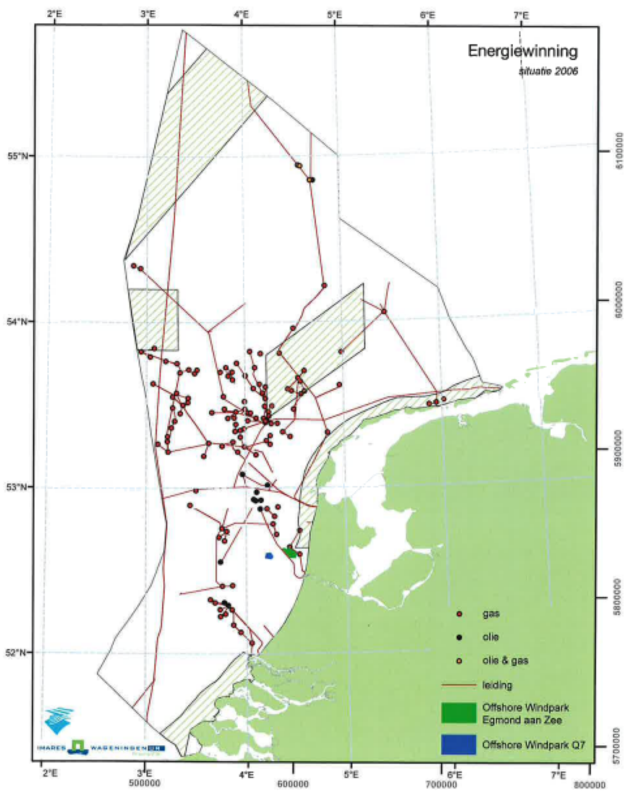


Figure 4.9. Overview of locations of oil and gas platforms and wind farms on the Netherlands' part of the North Sea (© Lindeboom *et al.*, 2008).

4.5 Explosions

The underwater pressure signature of a detonating explosion is composed of the initial shock pulse followed by a succession of oscillating bubble pulses, if the explosion is sufficiently deep not to vent through the surface (Urick, 1983; Richardson *et al.*, 1995).

A simple rule of thumb, based on Arons' measurements to a distance of 5000 charge radii (Arons, 1954), is that a detonation of one kilogram of pentolite releases approximately one megajoule of acoustic energy (Ch. 10 of Ainslie, 2008). Detailed information about the energy density spectra as a function of charge weight and depth can be found in e.g. Urick (1983).

In an extensive study into the effects of underwater blasts (Yelverton & Richmond, 1981) it was established that the impulse (i.e. the integral of the sound pressure over time) in the underwater blast wave was the parameter that governed biological damage and not peak pressure or energy.

There are various reasons for underwater explosions to occur:

1 **Mine and bomb clearance**: Clearing the NCP (Netherlands Continental Shelf) of sea mines and bombs is one of the tasks of the Royal Netherlands Navy. According to their information, 136 explosives have been cleared from the NCP in 2008, with an average charge weight of 60 kg. These explosives have been detonated using various types of charges: 119 times a 18 kg TNT charge, 3 times a 1.5 kg 'Seafox' and 14 times a 100 kg mine destruction charge. So the average charge weight for the detonations is 78 kg, which releases about 78 MJ of acoustic energy. The total annual charge weight is about 12 tons. In addition to that, an estimated maximum of 1.3 tons charge weight of ammunition was cleared by the DDG (Duik en Demonteer Groep) in 2008, at near-shore locations (Schulpengat, Marsdiep, Texelstroom and Petten). There is also an unspecified limited amount of explosions for training of the Marines. This leads to an estimated maximum for the total released acoustic energy by explosions of circa 14 GJ per year.

2 **Blasting for platform and monopile demolition**: Using explosives is one of the techniques that may be used in the decommissioning of off-shore structures like oil & gas platforms and wind turbine foundations. Typical charges of 10-50 kg may be used to cut a pile (Nedwell & Howell, 2004), which yield about 10-50 MJ of acoustic energy. To our knowledge, this kind of blasting is currently not applied at the NCP.

3 **Ship shock trials**: New classes of military vessels undergo tests, called ship-shock trials, to determine their ability to withstand explosions (U.S. Marine Mammal Commission, 2004). However, these tests are not carried out in the North Sea. The Royal Netherlands Navy has tested their latest class of frigates (Figure 4.10) at the Swedish facility in the Stockholm Archipelago (Baltic Sea) and the UK uses shock test facilities west of Ireland.

Figure 4.10. Shock testing of the air-defence and command frigate Hr.Ms. Evertsen at the Stockholm Archipelago.

4.6 Offshore construction: pile driving

The percussive piling for offshore installations is one of the stronger sources of underwater noise (Madsen *et al.*, 2006). A quantitative comparison of the results of various studies in which the underwater noise from pile driving has been measured and reported (e.g. Madsen *et al.*, 2006; Blackwell *et al.*, 2004; David, 2006; De Haan *et al.*, 2007; Nedwell *et al.*, 2006) is difficult, due to the lack of standardisation in the level definitions and data processing. However, there is a recent trend to present the measurement results in terms of the uniform measures Sound Exposure Level, Pulse Duration, Source Level and Peak Level (De Jong & Ainslie, 2008; Elmer *et al.*, 2007; Neumann & Gabriel, 2004; Nehls *et al.*, 2007; Robinson *et al.*, 2007), see §1.2.1.

Table 4.2, from Nehls *et al.* (2007) with data added from Robinson *et al.* (2007) and De Jong & Ainslie (2008), presents an overview of available data from various off-shore pile driving works. The data in this table were obtained from measurements at different water depths H [m] and at different distances r [m] to the source. For better comparability, values are normalised to a distance of 500 m and a water depth of 20 m, using the following scaling:

$$L_{500\,\mathrm{m}} = L_{\mathrm{measured}} + 5\log_{10}\left(H/20\,\mathrm{m}\right) + 15\log_{10}\left(r/500\,\mathrm{m}\right). \tag{4.4}$$

The presumed trend of noise level with distance to the source of $15\log_{10}(r)$ is based on measurements in the North Sea and the Baltic Sea at about 2500 m distance (Nehls *et al.*, 2007). The proposed inverse dependence on water depth is based on Weston (1971). Note that it differs from the depth dependence as proposed in Nehls *et al.* (2007), for which the reference is not clear. As stated in Nehls *et al.* (2007): "*As a consequence of the difficulties to obtain precise values on sound propagation in different water depths, we will not refer to the source level calculated from measurements in greater distance but calculate all values to a standard of 500 m from source. The error in transferring values from distances of 250 m or 1000 m to 500 m will be little affected by differing assumptions on noise propagation whereas an extrapolation to a distance of 1 m at source may differ in the order of several 10 dB*". We strongly support this reasoning. However, the data at two distances from the same UK test pile (Robinson *et al.*, 2007) in Table 4.2 demonstrate that the proposed scaling of (4.4) leads to a difference of only 3 dB in the estimation of the scaled SEL at a distance of 500 m.

Figure 4.11 (copied from Nehls *et al.*, 2007) presents some measured 1/3-octave spectra of the SEL for a single piling stroke. The average spectrum of the SEL measured at

1 km from the pile in the Q7 park (De Jong & Ainslie, 2008) is very similar to that of the Amrunbank piling. The highest sound pressures are reached at low frequencies between 100 to 300 Hz, with the exception of the port constructions, where the low frequency sound is probably subject to a high propagation loss in the very shallow water environment.

Table 4.2. Summary of measurement results for different pile driving works, based on Table 2-1 from Nehls *et al.* (2007), with the lower three rows added, based on data from Robinson *et al.* (2007) and De Jong & Ainslie (2008). Energy and Sound Exposure Level (SEL) are given per single stroke (or blow). Normalised values in the last columns were scaled to a distance of 500 m and a water depth of 20 m, using (4.4).

Project	Pile diameter [m]	Water depth [m]	Measuring depth [m]	Measuring Distance [m]	Blow energy [kJ]	Peak Level [dB re 1 μPa^2]	SEL [dB re 1 μPa^{2}s]	Normalized Peak Level [dB re 1 μPa^2]	Normalized SEL [dB re 1 μPa^{2}s]
Jade port construction, Germany, 2005	0.9	11	5	200	70-200	188	162	181	155
Jade port construction, Germany, 2005	1	11	5	340	70-200	190	164	186	160
FINO 1, Germany, 2001	1.6	30	10	750	80-200	192	162	196	166
SKY 2000, Germany, 2002	3	21	5	260	200	n/a	170	n/a	166
FINO 2, Germany, 2006	3.3	24	5	530	300	190	170	191	171
Amrunbank West, Germany, 2005	3.5	23	10	850	550	196	174	200	178
North Hoyle, UK, 2003	4	7-11	5	955	450	192	155?	194	176?
Scroby Sands, UK, 2003	4.2	1-11	<5	500	n/a	194	n/a	191	n/a
Kentish Flats, UK, 2005	4.3	3	2	243	400	189	n/a	180	n/a
Barrow, UK, 2006	4.7	15-20	5?	500	n/a	198	n/a	198	n/a
Burbo Bank, UK, 2006	4.7	<10	5?	500	n/a	190	n/a	188	n/a
Test Pile, UK, 2006	2	8-15	4-7	57	800	208	178	193	163
Test Pile, UK, 2006	3	8-15	4-8	1850	800	188	164	195	166
Q7 Park, NL, 2006	4	20-25	3-15	890-1200	800	195	172	198	175

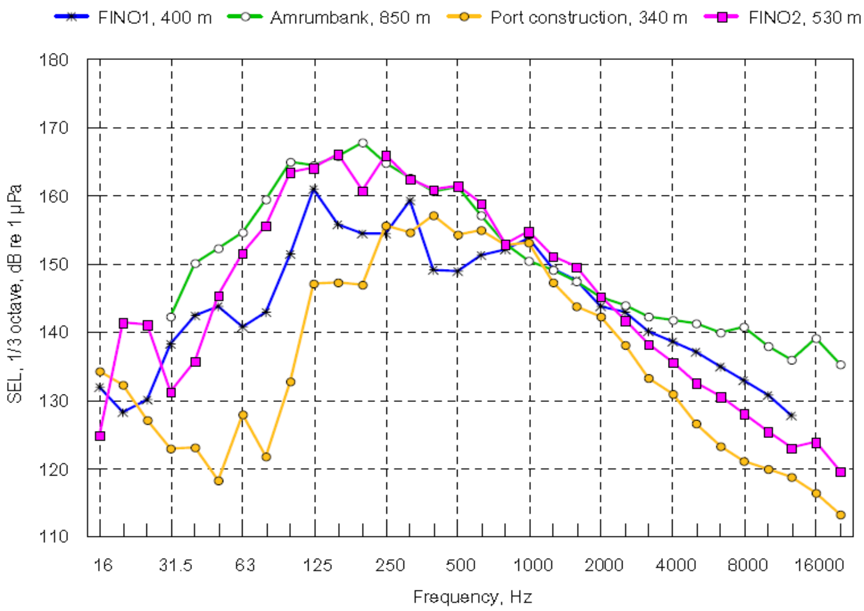


Figure 4.11. Third-octave band spectra of the single stroke SEL[6] of some of the pile-driving operations listed in Table 4.2, from Nehls *et al.* (2007).

4.6.1 *Acoustic energy and conversion efficiency*

As stated above, the distance of the measurements from the monopiles is generally too large to permit a reliable estimate of source level. The error will be the smallest for the data of Robinson *et al.* (2007) at 57 m. According to the semi-empirical model of Marsh & Schulkin (1962), in the frequency range 100 Hz to 10 kHz, propagation loss (PL) can vary between 28 dB re 1 m^2 (for a sand seabed at 100 Hz) and 34 dB re 1 m^2 (for sea state 3 at 10 kHz). A more precise calculation of PL is desirable; this calculation is intended as a rough estimate only. It is assumed that far-field conditions apply at the measurement distance. There is also a further uncertainty introduced by the accuracy of the model, which is estimated to be about 2-4 dB at short range, bringing the total uncertainty to about 4.5 dB. Using this estimation of the propagation loss, the energy source level of a single piling stroke can be deduced (De Jong & Ainslie, 2008) using:

$$\mathrm{SL}_E = \mathrm{PL} + \mathrm{SEL} = 209 \text{ dB re 1 } \mu\mathrm{Pa}^2\mathrm{m}^2\mathrm{s} \pm 4.5 \text{ dB}. \qquad (4.5)$$

The corresponding source energy E can be written as:

$$E = \frac{4\pi}{\rho_0 c_0} 10^{(\mathrm{SL}_E - 120)/10} \approx 2\text{ - }20 \text{ kJ}\ , \qquad (4.6)$$

where $\rho_0 c_0$ [Ns/m^3] is the characteristic impedance of sea water.

This is about 0.25-2.5% of the total hammer energy of 800 kJ. That means that the acoustic conversion efficiency for the piling process is much larger than that for surface ship propulsion (see §4.3.6).

[6] The Sound Pressure Level during the piling depends on the piling stroke rate (N strokes per second): SPL = SEL + $10\log_{10}(N)$.

The theoretical upper limit on SL_E if all the 800 kJ hammer energy were converted to sound (and none into fixing the monopile into the ground) is 230 dB re 1 μPa^2m^2s. If this energy were compressed into a time duration of (say) 10 ms, the source level based on rms pressure would be 250 dB re 1 μPa^2m^2. Any value higher than this implies a conversion efficiency close to or greater than 100%!

Assuming that the piling for one monopile requires about 4000 strokes (Robinson *et al.*, 2007; De Jong & Ainslie, 2008), the total acoustic energy released during the piling for a monopile is roughly 8-80 MJ. Based on this rough estimation, the piling for the Q7 wind park (61 monopiles) in 2006 generated 0.5-5 GJ of acoustic energy.

The Dutch government has set a target for the development of 6000 MW of wind power in the Dutch part of the North Sea by 2020. With an average power of 2 MW per turbine, and 96 turbines already installed, 2904 turbines will have to be placed in the coming 11 years. That is 264 turbines per year. Assuming that the building will be spread out equally over the years, that the turbine sizes are all equal and that they will all be placed on steel monopiles, the annual acoustic energy generation due to the piling would be about 2 to 20 GJ.

4.7 Offshore construction: alternative construction methods

The COWRIE report (Nehls *et al.*, 2007) discusses potential engineering solutions for the mitigation of the piling noise for the construction of monopile foundations for offshore wind turbines. Their analysis leads to the conclusion that a 15-20 dB noise reduction should be feasible, although at substantial cost.

There are more types of foundations for offshore wind turbines, e.g. Gravity and Tripod types (Figure 4.12), which require different ways of construction. The report of the E&P Joint Industry project (see §4.4, page 54) provides an excellent overview of various treatments and alternatives to pile driving. Unfortunately, there is virtually no information available to estimate the underwater noise that is associated with these techniques (Nedwell & Howell, 2004).

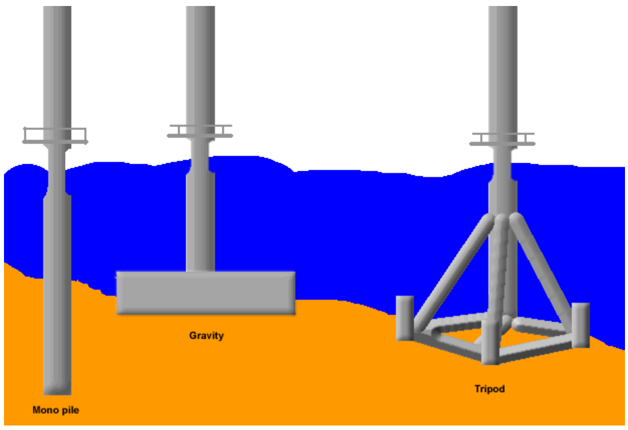


Figure 4.12. Overview of basic offshore wind turbine foundation types (source: offshorewind.net/Other_Pages/Turbine-Foundations) .

4.8 Wind farms: operational wind turbines and maintenance

Also during operation, wind turbines produce underwater noise. There is a limited amount of published data of the underwater noise of operational wind turbines (Madsen *et al.*, 2006; Institut für Statik und Dynamik, 2007; Betke *et al.*, 2004). The predominant noise from a wind turbine seems to be created by vibrations in the gear-box inside the nacelle. The vibrations are coupled to the water column and the seabed through the turbine foundations. There is considerable variation in the reported noise levels from operating wind turbines. A useful set of data is presented in the report of Institut für Statik und Dynamik (2007). It gives data of monitored underwater noise in wind farms in the Baltic Sea, at distances between 87 and 175 m of an operating turbine in relatively shallow water (6-12 m depth). Examples of measured underwater noise spectra are given in Figure 4.13. Further details can be found in the German report.
It was concluded in this German report that the measured underwater noise due to operational wind turbines was limited to tonal noise well below 1 kHz. No turbine related noise could be measured at higher frequencies.

For the purpose of the noise map generation in Chapter 6, the measurement data of the 2.3 MW Bonus wind turbine at *Paludans Flak* were used to estimate the source level of an operational wind turbine. The water depth at that site is 12 m, the wind speed 8-10 m/s, and measurements were taken at 100 m from the pile. The conversion to source level was done by assuming a propagation loss of $10\log_{10}$(range × water depth) for frequencies above the duct cut-off frequency (ca. 100 Hz) and below 1 kHz. Frequencies outside this range were omitted. This propagation loss formula is applicable to a sand seabed and for ranges up to about 10 water depths. Both conditions are satisfied here. The resulting source levels are given in Table 6.3 (§6.2.2)

Note that the available data are all for wind turbines in a relatively shallow water environment (≤ 12 m water depth). Larger offshore wind turbines in deeper water might produce higher noise levels, but the data to confirm this are still lacking.

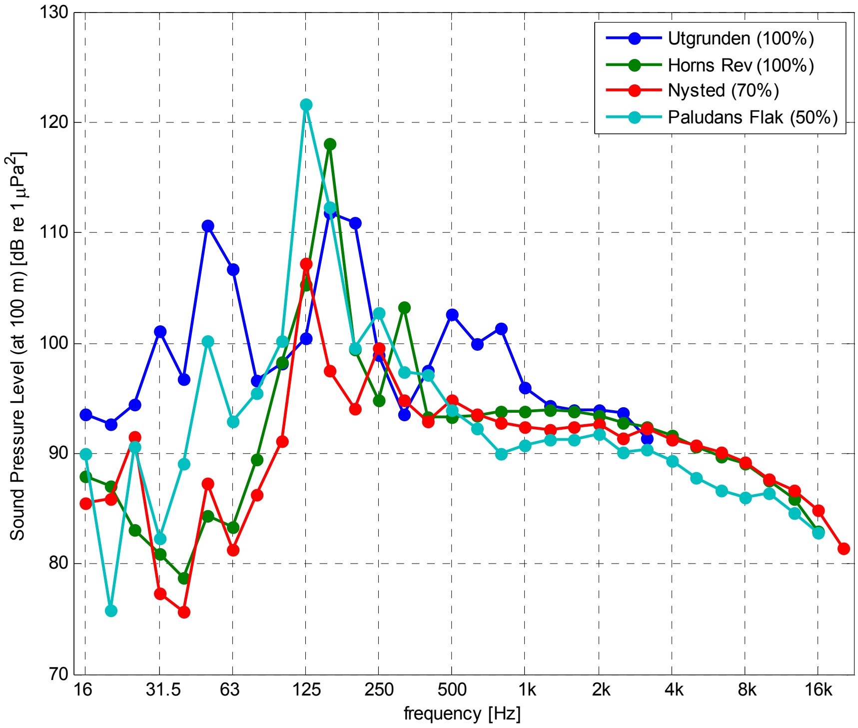


Figure 4.13 Example of 1/3-octave band spectra of the received underwater sound at about 100 m of operational wind turbines, recorded in four wind farms in the Baltic Sea, after the report of Institut für Statik und Dynamik (2007). The percentages in the legend refer to the produced electric power relative to the nominal power.

4.9 Industrial / harbour noise

Shipping and industrial activities in harbours and near shore may contribute to the local underwater noise in the area near the shore. No quantitative information has been found of this type of noise. The same is true for the underwater noise in harbours, which is outside the scope of this report.

5 Assessment of acoustic energy budget

The purpose of the source level estimates from the previous chapters is not to determine the impact of the sound but to determine where best to focus ones effort in assessing likely impacts. Total (acoustic) energy as such would not be a good indicator for impact. Impact depends on many other aspects, amongst others the relevant marine fauna species, frequencies, times, locations, etc. However, the total (acoustic) energy provides some guidelines as where to start. Hildebrand (2004) provides an estimate of total (global) acoustic energy output for various sound sources, averaged over a time period of one year. In Table 5.1, we present our own estimates for the North Sea and compare these with Hildebrand's global values (in brackets). It is first computed for anthropogenic sounds, and then for natural sounds. The assumptions and calculations through which these numbers were obtained have been discussed in Chapters 2-4.

5.1 Anthropogenic sound sources

Table 5.1. Estimation of annual average acoustic power for the largest anthropogenic sources.

Type of source	Estimated annual average of acoustic power output in the North Sea [GJ/year] (cf. global energy output from Hildebrand, 2004, in brackets)	Notes
Shipping	85-850 (3840)[7]	
Airgun arrays	30-300 (3900)	Based on 1400 km^2/y (3D) + 150 km/y (2D)[8], with a zero-to-peak source level of 255 dB re 1 $\mu Pa^2 m^2$
Navigation echo sounders	20-200 (36)	Assumed equal to 1% of shipping radiated noise
Fisheries sonar	3-30	Includes echo locators
Explosives	< 14 (3300)[9]	Mine disposal, etc.
Wind farms	2-20	Pile driving only
Military search sonar	0.2 (8670)[10]	Hull-mounted sonar + DUAV-4 dipping sonar[11]

The contribution from offshore industry activities other than pile driving in connection with wind farms (e.g. turbine noise, dredging, drilling) has not been estimated.

For the purpose of assessing its impact on the animal population, it is not the total acoustic energy per year transmitted by a given source that matters, but the received energy at any given location, weighted according to the sensitivity of the receiver.

[7] Hildebrand (2004) considers supertankers (3700 GJ/y) + merchant vessels (140 GJ/y) + fishing vessels (< 1 GJ/y).
[8] Jaarverslag Staatstoezicht op de Mijnen 2007.
[9] Hildebrand (2004) considers ship shock trials.
[10] Hildebrand (2004) considers sonars 53C (8500 GJ/y) + SURTASS (170 GJ/y).
[11] Minehunting sonar is excluded due to its high frequency; HELRAS dipping sonar is excluded because it is not yet in use. With HELRAS included, the total for military search sonar increases to 0.6 GJ/y.

An approach to obtain this kind of information for individual sources and to present it in noise distribution maps is discussed in Chapter 6.

In a preliminary attempt to get a more global assessment of the relevance of the various sources, it is proposed here to convert the annual average source power to an average acoustic energy that is distributed in the sea. The total acoustic energy, due to a point source in free space (with frequency dependent attenuation α), is related to the source power as described below.

Consider a point source of source factor S (defined as $10^{\mathrm{SL}/10}$, where SL is the source level). The source power W is

$$W = \frac{4\pi}{\rho c} S \,, \tag{5.1}$$

and the intensity I of the spherical wave is

$$I = \frac{S}{\rho c} \frac{\exp(-2\alpha r)}{r^2} \,. \tag{5.2}$$

The energy density E_V is

$$E_V = I / c \,. \tag{5.3}$$

Integrating the energy density over a spherical volume of radius R gives a total distributed energy E of

$$E = \frac{4\pi S}{2\rho c^2 \alpha} \left[1 - \exp(-2\alpha R)\right]. \tag{5.4}$$

Therefore the power and energy are related via

$$E = \frac{W\left[1 - \exp(-2\alpha R)\right]}{2\alpha c} \,. \tag{5.5}$$

If the integral is carried out over all space, then this becomes

$$E = \frac{W}{2\alpha c} \,, \tag{5.6}$$

giving a simple way of calculating the total acoustic energy (in joules) for a source of known frequency (Table 5.2, column 5), which is a better indicator of likely impact than the average source power (in GJ/year) in column 2 of Table 5.2. It accounts for the fact that the propagation loss increases with frequency, which limits the impact area of high-frequency sources relative to low-frequency sources of the same source power.

The last column of Table 5.2 can be understood by means of an analogy with light energy. Imagine a light bulb in an enclosed room that is permanently switched on. Every cubic centimetre in the room contains a certain amount of light energy (say N joules), which corresponds to a light energy density of N joules per cubic centimetre. If this energy density is integrated for the entire room the result is the total amount of light energy in the room, a number that is independent of time. The energy in the last column is analogous to this integrated energy, except that we are talking about sound instead of light, and the integral is over all space instead of being confined to a room. For intermittent sources of sound, it is the *mean* value of the total energy, averaged over a long period of time (say over one year).

Table 5.2. Estimation of total acoustic energy for the largest anthropogenic sources.

Type of source	Order of magnitude estimate of annual average of acoustic power output in the North Sea [GJ/year]	Order of magnitude estimate of frequency [kHz]	Order of magnitude estimate of absorption [dB/km]	Order of magnitude estimate of total (free space) energy $E = W/(2\alpha c)$ [kJ]
Airgun arrays	100	0.1	0.0012	**8000**
Shipping	270	0.3	0.01	**3000**
Wind farm construction (pile driving)	9	0.1	0.0012	**700**
Explosions	7	0.1	0.0012	**500**
Navigation echo sounders	60	30	8.2	0.7
Fisheries sonar	10	30	8.2	0.1
Military search sonar[12]	0.2	10	1.2	0.02

The numbers are very sensitive to the precise choice of frequency (factor 3 change in frequency can give factor 10 change in absorption), so one order of magnitude does not mean much. In particular, the top four in the list (seismic surveys, shipping, pile driving and explosives) are all within one order of magnitude (between 500 and 8000 kJ) in terms of the total energy calculated in this way, and any one of the four could turn out to be the most important in terms of their environmental impact.

It is stressed that this energy estimation is only meant for a first assessment of relevance. It takes no account of:

- temporal and spatial distribution of the sound;
- propagation conditions in shallow water in general and the North Sea in particular;
- hearing sensitivity of individual species.

We draw attention especially to the third bullet because the calculation of total energy tends to push high-frequency sounds to the bottom of the table, as in this case the region of high energy density is limited to the immediate vicinity of the source. Such sources may nevertheless still have significance to an animal that is particularly sensitive to high-frequency sound. The main message that we wish to convey with this table is that, if one is preparing a risk mitigation strategy, it makes sense to focus resources to the sources at the top of table and work down, and not the other way around.

[12] HELRAS dipping sonar is excluded because it is not yet in use. With HELRAS included, the total free-space energy estimated for military search sonar increases from 0.02 kJ to 2 kJ.

5.2 Natural sources

Table 5.3. Estimation of total acoustic energy for the largest natural sources.

Type of source	Estimated annual average of acoustic power output in the North Sea [GJ/year]	Notes
Wind	2-9	Above 1 kHz; Based on 5-10 m/s wind speed
Rain	0.3-1	Above 16 kHz

The total sound energy from lightning strikes is excluded because of the uncertainty associated with its value (see Section 2.4).

6 Noise maps for the North Sea

6.1 Introduction

Part of the present study is the production of (indicative) noise distribution maps for the Dutch sector of the North Sea (NCP/EEZ). It was agreed on with the customer to make maps for a limited number of sources, which are listed in Table 6.1.

Table 6.1. Noise sources for which noise maps are made.

Noise source	Number of maps	Remarks
Wind turbines	2	For operational wind farms
Dredgers	2	Expectation for Maasvlakte 2 (MV-2) with 2 and 6 active trailing suction hopper dredgers
Wind	3	3 wind speeds
Rain	2	2 precipitation rates or areas

The reader might notice that neither of the two anthropogenic sources considered here are included in the acoustic energy budget of Chapter 5 (shipping, seismic airguns, pile-driving and underwater explosions). One reason for this is that the choice for these sources (dredgers and wind turbines) was made during the project preparation stage (in consultation with the customer) and hence before any of the energy calculations. Another reason is that, of all the sources considered in Table 5.2, only one (shipping) can be considered as a continuously radiating source, which is an important consideration for computing a noise map.

Plotted in the noise maps is the received Sound Pressure Level (SPL), integrated over frequency for a band of 10 Hz to 200 kHz (agreed on with the customer).
Lower frequencies will not propagate in most of the shallow NCP area and source levels are hard to measure accurately for such low frequencies. The frequency maximum is set to account for the harbour porpoise, of which the hearing sensitivity extends to frequencies up to 160 kHz. Rain noise will be at higher frequencies (> 1 kHz) than the others. The actual frequency band for which the noise maps are computed is also dependent on the available source level spectra.

For the modelling, a distinction is made between point sources, such as wind turbines and dredgers, and sheet sources, such as wind and rain.

6.2 Point sources (dredgers, wind turbines)

The method used to calculate propagation from point noise sources is based on Weston (1976). The method distinguishes between different propagation regimes, depending on range, frequency and seabed composition. Close to the source, the spreading is spherical (propagation factor ~ $1/r^2$, range r is distance between source and receiver), while it becomes cylindrical further away ($1/r$). Beyond the cylindrical regime, a so-called 'mode-stripping' regime ($1/r^{3/2}$) is identified, beyond which a fast exponential decay takes place in the 'single-mode' regime. Furthermore, the method accounts for attenuation by absorption, bottom and surface reflection and duct cut-off for low frequencies in shallow water. The method neglects variations of sound speed with depth, but does account for variations of the bottom height / bathymetry (e.g. influence of minimum depth between source and receiver). The latter mechanism is most influential for the propagation of acoustic noise.

For the present dredger and wind-turbine results, the following assumptions are made for the relevant environmental properties in the model:

- Constant wind speed (10 m above sea): $\hat{v}_{10}$ = 6.5 m/s (sea state 3 or Beaufort force 3-4); This is a reasonable annual mean value near the Dutch coast (see §6.3)
- Uniform grain size: median grain diameter d_{50} = 0.25-0.5 mm (medium sand)
  - Mean grain size $M_z = -\log_2[d_{50}/1\text{ mm}]$ = 1-2 ϕ ≈ 1.5 ϕ
  - Sound speed ratio $c_{\text{bottom}}/c_{\text{water}}$ = 1.1978 (c_{water} = 1490 m/s)
  - Density ratio $\rho_{\text{bottom}}/\rho_{\text{water}}$ = 2.086
  - Bottom absorption coefficient α_b = 0.88 [dB/λ]

  The sediment properties are taken from Ainslie (2008) (Ch. 4, table in §4.4.1.4). The medium grain size M_z = 1.5 ϕ is a good assumption for the Dutch coastal waters, see below.

The noise maps presented in this chapter have been calculated using the 1 arc-minute resolution bathymetry maps of GEBCO (http://www.gebco.net). In the NCP area, this gives spatial resolution cells of lon × lat ≈ 6/10 × 1 nmi^2 (1 nautical mile nmi = 1852 m). A higher resolution of 200 × 200 m^2 can be obtained using bathymetric data of the Netherlands Hydrographic Office, see Figure 6.1 (top-left), that was kindly provided to us by the Geological Survey of the Netherlands. However, for the present purposes, such high spatial detail is not needed. Also, a conversion of the water depth from the Low Low Water Spring tide (LLWS) reference of the 200 × 200 m^2 map to the Mean Sea Level (MSL) reference of the GEBCO 1-minute map would be required. The MSL depth is more appropriate for propagation calculations than LLWS or LAT (Lowest Astronomical Tide, preferred reference for navigation charts).

In addition to bathymetric data, we also obtained grain-size distributions from the Geological Survey of the Netherlands, see Figure 6.1 (top-right and bottom-left). These grain-size data (also property of the Netherlands Hydrographic Office) provide separate distributions for the sand and silt fractions. The light-grey area in the silt map indicates regions where no silt is found. Coarse gravel (‘grind en stenen’) is spotted only at a few places (see Figure 6.1, bottom-right graph from www.noordzeeatlas.nl) and can be neglected. However, what we need is a combined grain-size distribution ranging from fine silt to coarse sand. Nevertheless, the present sand and silt maps as displayed in Figure 6.1 are valuable in that they confirm that the sand in the coastal region is on average of medium grain size (M_z = 1.5 ϕ), and that there is a clear (inverse) correlation between (sand) grain size and water depth that may be exploited in future model developments. Note that the effect of modelling some regions as mud instead of sand would be to reduce the predicted noise levels (due to higher bottom absorption), primarily in the muddy regions themselves.

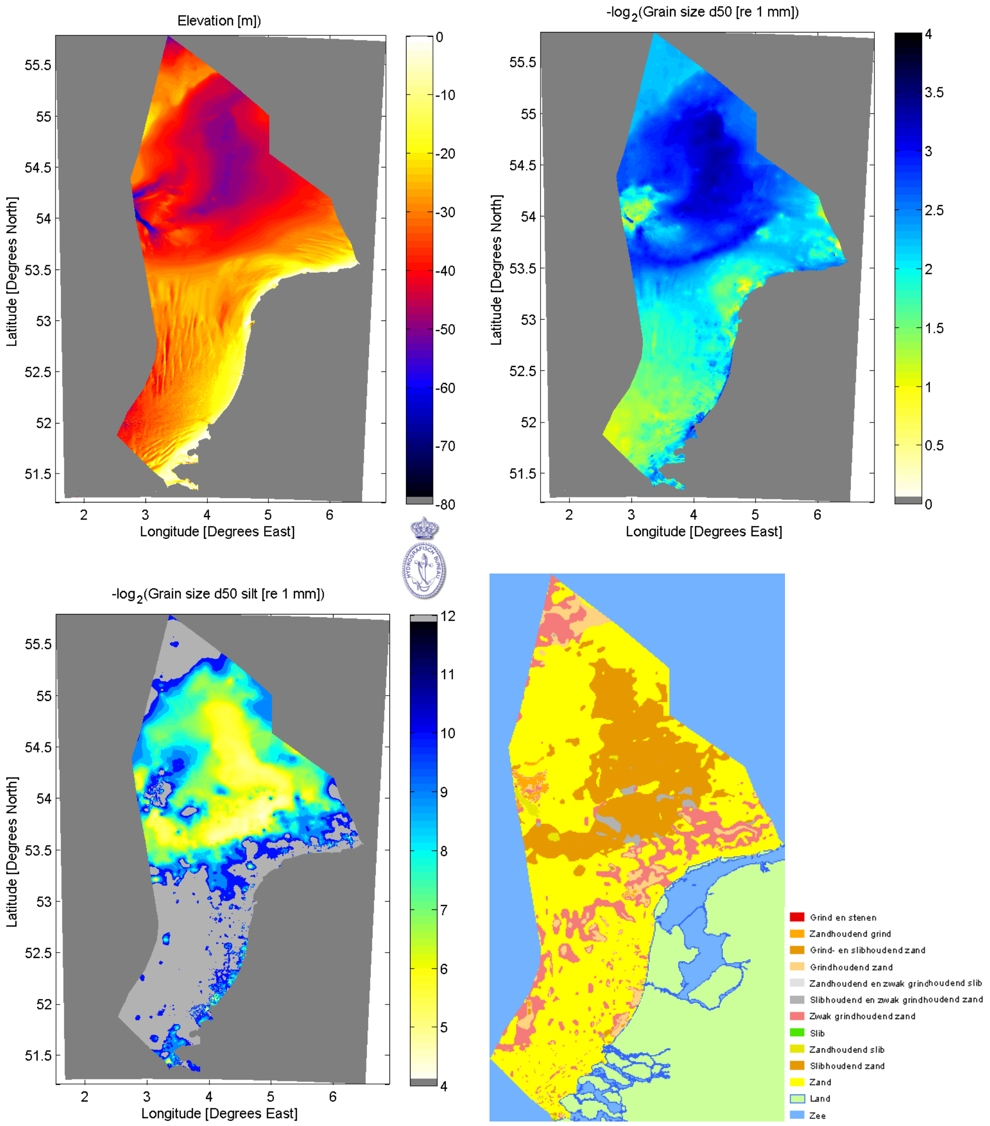


Figure 6.1. Bathymetry and sediment maps for the NCP area (property of the Netherlands Hydrographic Office; lower-right illustration reproduced from www.noordzeeatlas.nl).

6.2.1 *Dredger*

As a dredger source, we have selected the trailing suction hopper dredger *Gerardus Mercator* from the Sakhalin website (see §4.3.3). The source level distribution for this dredger is reproduced in Figure 6.2. Table 6.2 shows the (1/3-octave) source levels used in the model computations. No source level information is available for dredgers either in use or likely to be used in the North Sea. It is not known whether the *Gerardus Mercator* is representative of such dredgers.

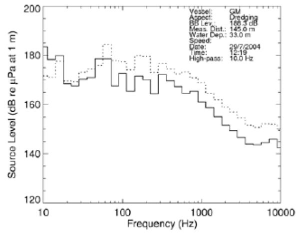
Dredging THSD	*Gerardus Mercator*: Trailer Hopper Suction Dredger 	Trailer Hopper Suction Dredger (hopper size: 18,000m³) using suction to excavate large volumes of soil to excavate the seabed. Spoil is stored on the side of the trench and is returned once pipeline has been installed. Vessel uses thrusters to maintain station.	 **Figure:** 1/3-octave source levels abeam of *Gerardus Mercator* while dredging. **BROADBAND LEVEL (dB re 1 µPa) = 188.3**

Figure 6.2. Information on the trailing suction hopper dredger *Gerardus Mercator* (Sakhalin website).

Table 6.2. 1/3-octave source level distribution of trailing suction hopper dredger *Gerardus Mercator*.

Centre frequency (Hz)	1/3-octave rms source level (dB re 1 $\mu Pa^2 m^2$)
10	183
12.5	178
15	180
20	168
25	168
31.5	170
40	171
50	179
63	179
80	167
100	173
125	165
160	172
200	170
250	164
315	172
400	169
500	167
630	165
800	165
1000	161
1250	159
1600	155
2000	152
2500	149
3150	147
4000	144
5000	144
6300	144
8000	146
10000	142

The noise levels produced by this dredger source have been computed for two locations, see the top and bottom green boxes in Figure 6.3, respectively:

1. North of "Waddeneiland" Terschelling (arbitrary location, single dredger);
2. West of the Rotterdam harbour entrance: "zandwinningsgebied Maasvlakte 2", for 1, 2 and 6 dredgers.

Zooms of these areas and the computed noise level distributions are displayed in Figure 6.4 to Figure 6.11. The colour bar is scaled between 90 dB re 1 μPa^2 (background level) and 145 dB re 1 μPa^2 (maximum noise level for the case of 6 dredgers). The method used for the calculation is based on total energy flux and is not sensitive to the precise choice of source or receiver depth. The maps of anthropogenic sound can be thought of as the result of a depth average over both source and receiver depths.

It is clear from Figure 6.5 and Figure 6.8 to Figure 6.10 that the noise does not reach the land due to the shallow water near the coast. The effect of the bathymetry can also be seen seawards. The noise spreading decreases when moving the dredger closer to the shore, where the water becomes shallower, as is shown by the results in Figure 6.11. Figure 6.6 shows the contribution of the different frequencies (per octave) on the total noise level.

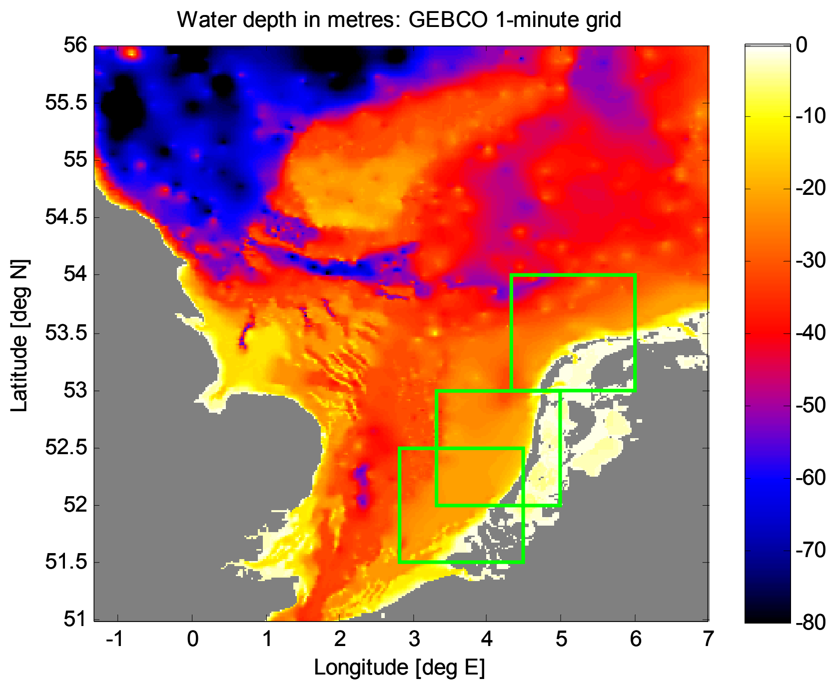


Figure 6.3. Bathymetry chart (GEBCO) of the North Sea. Grey indicates areas above (mean) sea level. The three regions that have our special interest are marked with green boxes.

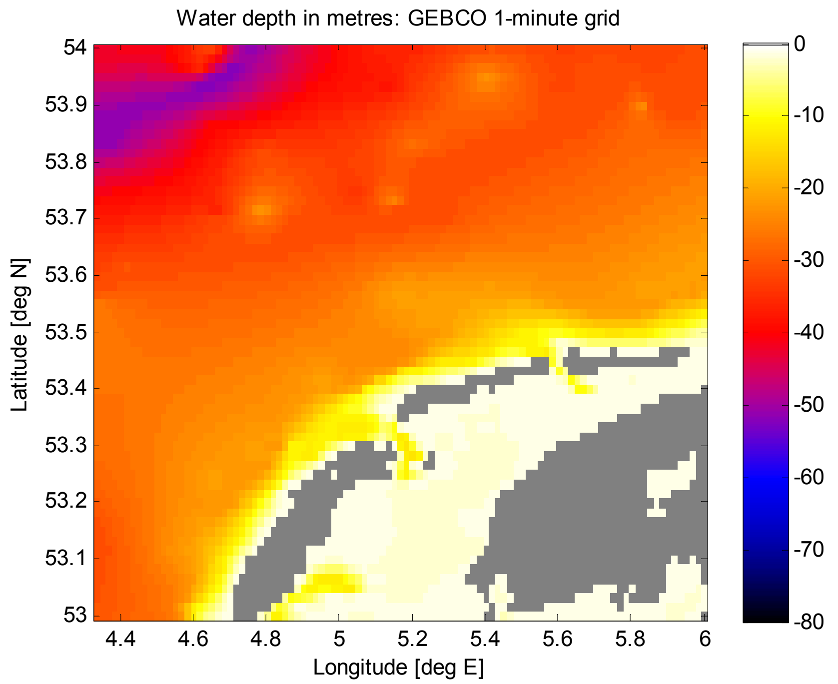


Figure 6.4. Zoom of the bathymetry chart for the region north of the "Waddeneilanden".

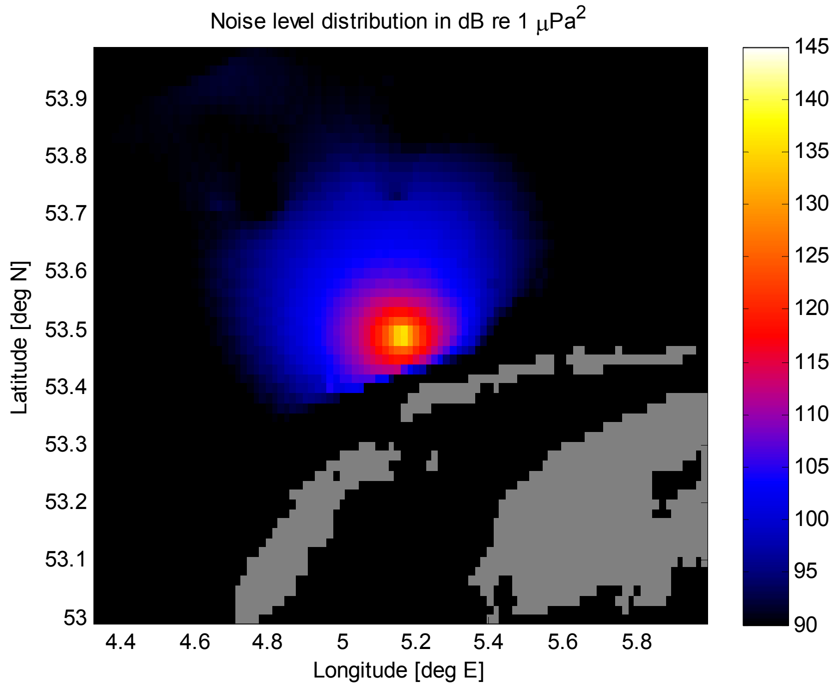


Figure 6.5. Computed total broadband noise distribution for the dredger *Gerardus Mercator* located at (5°10'12"E, 53°30'0"N). The local water depth is 23 m.

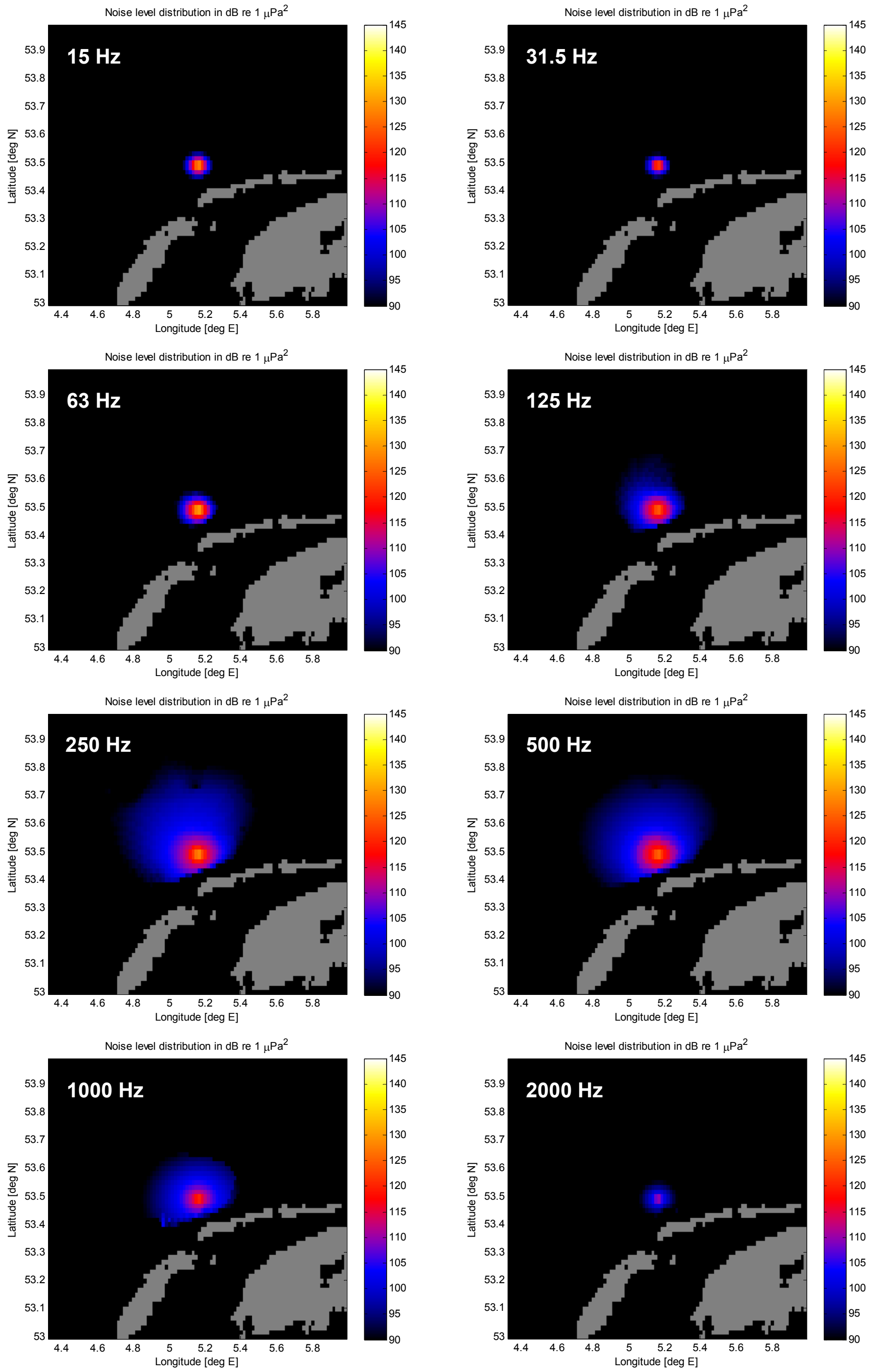


Figure 6.6. The computed noise distribution of Figure 6.5, in octave bands for 8 octaves with centre frequencies of 15 Hz, 31.5 Hz, 63 Hz, 125 Hz, 250 Hz, 500 Hz, 1000 Hz and 2000 Hz. Octaves 9 and 10 (4 and 8 kHz, not shown) contribute only little to the total noise level ('blue shades only').

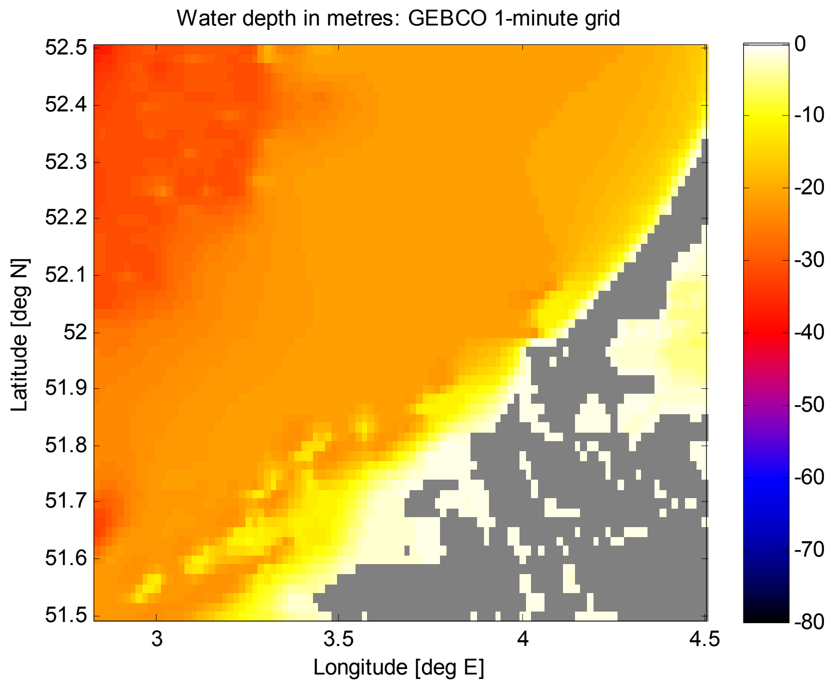


Figure 6.7. Zoom of the bathymetry chart for the region west of the Rotterdam harbour.

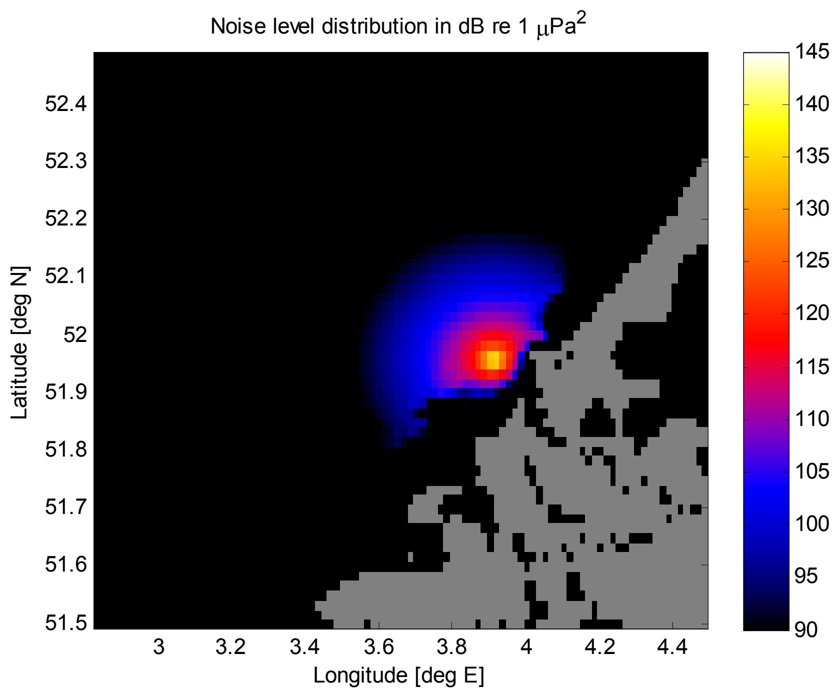


Figure 6.8. Computed total broadband noise distribution for the dredger *Gerardus Mercator* located at (3°54'56.4"E, 51°58'2.0"N). The local water depth is 17 m.

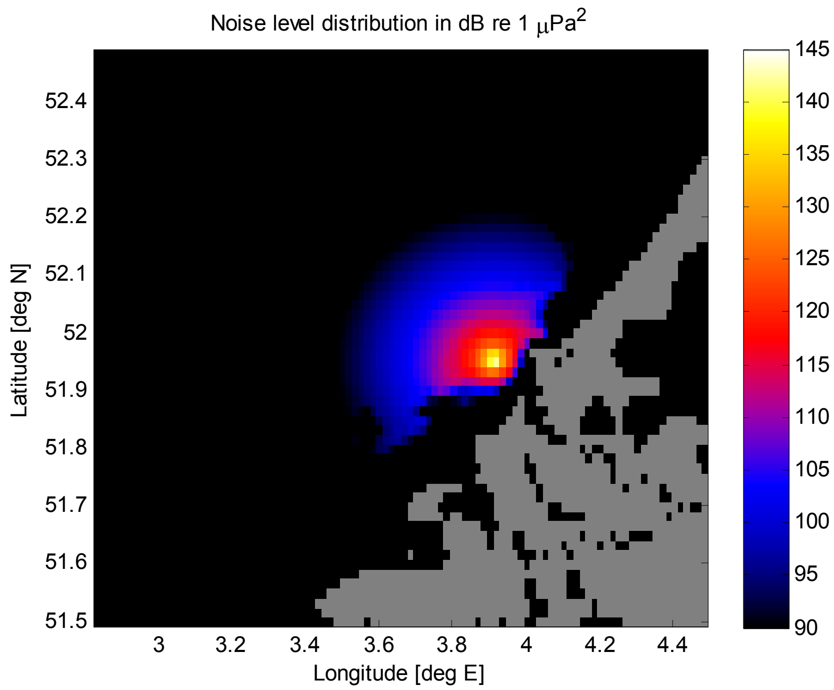


Figure 6.9. Computed total broadband noise distribution for two dredgers. A second (identical) dredger has been added at 0.5 nmi south of the first one (from Figure 6.8). The local water depth is 17 m for both dredgers.

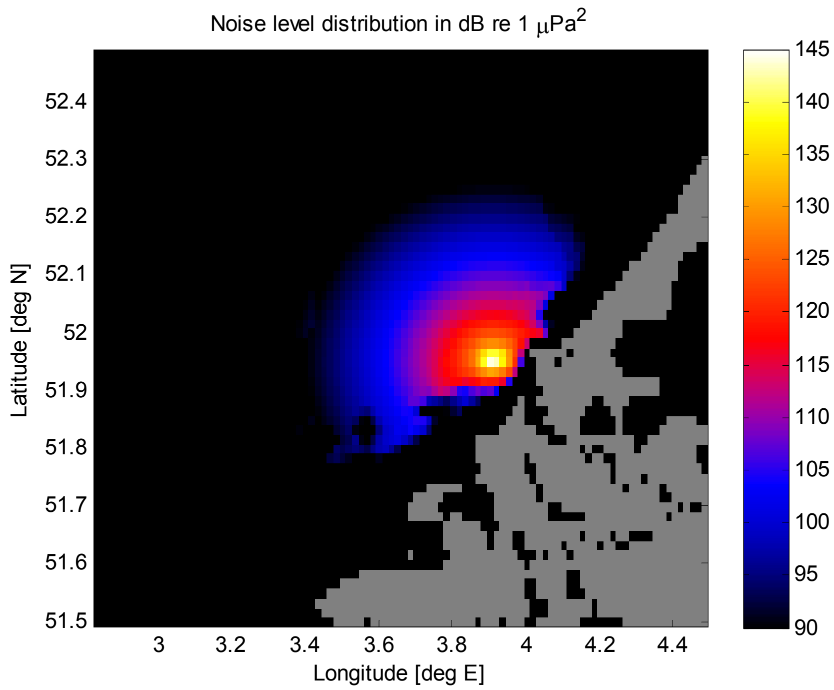


Figure 6.10. Computed total broadband noise distribution for six dredgers. The couple from Figure 6.9 has been duplicated both 0.5 nmi to the east and 0.5 nmi to the west. The local water depth is 18 m for the two most westward dredgers and 17 m for the others.

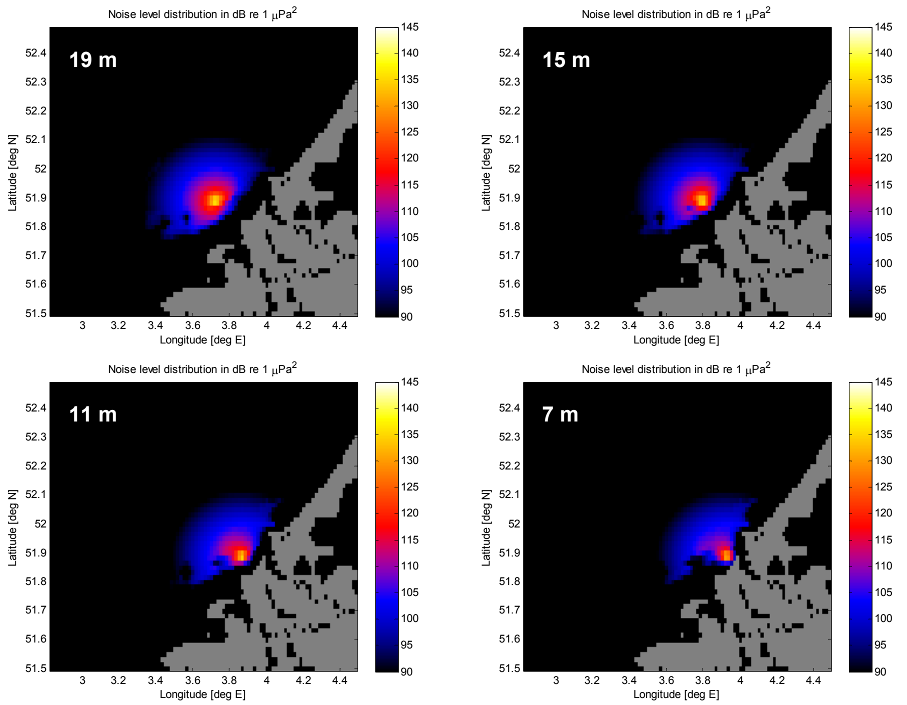


Figure 6.11. Illustration of the decay of the total broadband noise distribution when the source (dredger *Gerardus Mercator*) moves eastwards to shallower waters. The dredger starts at (3°43’48”E, 51°54’0”N). In the next three pictures, the dredger moves eastwards with steps of approx. 4’.

6.2.2 *Wind turbine*

As a second case, we have chosen operational wind turbines as a source. We use the measured sound pressure levels for the *Paludans Flak* wind turbine (Betke *et al.*, 2004) that we have converted to source levels (see Table 6.3 and Figure 6.12), as described in Chapter 4. The locations are chosen in the Q7 wind farm area near IJmuiden (*Princes Amalia windpark*). The local water depth is 21 m. No source level information is available for the wind turbines at this wind farm. It is not known whether the *Paludans Flak* turbine is representative of these turbines.

Table 6.3. 1/3-octave source level spectrum of wind turbine *Paludans Flak*.

Centre frequency (Hz)	125	160	200	250	315	400	500	630	800	1000
1/3-octave rms source level (dB re 1 μPa²m²)	154	143	131	134	128	127	125	123	121	122

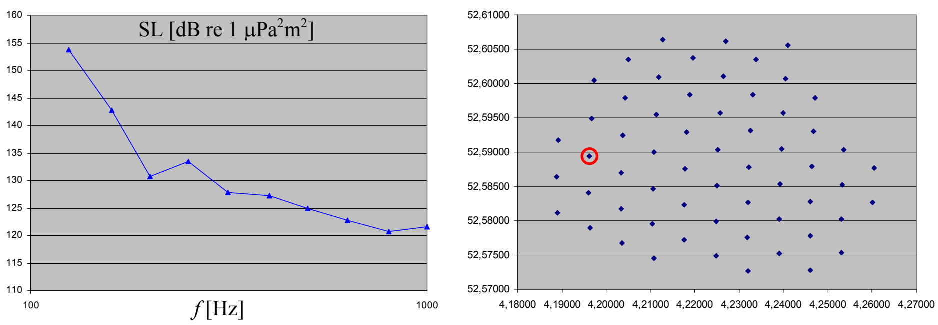


Figure 6.12. 1/3-octave source level spectrum of wind turbine *Paludans Flak* (left) and (proposed) locations (decimal lon-lat) of wind turbines in the Q7 wind farm (right; red circle marks monopile #42).

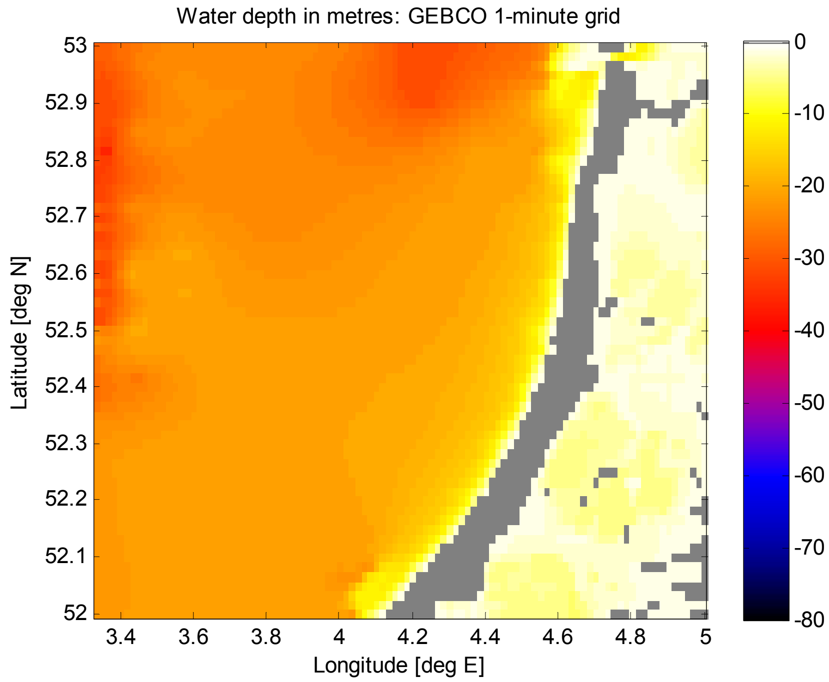


Figure 6.13. Zoom of the bathymetry chart for the region west of IJmuiden.

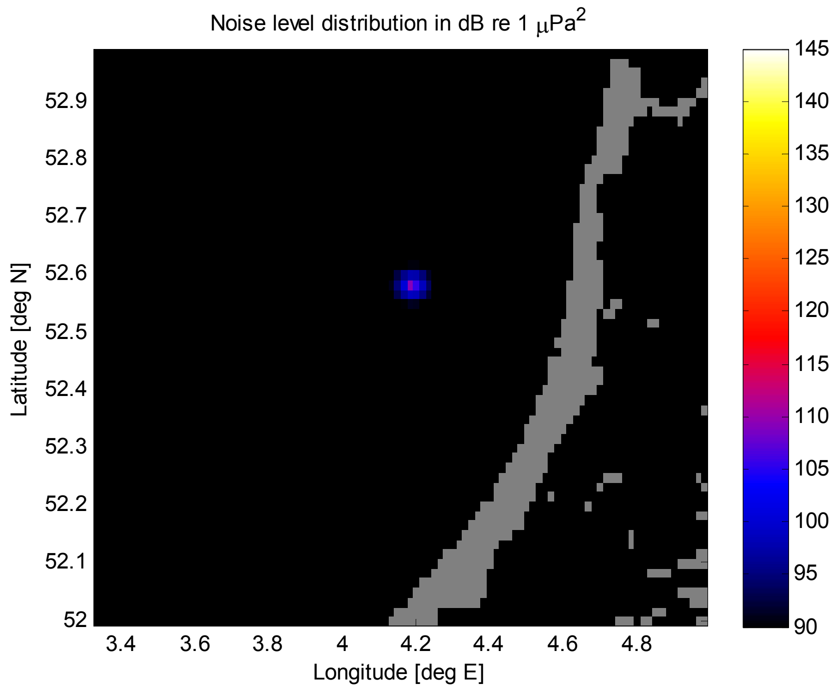


Figure 6.14. Computed total broadband noise distribution for a *Paludans Flak* wind turbine located at (4°11'50.3"E, 52°35'20.9"N). This location equals (approx.) the location of Q7 wind turbine "42" (*Princes Amalia windpark*). The local water depth is 21 m.

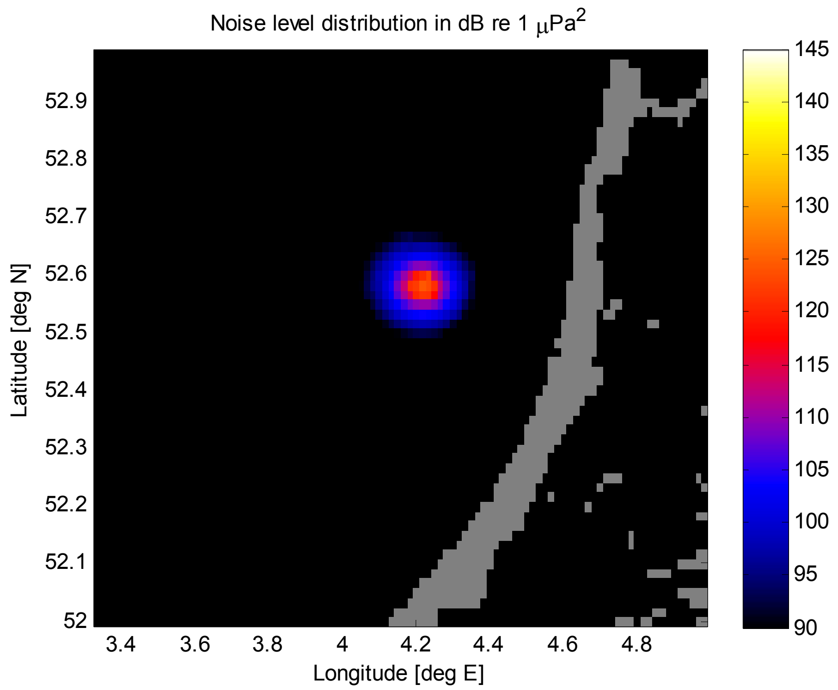


Figure 6.15. Computed total broadband noise distribution for 60 *Paludans Flak* type wind turbines located in the Q7 area. The locations are shown in Figure 6.12. The wind turbines are separated from each other by approx. 1/3 nmi. The local water depth is 21 m.

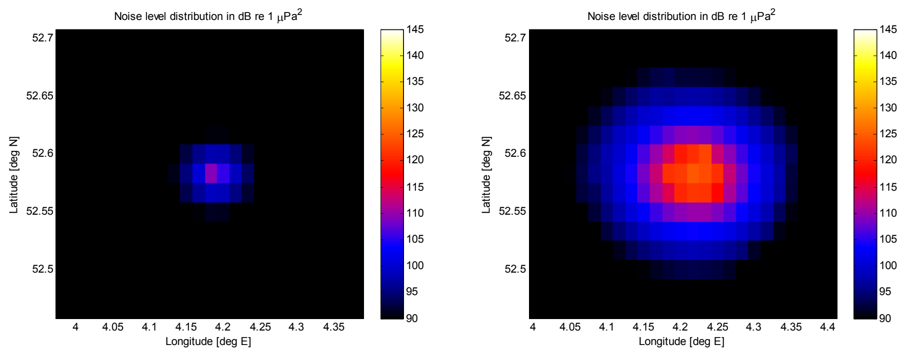


Figure 6.16. Zooms of the noise distributions in Figure 6.14 (left) and Figure 6.15 (right).

6.3 Sheet sources (wind, rain)

Realistic wind-speed distributions have been extracted from KNMI's Climate Explorer (climexp.knmi.nl), see Figure 6.17 and Figure 6.18 for 30-year averages (from the ERA-40 database) over whole years (Figure 6.17) and over January and July months only (Figure 6.18). The average wind speeds are highest in January and lowest in July. These mean velocity fields have been used for the velocity $\hat{v}_{10}$ in the sheet source models for both wind and rain, which are given by equations (2.3) and (2.8)–(2.11). The prediction excludes the contribution from distant sources at low frequency.

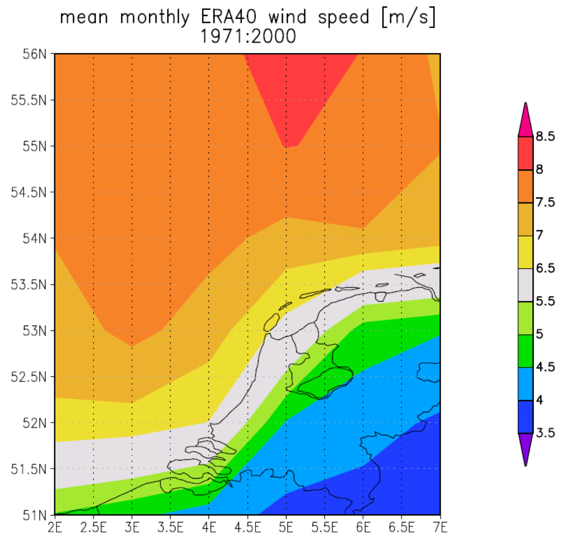


Figure 6.17. Mean wind speed at 10 m above the (sea) surface. It concerns averaged values over a time span of 30 years (1971-2000), originating from the ERA-40 database (Sept. 1957 – Aug. 2002).

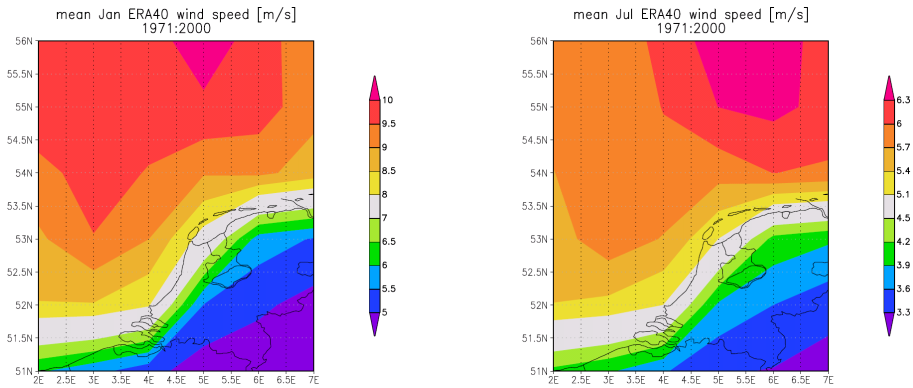


Figure 6.18. Mean wind speed at 10 m above the (sea) surface in January (left) and July (right).

KNMI also provided us with suggestions for representative values of the precipitation rate and shower patch area for a typical rain shower at the North Sea (KNMI, 2008). The selected rain rate is 5 mm/h. The rain shower is not assumed to cover the whole modelled area. Rather, the level at any point should be interpreted as the sound pressure level due to rainfall if it were raining at that point.

The next pages show the noise maps for wind and rain, computed separately for the frequency bands 10-1000 Hz (wind) and 1-200 kHz (wind and rain). The LF wind noise map can be regarded as a reference for the dredger and wind-turbine maps, while the HF wind noise map can be regarded as a reference for the rain noise map. It can be seen from the figures that:

- noise levels are low, when compared to the dredger and wind turbine;
- variation of the noise levels over the NCP is small;
- wind noise is mainly correlated with the wind speed (no depth dependence);
- rain noise is mainly correlated with the rain rate, but also with the receiver's depth due to the high absorption of the rain-noise energy at the higher frequencies (resulting in a larger effective depth).

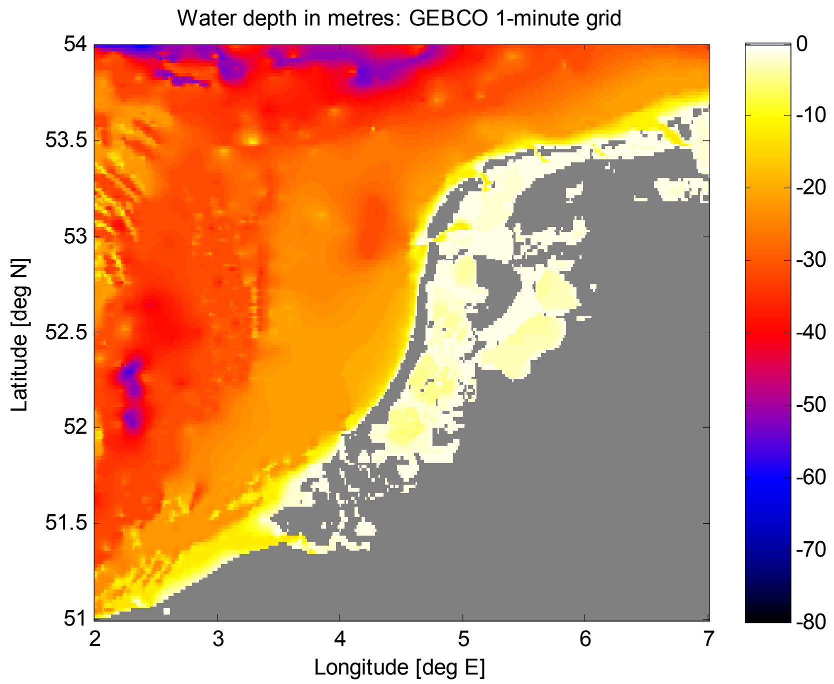


Figure 6.19. Bathymetry chart of the Dutch coastal waters.

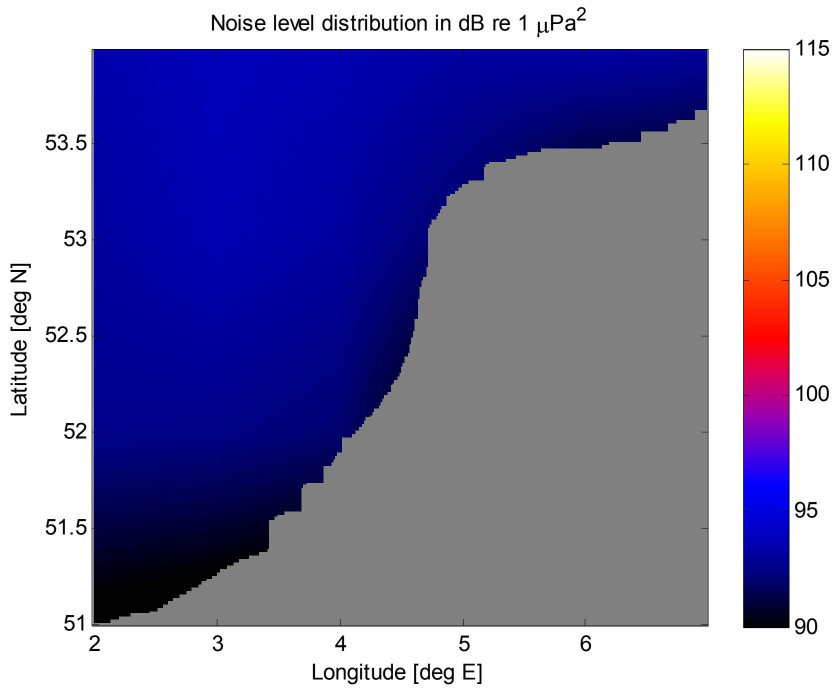


Figure 6.20. Computed wind noise level for the frequency band 0.01 – 1 kHz. The receiver depth for this noise map is $z = H$, but a visually identical map results for $z = 0.1$ m. The (max.) received sound pressure level is 94 dB re 1 μPa^2, independent of depth.

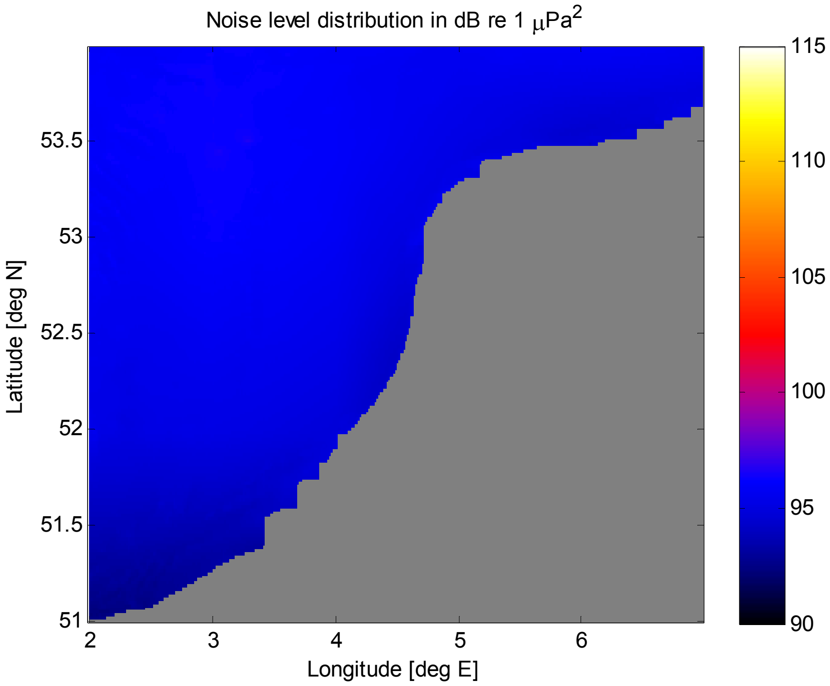


Figure 6.21. Computed wind noise level for the frequency band 1 – 200 kHz. The receiver depth for this noise map is $z = H$, but a visually identical map results for $z = 0.1$ m. The (max.) received sound pressure level is 97 dB re 1 μPa², independent of depth.

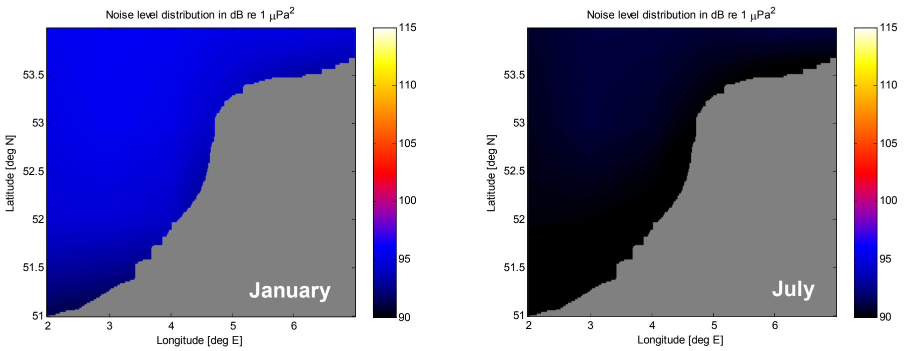


Figure 6.22. Computed wind noise level for the frequency band 0.01 – 1 kHz in January (left; SPL_{max} = 96 dB) and July (right, SPL_{max} = 91 dB). The receiver depth for this noise map is $z = H$, but a visually identical map results for $z = 0.1$ m.

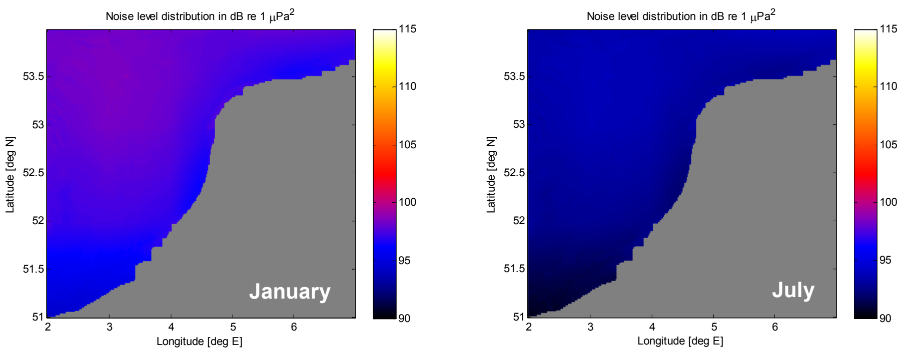


Figure 6.23. Computed wind noise level for the frequency band 1 – 200 kHz in January (left, SPL_{max} = 99 dB) and July (right, SPL_{max} = 94 dB). The receiver depth for this noise map is $z = H$, but a visually identical map results for $z = 0.1$ m.

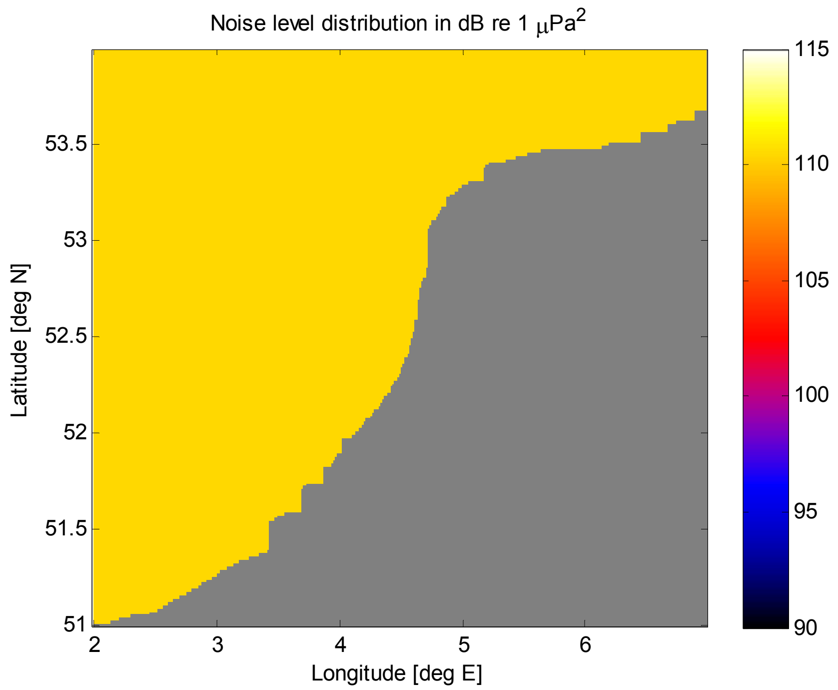


Figure 6.24. Computed rain noise level for the frequency band 1 – 200 kHz. The rain rate is 5 mm/h. The wind speed is given by Figure 6.17. The receiver depth for this noise map is $z = 0.1$ m. The (max.) received sound pressure level is 111 dB re 1 μPa^2.

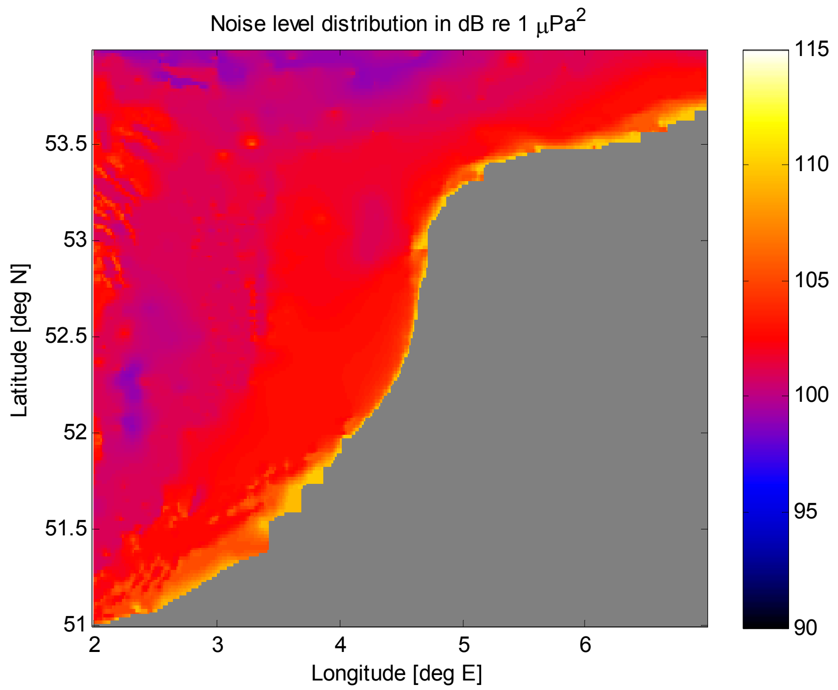


Figure 6.25. Computed rain noise level for the frequency band 1 – 200 kHz. The rain rate is 5 mm/h. The wind speed is given by Figure 6.17. The receiver depth for this noise map is $z = H$. The (max.) received sound pressure level is 110 dB re 1 μPa^2.

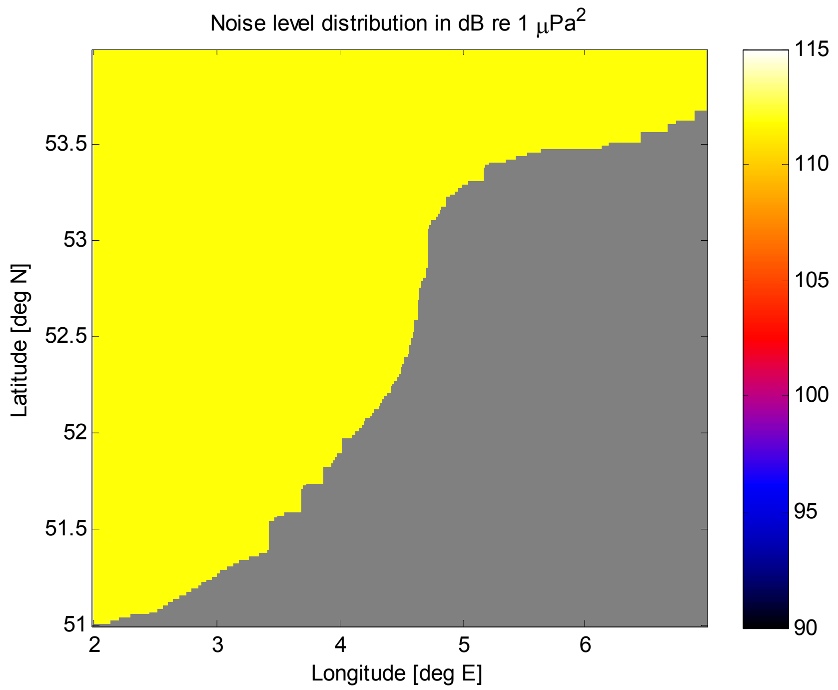


Figure 6.26. Computed rain noise level for the frequency band 1 – 200 kHz. The rain rate is 10 mm/h. The wind speed is given by Figure 6.17. The receiver depth for this noise map is z = 0.1 m. The (max.) received sound pressure level is 112 dB re 1 μPa^2.

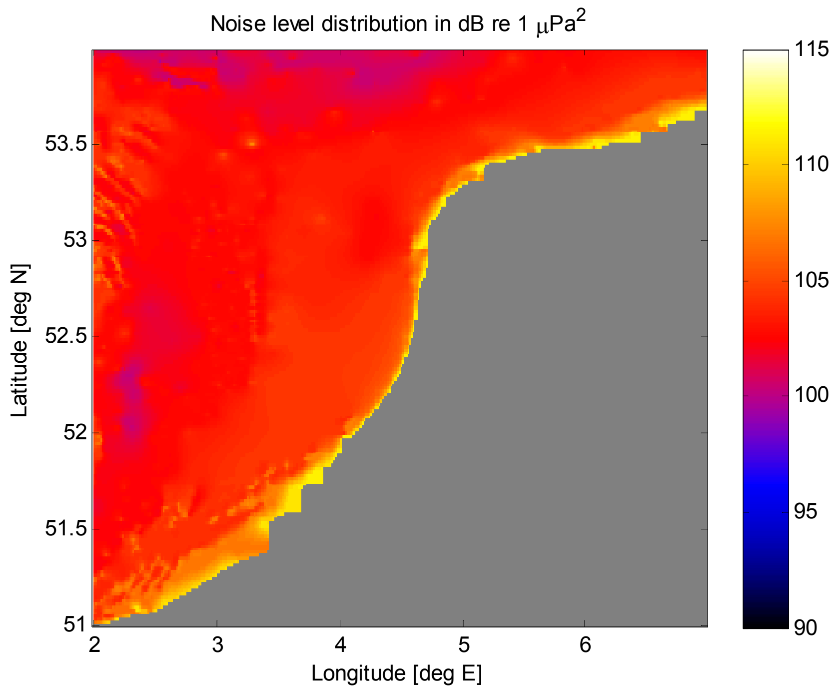


Figure 6.27. Computed rain noise level for the frequency band 1 – 200 kHz. The rain rate is 10 mm/h. The wind speed is given by Figure 6.17. The receiver depth for this noise map is z = H. The (max.) received sound pressure level is 111 dB re 1 μPa^2.

7 Mitigation measures

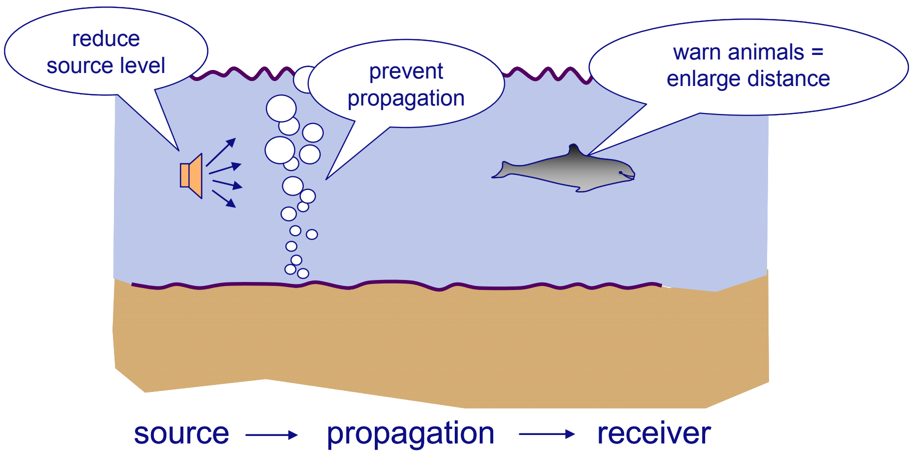
7.1 Introduction

Mitigation measures aim at eliminating the harmful effects of man-made underwater sound, or at least at reducing the risk of harming marine ecosystems. In general, there are three options for mitigation measures:

- measures at the source side, to prevent the noise from being produced,
- measures that effect the propagation, to prevent the noise from reaching the receiver, and
- measures at the receiver side, to prevent the noise from being detected.

Some familiar examples for the case of humans-and-noise help to understand these options:

- measures at the source side:
  - road traffic: silent tyres, silent asphalt, whisper trucks,
  - air traffic: whisper jets,
- measures that effect the propagation:
  - noise barriers,
  - airport-at-sea, or steep descent to an airport: increase the distance between sound source and receiver,
- measures at the receiver side:
  - acoustic vent,[13]
  - earplugs.



In the underwater world, the possibilities are based on exactly the same options. Examples are:

- measures at the source side:
  - shipping: silent ship design[14], e.g. by reducing cavitation,
  - wind-turbine foundation: no pile driving, but alternative techniques based on vibrating, or a large concrete foundation (gravity structure),
  - sonars: lower sound level; no transmission in the presence of certain species,

[13] In Dutch: suskast.
[14] Note that this would also be beneficial for the ship's crew.

  - seismic sources: only transmit relevant frequencies,
- measures that affect the propagation:
  - noise barrier like bubble screen (bubble curtain), or solid barrier,
- measures at the receiver side:
  - no possibilities at the animal itself (no ‘earplug’ equivalents),
  - options to protect particular areas are:
    - noise barrier like bubble screen,
  - ‘warn’ the animals such that they move away from the sound source, i.e. increase the propagation distance; Only possible for species that are sufficiently ‘mobile’, e.g. not effective for fish larvae or microphytobenthos; Examples are:
    - ramp-up scheme for sonars,
    - acoustic deterrents, see also Section 3.8; some sort of pinger that produces audible-but-not-too-loud noise dedicated to warn sea mammals (in particular porpoises); originally designed to keep porpoises away from gill nets.

Note that the field of noise mitigation measures above water with the aim to protect humans is much more advanced than the field of noise mitigation measures underwater with the aim to protect marine ecosystems. Reasons are amongst other things:

- policy makers used to be more interested in above water sound than underwater sound and its effects,
- animals cannot be questioned, instead their behaviour/response to sound must be studied and monitored, not only in captivity, but also in their natural habitat,
- marine fauna is more difficult to study than terrestrial fauna,
- underwater measurements are much more difficult and expensive to carry out than above water measurements,
- underwater sound travels over larger distances than above water sound.

As a consequence, in many cases the effectiveness of mitigation measures has not been proven yet.

Except for the mitigation measures as mentioned so far, in some cases there is the option to make sure that no noise is produced during certain times or in some areas. Well-known above-water sound examples are:

- time: reduction of night flights,
- time: closure of particular areas during breeding season,
- time: ‘Sunday rest’,
- area: reserve preservation areas.

One can imagine that also in the case of the underwater situation certain periods during the year, or certain areas, could be identified where animals are extra sensitive to being disturbed. For example, the period or the location where the young are born and suckled. At these locations or at these periods, no disturbing activities would be allowed, while elsewhere or at other times activities could continue. In this project, we exclude this type of measures from our scope and limit ourselves to the measures based on ‘source’, ‘propagation’ and ‘receiver’. These will now be discussed in more detail.

7.2 Measures at the source

- Lower sonar sound level (during exercises)

  Most sonar transmissions from military ships take place in peace time, during exercises. It is clear that the requirements are then less stringent than during military actions. This means that it would be possible to reduce the sonar source level in many cases. Furthermore, it is clear that the sonar source only needs to transmit frequencies within the envisioned processing band. Such a bandwidth limitation would not reduce the sonar capability in any sense, but the source level could be (much) lower. In the same category, the prevention of harmonics can reduce the impact of low frequency sonar signals significantly in case of marine mammals.

- Seismic sources that only transmit frequencies in the relevant frequency band

  Current airgun arrays produce frequencies well above those that are relevant to the seismic exploration method. Such high frequencies do not penetrate to the depths that are relevant to seismic exploration. Currently, alternative sources are being studied, that could be classified as ‘marine vibrators’. The advantage of such sources is twofold: first they would only produce the frequencies that are relevant, second they could transmit chirps (or sweeps, or transient signals) rather than impulsive signals. I.e., the required acoustic energy would be transmitted in a longer period of time at a lower source level rather than in a very short period of time at a higher source level. However, currently the use of marine vibrators is not generally accepted by the marine seismic industry (although the land seismic vibrator is the standard source for seismic exploration on land).

- No sonar transmission or seismic surveying in the presence of specific marine animals

  A ‘marine mammal observer’ is present during the survey. This observer determines the presence of the specific marine animals, e.g. via visual observation using field-glasses, or using a passive sonar (array) that ‘listens’ to the sounds of the animals. The marine mammal observer is authorized to take the appropriate measures, amongst which is to put the sonar transmissions, or the use of airguns (temporarily) on hold. However, the observation range is limited. During night time, no visual observation is possible at all, while during day time the range is variable, depending on the weather conditions, but not likely to be more than several kilometres in good conditions. With means for passive acoustic detection, the range can be extended. However, the possible range for damage due to loud activities like pile driving can be even larger, which reduces the effectiveness of the measure.

- Alternatives to pile driving at sea

  There exist alternatives to pile driving at sea. A well-known example is vibrodriving, where rotating eccentric weights create an alternating force on the pile, vibrating it into the ground. This technology has been developed to reduce harm to the environment. It is only suitable for smaller piles (Elmer *et al.*, 2007). Another example is the use of a steel or concrete prefab foundation as an alternative to the so-called monopiles which were used in the park at Egmond aan Zee. Such foundations can be placed without pile driving (Madsen *et al.*, 2006; The Danish wind industry association, www.windpower.org). This means that the construction of wind-energy farms does not necessarily imply pile driving.

- Silent ship design

  Naval vessels and fishery research vessels are built to underwater noise requirements, which specify much lower radiated underwater noise levels than those found for conventional ships. The design technology is available to match ship propellers to the expected inflow in order to reduce cavitation and to reduce machinery noise by means of acoustic measures like resilient mounts and acoustic enclosures. See Ross (1976).

- Frequency shaping

  Because the hearing frequency ranges of the animals are limited and the audiograms are U-shaped, any change in the spectrum of a noise source towards a less sensitive part of the hearing threshold curve is an improvement. Solutions that act on frequency bands of noise sources should therefore be considered in addition to solutions that aim at reducing the number of decibels.

7.3 Measures to propagation

- Bubble screen (or bubble curtain)

  A noise barrier like a bubble screen reflects the sound, such that the sound energy is concentrated at one side of the barrier, whereas propagation to the other side is reduced. The principle is based on the impedance mismatch between water and air. Bubble screen barriers can lead to a reduction of 3 to 5 dB (Würsig *et al.*, 2000) or even up to 20 dB (Spence *et al.*, 2007). However, the effects on marine mammals have not been quantified. A bubble screen could be used close to a source, but it could also be used close to an area-to-be-protected. It depends on local circumstances which option is to be preferred. Note that the effects of a bubble screen strongly depend on the size and the amount of the air bubbles produced (i.e. thickness of the screen). Furthermore, currents may distort the effect because of drifting bubbles and the principle is bounded to a certain maximum depth. This is because of practical reasons related to the required compressors and principle reasons related to the bubble size distribution, which is a function of depth.
  Note that a bubble screen itself is a source of sound, which may for some low frequencies (order hundreds of Hz) be louder than the sound source it is supposed to suppress.

- Solid barrier

  Solid barriers are mentioned by Spence *et al.* (2007). The principle is the same as that of a bubble screen, but the material 'air' is replaced by 'foam'. The foam is mounted in a frame in some way. Attenuation up to 20 dB is reported. The method is restricted to shallow water. An alternative is to remove the water from a solid casing that surrounds the sound source. This expensive method effectively blocks the sound radiation into the water. Obviously, the construction of the casing may give rise to underwater sound production.

7.4 Measures at the receiver

We do not know of any possibility to protect animals directly from the harmful effects of too much sound. A sound barrier could be used to protect important (small) areas, think of breeding or feeding grounds, or to create a 'silent passage'. However, given the size (and distribution) of the involved areas and the non-sedentary life style of all marine mammals and fish, this option does not seem to have widespread applicability.

- Acoustic deterrent

  The idea here is to deploy an acoustic deterrent (or 'pinger') prior to activities that produce a lot of noise. An acoustic deterrent produces sound (or ultrasound) itself, e.g. in the frequency range of 5 to 160 kHz. The assumption is that smart marine mammals would move away from the location of the pinger to a safe distance, i.e. large enough for the noise to drop below unpleasant levels. In practice, not much is known about whether or not this assumption is correct. One can imagine that smart marine mammals even get attracted by the sounds the pinger produces, out of curiosity. In any case, the method is not suitable for slow-moving animals, think of fish larvae. Note that the use of acoustic deterrents increases the total amount of sound energy in the water, and frequent use might cause temporary or even permanent loss of habitat (Franse, 2005). Other risks are: the sound of an acoustic deterrent may be too loud for an animal at a short distance (see also sonar ramp-up scheme).

- Sonar ramp-up scheme

  A sonar ramp-up scheme means that the sonar is started in a low-power mode after which the power is increased to a maximum level during a specified time. This time should be large enough for the animals to relocate to a ‘safe’ distance.
  The assumption is that the animals indeed respond in this manner to the sound, either instinctively or because they have learned to do so. At this time there is no information available that supports this assumption. One of the complicating factors is that a certain mitigation measure in most cases is not stand-alone. Instead, it is part of a whole suite of such measures. One of the other usual measures is that it is not allowed at all to start sonar transmissions if marine mammals are present in the area. An unwanted side effect of a sonar ramp-up scheme is that it is likely to increase the total duration of a sonar operation, thus increasing also the total acoustic energy transmitted by the sonar source.

8 Recommendations for future research

Based on the results presented in this report, the following recommendations can be made for future research:

- Clear generic guidelines / procedures should be established for the measurement, processing and quantification of underwater sound, such that future studies and measurement campaigns will lead to comparable results. This involves both hardware aspects, i.e. how to measure, and software aspects, i.e. how to process the measured data. It also involves taking into consideration international work in this field.
- There is a large demand for proper measuring protocols and measurements of natural and anthropogenic underwater sound in the North Sea (i.e. measurements that comply with the mentioned guidelines) for further development of the propagation modelling and validation of the resulting sound maps. Both the spatial distribution over the NCP (Netherlands Continental Shelf) and the variation with time on a short (minutes, hours) or long time scale (seasons, years) should be sampled with sufficient resolution.
- The main contributions to anthropogenic sound energy in the North Sea are found to come from shipping, seismic surveys (airguns), underwater explosions and pile driving. Underwater sound maps (including frequency spectra) should become available for these sources, and ideally including the effects of variations of bottom type across the NCP region.
- The available and the still-to-be-acquired data should be stored in a central database (e.g. as has been done for groundwater levels) with well-defined and annotated data of sources, mitigation measures, propagation and background noise. This database could be filled via mandatory monitoring for all MER (environmental impact assessment, Dutch: milieu-effect-rapportage) liable off-shore projects.
- It should be investigated whether the method used for the calculation of propagation losses and the generation of underwater sound maps can (in the long term) be further developed to a generally applicable legal basis for underwater sound (‘rekenvoorschrift’), as exists for sound in air (industrial and traffic noise).
- There is a large demand for research on the possible impact of underwater sound on diverse species (both individually and for populations, in short and long term). This refers to the individual physiology and the short term dose-response relationship as well as to the long term impact on the population. It is therefore recommended that experts from various disciplines (acousticians, ecologists, biologists) establish some sort of platform with the aim of improving the collaboration.

9 Acknowledgements

The authors wish to thank Herman Peters (Rijkswaterstaat), Ron Kastelein (SEAMARCO) and Paul van Walree (TNO) for their detailed and constructive reviews of draft versions of this report.

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11 Signature

The Hague, February 2009

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A Noise source characteristics

A.1 Introduction

The source characteristics and (anthropogenic) usage information that we have been looking for were the following:

- Source level SL (or output power)
- Beam width θ (for sonars)
- Frequency band B
- Pulse duration T
- Repetition rate N
- Location (where, e.g. shipping lanes)
- How often? (e.g. how many ships)
- Origin (measurements, modelling, …)

Unfortunately, a complete information set with all these properties for a specific source is usually not found in the literature. The information that we did find, however, has been collected in the tables presented in the following sections.

A.2 Natural noise sources

Information on sounds made by mammals (echo-location clicks and other vocalization) has been collected in the table below. For information on other natural sounds (wind, rain, lightning, etc.), see Chapter 2.

Table A.1. Natural noise sources: mammals (echo-location clicks and other vocalization).

	Frequency range [kHz]	**Dominant frequency [kHz]**	**Source level [dB re 1 μPa^{2}m^2]**	**Pulse duration [s]**	**Reference**
Harbour porpoise (Phocoena phocoena)					
Clicks (not demonstrated as echolocation)	2		100 (p-p)		Richardson *et al.* (1995) (Busnel & Dziendzic, 1966)
Clicks (echolocation)	110-150		135-177 (p-p)		Richardson *et al.* (1995) (Busnel *et al.*, 1965; Mohl & Andersen, 1973; Kamminga & Wiersma, 1981; Akamatsu *et al.*, 1994)
White-beaked dolphin (Lagenorhynchus albirostris)					
Squeals		8-12			Richardson *et al.* (1995) (Watkins & Schevill, 1972)
Clicks (echolocation)	≤ 325		≤ 207 (p-p)		Mitson (1990)
Bottlenose dolphin (Tursiops truncatus)					
Whistles	0.8-24	3.5-14.5	125-173		Richardson *et al.* (1995) (Lilly &

	Frequency range [kHz]	Dominant frequency [kHz]	Source level [dB re 1 µPa^{2}m^2]	Pulse duration [s]	Reference
					Miller, 1961; Tyack, 1985; Caldwell *et al.*, 1990; Schultz & Corkeron, 1994; Wang Ding *et al.*, 1995)
Low-frequency narrowband	< 2	0.3-0.9			Richardson *et al.* (1995) (Schultz *et al.*, in press)
Rasp, grate, mew, bark, yelp					Richardson *et al.* (1995) (Wood, 1953)
Clicks (echolocation)	110-130		218-228 (p-p)		Au *et al.* (1974); Au (1993)
Harbour seal (Phoca vitulina)					
Clicks (fore-flipper slaps on the water surface)		12-40			Richardson *et al.* (1995) (Noseworthy *et al.*, 1989, etc.)
Roar	0.4-4	0.4-0.8			Richardson *et al.* (1995) (Hanggi & Schusterman, 1992, 1994)
Social sounds	0.5-3.5			0.019-0.4	Richardson *et al.* (1995) (Beier & Wartzok, 1979)
Bubbly growl	< 0.1-0.4	< 0.1-0.25			Richardson *et al.* (1995) (Hanggi & Schusterman, 1992, 1994)
Grunt, groan	< 0.1-4				Richardson *et al.* (1995) (Hanggi & Schusterman, 1992, 1994)
Creak	0.7-4	0.7-2			Richardson *et al.* (1995) (Hanggi & Schusterman, 1992, 1994)
Pup (simultaneously in-air and underwater when the pup's head is in air)					Richardson *et al.* (1995) (Renouf, 1984; Renouf & Perry, 1983; Renouf & Perry, 1985, 1988)
Grey seal (Halichoerus grypus)					

	Frequency range [kHz]	Dominant frequency [kHz]	Source level [dB re 1 µPa^{2}m^2]	Pulse duration [s]	Reference
Hiss	0-40				Richardson *et al.* (1995) (Oliver, 1978)
Clicks (clusters), less frequently	0-30				Richardson *et al.* (1995) (Schevill *et al.*, 1963)
Clicks (isolated)					Richardson *et al.* (1995)
6 different call types (breeding period)	0.1-5	0.1-3			Richardson *et al.* (1995) (Asselin *et al.*, 1993)
Knocks	≤ 16	≤ 10			Richardson *et al.* (1995) (Asselin *et al.*, 1993)

A.3 Intentional anthropogenic noise sources

Information on several anthropogenic noise sources treated in Chapter 3 (air guns, acoustic deterrents, echo sounders, sub-bottom profilers) has been collected in the table below.

Table A.2. Anthropogenic noise sources (air guns, acoustic deterrents, echo sounders, sub-bottom profilers).

	Signal type	Frequency range [kHz]	Source level [dB re 1 µPa^{2}m^2]	Pulse duration [ms]	Beam width [deg]	Repetition time (inter-pulse interval) [s], or repetition rate [Hz]
Airgun and airgun arrays						
Large array[15]	3397 inch^3 = 0.056 m^3 = 56 litre array	0-0.2	254 (z-p)	5-10 ms (energy pulse rise-time for positive excursion near the source)	Radiation pattern is concentrated downwards	During normal operations, arrays are fired every 10-15 s
Large array[16]	2250 inch^3 = 0.037 m^3 = 37 litre (Western Geophysical) array of 24 airguns in three identical strings		255 (z-p) computed for a 1 ms sampling interval (500 Hz bandwidth)		Radiation pattern is concentrated downwards	
Large array[17]	> 10 litre	0.01 – 1	220 (p-p)	Few milliseconds	Apex angle: 90°	8-19 s

[15] Caldwell & Dragoset (2000); The detector placement is crucial: a position must be found where the detector is equidistant or nearly equidistant from all elements in the array
[16] www.westerngeco.com
[17] Impacts of Marine Acoustic Technology on the Antarctic Environment, SCAR, July 2002

	Signal type	Frequency range [kHz]	Source level [dB re 1 μPa^{2}m^2]	Pulse duration [ms]	Beam width [deg]	Repetition time (inter-pulse interval) [s], or repetition rate [Hz]
Small array	10 inch^3 = 0.16 litre		210-220 (p-p)		Radiation pattern is concentrated downwards	0.25-7 s
Acoustic deterrents[18]						
DRS-8[19]	Tonal 'known effect' reference sound	0.6 (tonal)		Signal duration: 300 ms	Omnidirectional beam pattern at 2 kHz	Signal interval: 4 s
High Impact Saver[20]	Digital, wide band	Double signal: 30 kHz and 30 – 160 kHz wide band sweeps, harmonics up to 180 kHz	155	200-900 ms randomized		4-16 s pseudo randomized
Long Line Saver	Digital, wide band	Single signal, 60 kHz wide band sweeps, harmonics up to 180 kHz	155	200-400 ms randomized		4-16 s pseudo randomized
Endurance Saver (targeted for harbour porpoise): North Sea	Digital, wide band	Single signal, 90 kHz wide band sweeps, harmonics up to 180 kHz	140	200-400 ms randomized		4-30 s pseudo randomized
AQUA mark 100[21] (targeted for harbour porpoise): North Sea	Digital, wide band/tonal	20-60 kHz, harmonics up to 160 kHz	145	200-300 ms		4-30 s pseudo randomized
AQUA mark 200 (targeted for dolphin): Mediterranean area	Digital, wide band/tonal	5-60 kHz, harmonics up to 160 kHz	145	200-300 ms		4-30 s pseudo randomized
AQUA mark 210 (targeted for dolphin where predation is severe):	Digital, wide band/tonal	5-60 kHz, harmonics up to 160 kHz	150	50-300 ms		4-30 s pseudo randomized

[18] Franse (2005); Kastelein *et al.* (2007); Incidental catches of small cetaceans, Report SEC (2002) 1134, STECF, Brussels (Table 3 on p. 26)
[19] www.oceanears.com/7550.html
[20] www.savewave.net
[21] www.subsea.org/company/listdetails.asp?companyid=206

	Signal type	**Frequency range [kHz]**	**Source level [dB re 1 µPa²m²]**	**Pulse duration [ms]**	**Beam width [deg]**	**Repetition time (inter-pulse interval) [s], or repetition rate [Hz]**
Mediterranean area						
AQUA mark 300	Digital, wide band/tonal	10 kHz	145	300 ms		4 s
FMDP-2000[22]	Digital, tonal	10 kHz ± 2 kHz	132 (± 4)	300 ms ± 15 ms		4 s ± 0.2 s
NetMark 1000 (for harbour porpoise)	Analogue, tonal	10 kHz	130-150	300 ms		4 s
Acoustic communication equipment[23]						
Source 1	Chirp (continuously varying frequency)	30, 50, 70 and 90 kHz	Up to 116 (± 3)	Signal block duration: 2 s		Signal block interval: 0.5 s; duty cycle: 80%
Source 2	Direct sequence spread spectrum (three different blocks)	26 kHz	123 (± 3)	Signal block duration: 1 s		Signal block interval: 0.7 s; duty cycle: 60%
Source 3	Modulated frequency shift keying (noise)	24 kHz	130 (± 3)	Signal block duration: continuous		Signal block interval: 0 s; duty cycle: 100%
Single beam echo sounders						
Kongsberg EA400[24]		33, 38, 50, 70, 120, 200, 210, 710		38 kHz: 4 ms; 50 kHz: 2 ms; 120-710 kHz: 1 ms	Depending on transducer, 2.8 (@ 710 kHz) – 21 (@ 38 kHz)	Ping rate: max. 20 per second
Kongsberg EA400 SP (portable, splash-proof version of the EA400)		38 to 710; optional: 33, 210		Likely to be similar to the EA400	Likely to be similar to the EA400	Up to 20 per second
Kongsberg EA600		12, 33, 38, 50, 70, 120, 200, 210, 710		Likely to be similar to the EA400	Likely to be similar to the EA400	Likely to be similar to the EA400
Kongsberg MS1000ES[25]		200, 675		TX pulse length: 20-1000 µs	200 kHz: 10° or 3°; 675 kHz: 2.5°	Up to 10 pings per second
BioSonics DT-X Digital Scientific Echosounder[26]		38, 70, 120, 200, 420		0.1-1.0 ms (user selectable)	Standard widths: 6° to 10° (@ –3 dB), other beams	0.01-30 pulses/second

[22] www.fumunda.com/how.php
[23] Kastelein *et al.* (2005)
[24] www.km.kongsberg.com
[25] Max. range: 400 m for 200 kHz, 150 m for 675 kHz
[26] www.biosonicsinc.com/echosounder-products

	Signal type	Frequency range [kHz]	Source level [dB re 1 µPa²m²]	Pulse duration [ms]	Beam width [deg]	Repetition time (inter-pulse interval) [s], or repetition rate [Hz]
(single and split beam)					available	
Fish finding echosounders						
Simrad ES60[27] (single/split beam)		12, 18, 27, 38, 50, 70, 120, 200				
Simrad SD 570		57	Single beam: 220; Omni: 214		Horizontal: 12°, 360°; Vertical: 12°	
BioSonics DT-X Digital Scientific Echosounder (single and split beam)		38, 70, 120, 200, 420		0.1-1.0 ms (user selectable)	Standard widths: 6°-10° (@ –3dB), other beams available	0.01-30 pulses / second
Sidescan beam echo sounders						
Kongsberg EA400 SP		120, 200				Up to 20 per second
Kongsberg EA400/600 sidescan option		120, 200			At 120 kHz: longitudinal 1.9°, transverse 55°; At 200 kHz: longitudinal 0.5°	
Kongsberg EM3002		300		150 µs	130° (single head); 200° (dual head)	40 pings per second
Sub-bottom profiler						
Geochirp II[28]		0.5-13	205 ± 3	32 ms	55° @ 3.5 kHz; 40° @ 5.0 kHz; 30° @ 7.0 kHz	Chirp sweep: max 4 per sec for 32 ms; pinger waveforms: 10 per second
Geopulse profiler T134[29]		3-7	16 transducer array: 225; 8 or 9 transducers: 220; 4 transducers: 214		4 transducers: 55° @ 3.5 kHz, 40° @ 5.0 kHz, 30° @ 7.0 kHz	1, 2, 4, 8, 16, or 32 cycles of the frequency selected

[27] Range min. 5 m, max. 5000 m; Single, dual or split beam; Variable sound velocity: 1400 to 1700 m/s; bottom expansion: 5 m to 7500 m
[28] www.geoacoustics.com/Specifications/GeoChirp_II.htm
[29] www.geoacoustics.com/Specifications/GeoPulse%20Profiler.htm

	Signal type	Frequency range [kHz]	Source level [dB re 1 µPa²m²]	Pulse duration [ms]	Beam width [deg]	Repetition time (inter-pulse interval) [s], or repetition rate [Hz]
Massa TR1075A[30]		2.5-10	201		80° conical beam angle	
Benthos SIS-3000[31]		2-7	203			
Innomar SES-2000Compact[32]		5-15	236	0.066-0.5 ms		Up to 30 per second depending on range

A.4 Unintentional anthropogenic noise sources

The available information on unintentional anthropogenic noise sources is limited, as is explained in Chapter 4. The table below summarizes the source levels of a number of broadband, continuous noise sources: shipping, dredging and drilling. In most cases, the frequency range for these sources is determined by the measurements and not necessarily related to the actual source frequencies. There is virtually no information about source directionality. Some information about source locations and about impulsive noise sources (explosions and pile driving) is given in Chapter 4.

Table A.3. Unintentional anthropogenic noise sources: shipping, dredging and drilling

Type	Average length [m]	Average speed [kn]	SL [dB re 1 µPa²m²]	Frequency [Hz]	Reference	Remarks
Oil / chemical tanker	180	12-15	182	71-141	Hatch *et al.* (2008)	
LNG tanker	246	10-14	182	71-141	Hatch *et al.* (2008)	
Cargo / container	205	13-17	179	71-141	Hatch *et al.* (2008)	
Tug	34	7-9	172	71-141	Hatch *et al.* (2008)	
Cruise ship	187	13-17	181	71-141	Hatch *et al.* (2008)	
Private yacht	38	8-13	162	71-141	Hatch *et al.* (2008)	
Research vessel	50	4-13	160	71-141	Hatch *et al.* (2008)	
Supertanker	266-340		180-190	7	Richardson *et al.* (1995)	Tonal noise
Supertanker	244-366	7.7-11.3	205	10-1000	NRC (Frisk *et al.*, 2003)	RANDI model
Large tanker	153-214	7.7-9.3	195	10-1000	NRC (Frisk *et al.*, 2003)	RANDI model
Tanker	122-153	6.2-8.2	188	10-1000	NRC (Frisk *et al.*, 2003)	RANDI model
Merchant	84-122	5.1-7.7	182	10-1000	NRC (Frisk *et al.*, 2003)	RANDI model
Fisher	15-46	3.6-5.1	160	10-1000	NRC (Frisk *et al.*, 2003)	RANDI model

[30] Ainslie (2008), Ch. 10; www.massa.com/underwater_comericaloceanographic.htm
[31] www.benthos.com/seafloor-bottom-mapping-survey-sonar-sis-3000.asp
[32] www.innomar.com/produ_2000compact.html

Type	Average length [m]	Average speed [kn]	SL [dB re 1 μPa^{2}m^2]	Frequency [Hz]	Reference	Remarks
Cruise ships	188-260	10	175-185	10-40000	Kipple (2002) (Glacier Bay National Park)	
Cruise ship	230	19	195	10-40000	Kipple (2002) (Glacier Bay National Park)	One ship
Bulk carrier	173	8-16	178-192	10-40000	Arveson & Vendittis (2002)	*M/V Overseas Hariette*
Gravel carrier	219	0	157	31.5-2000	Carr *et al.* (2006)	*Peter R Cresswell*
Supertanker	N/A	N/A	187-232	Broadband	Fisher & Brown (2005)	Estimated
Freighters, bulk carriers, large tankers	N/A	N/A	185-200	Broadband	Fisher & Brown (2006)	Estimated
Tankers, merchant ships	N/A	N/A	155-190	Broadband	Fisher & Brown (2007)	Estimated
Medium-small motor-powered vessels	N/A	N/A	150-160	Broadband	Fisher & Brown (2008)	Estimated
Pipelay for deep water	N/A	0	179	10-2000	Sakhalin, Table 4.7	*Semac One*
Tug, anchor pull	N/A	0	184	10-10000	Sakhalin, Table 4.7	*Katun*
Tug, transiting	N/A		190	10-10000	Sakhalin, Table 4.7	*Katun*
Supply ship	N/A	Full	186	10-10000	Sakhalin, Table 4.7	*Neftegaz 22*
Pipelay barge	N/A	0	167	20-10000	Sakhalin, Table 4.7	*Castoro II*
Cutter Suction Dredger	N/A	0	183	31.5-10000	Sakhalin, Table 4.7	*JFJ de Nul*
Support vessel, discharging spoil	N/A	0	184	20-10000	Sakhalin, Table 4.7	*Pompei*
Tug, transiting	N/A	N/A	192	31.5-10000	Sakhalin, Table 4.7	*Fujisan Maru*
Support vessel, transiting	N/A	Full	180	20-10000	Sakhalin, Table 4.7	*DN43*
Trailing Suction Hopper Dredger	N/A	0	188	10-10000	Sakhalin, Table 4.7	*Gerardus Mercator*
Trailing Suction Hopper Dredger	N/A	0	180	10-10000	Sakhalin, Table 4.7	*Tacola*
Survey vessel, transiting	N/A	N/A	191	20-10000	Sakhalin, Table 4.7	*Setouchi Surveyor*
Dredging	N/A	0	186	20-500	Richardson *et al.* (1995)	*Aquarius*
Dredging	N/A	0	172	20-500	Richardson *et al.* (1995)	*Beaver Mackenzie*
Drilling unit	N/A	0	174	20-1000	Richardson *et al.* (1995)	*Kullul Conical*
Drillship	N/A	0	186	20-10000	Richardson *et al.* (1995)	*Explorer II*
Fishery research vessels	N/A	11	163	10-100000	Mitson (1995)	ICES 209 requirement

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