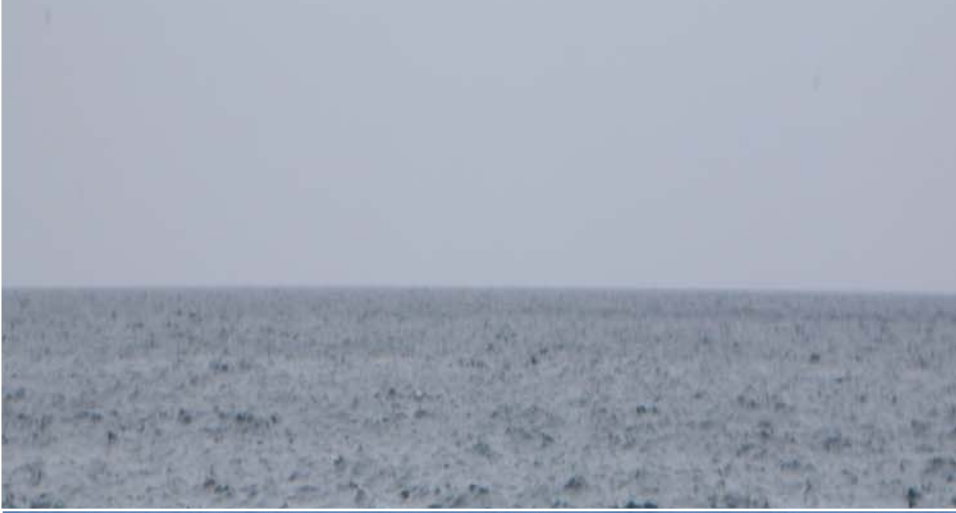
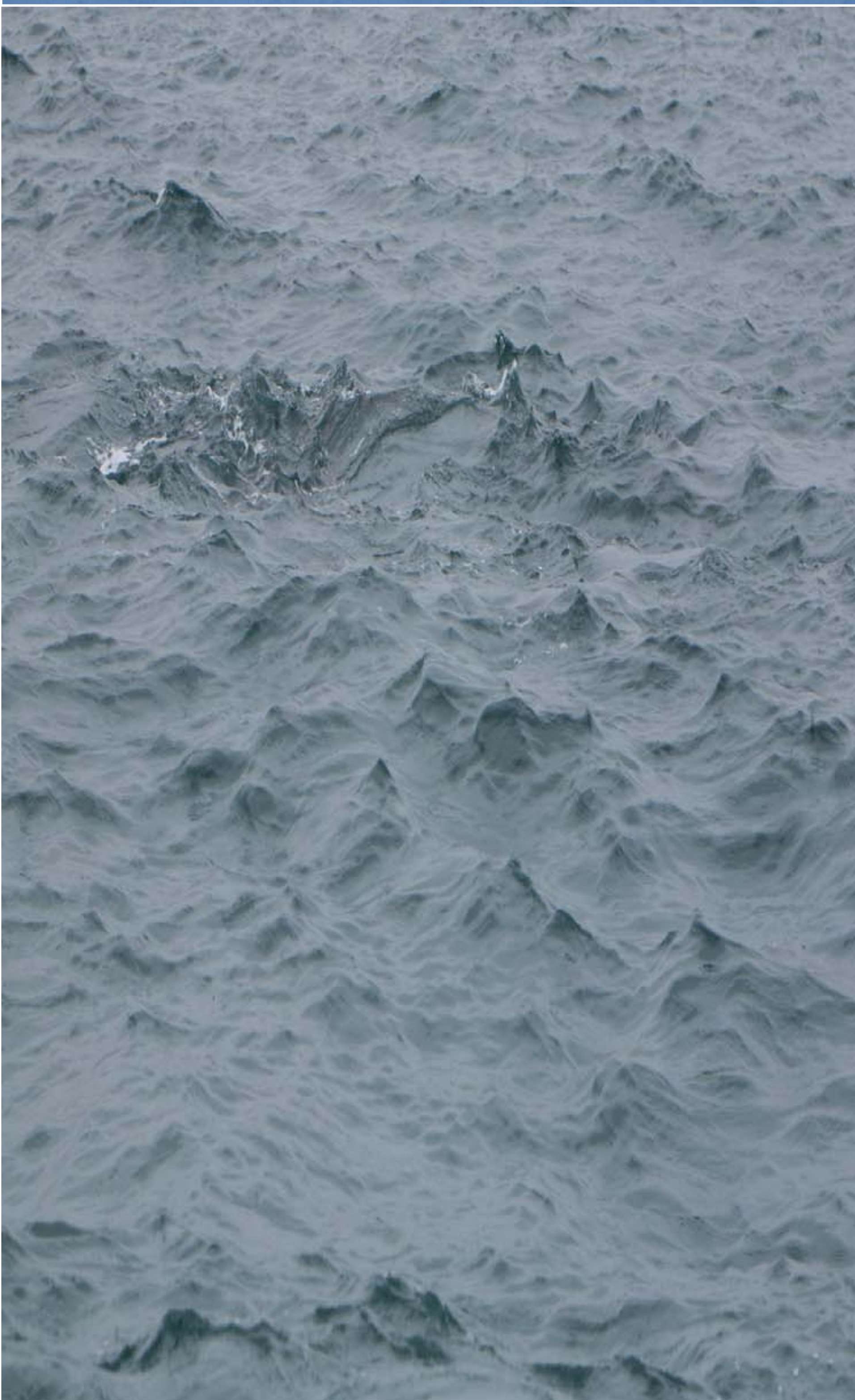


2008

Joint Industry Programme on Sound and Marine Life Review of Existing Data on Underwater Sounds Produced by the Oil and Gas Industry

Issue 1



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August 2008

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Joint Industry Programme on Sound and Marine Life

Review of Existing Data on Underwater Sounds Produced by the Oil and Gas Industry

Issue 1

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Executive Summary

During the exploration, development, production and decommissioning phases of offshore oil and gas reserves these activities contribute to the noise levels in the oceans, estuaries and rivers of the world. The purpose of this report is to catalogue and assess the available data that characterise the underwater sounds made by the oil and gas industries in all phases of their activities.

Measurements of underwater sounds are scarce. Given the volume of traffic and industrial activity in, on or by the shores of the oceans it is surprising that so little is known of the likely impact man made noise may have within the oceans.

Measurements made over the last 40 years at a site off the southern Californian coast show a general increase in low frequency noise in the ocean with time. The increase in this noise level has been widely attributed to increases in shipping and other anthropogenous (human made) noise (this is often termed anthropogenic noise). The significant amount of shipping and other activities attributable to oil and gas industries contributes to this rise in the total background noise in the ocean. In some areas, ocean noise background levels have doubled every decade for the last six decades mainly due to the increase in shipping. (McDonald, Hilderbrand et al. 2006)

Few measurements have been made on underwater noise sources, and those that have been made are often limited in their scope due to vessel time, operational and weather constraints. Comparison between measurements by different observers can be difficult due to the vast range of ever changing conditions encountered in the ocean seabed, and sea-surface. Many metrics can be used to describe the acoustic properties of a sound source with little standardization between experiments.

Local conditions (geographic, geological, oceanographic and meteorological) all have a very substantial impact on the way in which sound propagates from a source through the water to a measurement receiver. As the receiver is often a considerable distance from the source it is usually necessary to measure many other parameters in order to attempt to determine the true nature of the source itself.

This report reviews the available data on noise in the oceans produced by the oil and gas industries however; due to the scarcity of data in some areas other noise sources are included in some sections for comparative purposes.

The noise levels are presented as the measured values by the researcher and then in an extrapolated form in a consistent set of units. To do this extrapolation a number of assumptions have been made particularly relating to the local conditions under which the measurements were determined and the nature of the source signal.

The extrapolated values should be used as guidelines only as the variability of the transmission of sound and the nature of the sound source itself cannot enable an accurate translation between the remotely measured values and the extrapolated (back projected) values.

Contents

1. Introduction

"Human activities are increasing the level of sound in the oceans, causing widespread concern about the effect on marine mammals and marine ecosystems".

A report to congress from the Marine Mammal Commission, March 2007 (MMC 2007)

1.1 Background

Identifying the characteristics of anthropogenic noise sources was identified as a priority in the report of the International Workshop: Policy on Sound and Marine Mammals (Vos and Reeves 2005) and has been identified by the Oil and Gas Producers association (OGP) as an area of concern.

During exploration, development, production and the decommissioning phases of offshore oil and gas reserves the oil and gas industries contribute to the noise levels in the oceans, estuaries and rivers of the world. This noise contributes to the background noise of the oceans as well as causing local disturbance.

In general, sounds in the oceans originate from natural causes such as earthquakes, rainfall, and animal noises and anthropogenic activities such as shipping, seismic surveys, research activities and sonars.

The ambient noise in the ocean over the frequency band 20Hz to 300Hz is generally dominated by distant shipping noise (Urick 1967) (graph section 7.6). There is evidence to show that low frequency noise has increased at a rate of approximately 3dB per decade in the period from 1950 to 1998 (McDonald, Hilderbrand et al. 2006). This noise is thought to be primarily due to the increase in propeller driven vessels caused by the growing world economy. A simple relationship can be shown between the increase in gross domestic product and the increase in low frequency ocean noise (Frisk).

It has been suggested that a significant proportion of this noise is due to the activities of the oil and gas industries, which account for nearly 50% of the gross tonnage although being only 19% of the total number of vessels in the world's commercial fleet. (McDonald, Hilderbrand et al. 2006).

Whilst the evidence is that large vessels contribute to total ocean noise, small vessels and other sound sources, although not contributing to the global ocean acoustic environment, may be important localised sound sources.

1.2 Outline of review

This review assesses and tabulates the available information on underwater noise generated by the oil and gas industry. The review also includes sources of technical information and environmental review documents of relevance to the underwater sound produced by the oil and gas industries.

It is assumed that the reader has a general knowledge of oil industry activities however a useful review of the oil and gas industry and processes is given in the DTI document "An Overview of Offshore Oil and Gas Exploration and Production Activities" (DTI 2006).

The complex nature of underwater measurements makes the interpretation of published results complex. In this review only papers describing full details of measurements are considered. Secondary sources and grey literature have not been included except where scarcity of information or other details of the measurements are of importance. This has been the case in considering aircraft and helicopter noise where little published information on the underwater noise characteristics of current aircraft in use is available.

All the documents are indexed separately in a database format. For copyright reasons not all of these papers are available electronically.

The report is designed to be easily understood, and the tables are structured in groups of common activities. To facilitate the use of different measurement systems (FPS, SI, cgs, etc) conversion tables for the most common units are given in Appendix B. The units used in the report are those the most commonly used within the oil industry.

Some vessel names have been omitted from the report due to the commercial sensitivity of measurements and possible changes in the vessels performance.

1.3 General notes on underwater acoustics

Sound waves spread, dissipate and reflect from the sea surface and sea bed as they travel through the ocean away from their source. The characteristics of the received sounds depend not only on the characteristics of the source but also on the distance between source and receiver and the nature of the environment between them. Thus the received level of the source at a point in the water column is dependent on a large number of variables, such as water depth, source and receiver depths, temperature gradients, sea bed and sea surface properties, salinity and many others.

Not all sounds move through the ocean in the same way, high frequency sounds generally attenuate more quickly than low frequency sounds: a 100 Hz sound may be detectable after travelling hundreds or even thousands of kilometres, whereas a 100 kHz sound may travel for only a few kilometres, (MMC 2007). Typical attenuation characteristics of seawater are given in Appendix B figure 5. The oceans can form wave guides carrying sounds large distances and also form filters removing frequency components from the source signal. The detailed knowledge of the local conditions under which the measurements have been made is therefore very important for understanding the nature of the source.

In order to standardise underwater source measurements, source levels are normally quoted as if measured at 1 metre from the source. In most cases this is a theoretical point and in practice rarely can a measurement at 1m from the source be made (for example a super tanker propulsion system and hull may be hundreds of metres in length and therefore forms a very large distributed source). In order to determine the nature of the source as if measured at 1m then the receiver often needs to be a significant distance from the source and hence the nature of the changes made to the sound in its transit from source to receiver need to be understood. The number and type of variables in the ocean means that received sound levels will vary from the same source in different areas of water and hence a detailed survey of an area is required before any detailed and accurate modelling of the propagation and a detailed description of the acoustic properties of the source can be achieved (Hazelwood 2005). Generally detailed measurements of the ocean parameters cannot be made and hence simplified laws of sound spreading are applied to derive an approximation of the source nature and level. In a few cases detailed modelled results are available and these are quoted in the text.

1.4 Report structure

The report is aimed at giving a quick reference guide to sources of underwater sounds made by the oil and gas industry and the references to their detailed measurements. The report also includes tables of references related to underwater noise in general. Where available, third octave spectrum levels have been given in addition to the tabulated source level information. In some cases where detailed measurements and modelling of the environment have been made details on individual vessels have been given (courtesy of JASCO).

Section 2. The interpretation of reported measurements is complex and a number of assumptions need to be made when extrapolating the data into common units. This section outlines the methodology used in the constructing the tables.

It should be noted that there are many variables associated with the characteristics of underwater sound and there is much debate over which units and characteristics should be used to define an underwater sound. Where available a number of metrics have been quoted for the same noise source.

Section 3. Information is given on the nature of oil and gas industry underwater sounds and a review of the information available. In some cases the structure of the noise source is considered and methods for practical approximation of noise levels are given. The section gives a review of oil industry noise in a tabulated form for each group of noise types from published sources and gives some additional data from the grey literature where published information is lacking.

Section 4. Considers other sounds in the oceans and tabulates both man made noise and natural noise sources.

Section 5. The bio-acoustic impact of underwater sound has been the subject of many reports, papers and books notably Marine Mammals and Noise (Richardson, Greene et al. 1995) which gives considerable information on noise sources and their potential impact on marine mammals. Many reports consider the detail of particular industrial effects and a number of reports outline concerns regarding the overall impact of sound on the underwater environment typically (IFAW 2004). A summary of these reports and reference works is given in this section 5.

Appendix A. This gives definitions of the metrics used within the report and other common terms used in descriptions of underwater acoustics

Appendix B. Provides conversion tables to assist in interpretation of the tabulated data and information on sea water characteristics and noise levels

Section 6. Is the reference list of cited papers used in the report which is also available as a searchable database.

2. Notes on the use of the tables

2.1 Units.

The units used in the tables are those in common usage by the oil industry, these being typically a mixture of FPS and SI system, most publications report air gun capacities in cubic inches speed of vessels in knots and water depth in metres. Conversion tables to standard SI units are given in Appendix A.

Where reported, Sound Pressure Level (S.P.L.) is taken to mean the rms value of a continuous sound, quoted in dB re 1µPa. Where this is quoted for a pulse, the duration of the averaging of the pulse is stated when known.

There are many variables that can be used to define an underwater sound however most papers report basic parameters only. There is much debate over which units and characteristics should be used to define an underwater sound. This report, by necessity, takes a simplistic view as insufficient information is available to present consistent detailed information.

2.2 Measured Values

These values are the actual measurement values made in the field or extrapolated back to a 1m reference by the experimenters using measured values of sound spreading and absorption for the area in which the experiment was performed. Where multiple measurements have been made, the measurement generally the closest to the source has been quoted as this is likely to have the least errors associated with sound propagation. Where multiple hydrophones at different depths have been used either all data is presented or the higher value has been stated.

Where available the source levels for manufactured items or modelled values are given in the foot notes. There is often a considerable difference between the modelled values or the manufactures quoted value and the measured values. The reasons for this may be many including:

- Directionality of source in the vertical and horizontal planes (in particular air gun arrays)
- Sea-bed and sea-surface interactions at measurement position
- Absorption characteristics of seawater
- The depth of the receiver (McCauley, Fewtrell et al. 2000)
- Errors associated with the calculation of the transmission characteristics of the water between source and receiver

2.3 Extrapolated source values.

Authors of papers use many different metrics to describe the sound source level received at their measurement positions. These measurements are often described such that comparisons between different measurements cannot be readily made. The extrapolated values in the tables in section 3 are based on a back projection to the source using transmission coefficients either stated within the reviewed paper or typical of the water depths and conditions. This back projection inevitably has an associated error due to the local water transmission properties. These errors may be significant.

The details of the extrapolation methods used are given in Appendix A. In some cases where the nature of the source or the locality would lead to considerable uncertainty in the back projection calculation, the calculation has been omitted and only the measured results presented.

The broad band peak to peak level in MPa at 1m has been chosen as the standard reference as the majority of available information can be reasonably interpreted into these units. Where other information on the sound is available these are included in the tables as footnotes or included as separate charts.

2.4 Source values at one metre

It is common practice to quote source levels at one metre. Many of the sources described are large distributed sources but are described as though the sound source was located at one point, this gives a source value which may be considerably higher than any individual point measured in the near field but represents the addition of the distributed sources of sound when measured in the far field. In the case of a seismic sound source, an air gun array, the source level at 1m may be quoted as 250dB peak to peak re 1μPa at 1m as a theoretical value however as the sound source is spread over a large area at no point will the pressure exceed 235dB peak to peak, (Gausland 2000).

2.5 Water depth

Water depth plays a critical role in the transmission of sound, allowing in deep water, the formation of a sound duct carrying low frequency signals long distances and in shallow water forming a low frequency cut off filter. The depth of water can thus significantly modify the received source signal and is an important factor in the analysis of measurements.

Where water depth has been quoted it is the mean water depth of high and low tide or the depth stated by the paper author which is assumed to be the average water depth for the measurement area. Comments are made for any particular geographic circumstance.

2.6 Classification

Some non oil industry sounds have been included for comparison purposes or where the scarcity of information requires some further detail to typify the noise source
The noise sources have been classified as follows;

Other useful literature

2.7 One Third Octave level

One third octave band measurements are used to represent the hearing ability of the mammalian ear. It can be defined as the frequency band whose upper limit is $2^{1/3}$ (1.26) times the lower limit; bandwidth is proportional to centre frequency. Three adjacent one third octave bands span are octave. Where available one third octave band measurements are presented in the report.

3 Oil Industry Noise Sources and Tables of Measurements

3.1 Aircraft

Little published primary source information is available for underwater noise produced by overflying aircraft, fixed or rotary wing, associated with current oil and gas industry activities. As such measurements have been included from all data found for aircraft including references from Marine Mammals and Noise (Richardson, Greene et al. 1995) where estimated source levels are presented for fixed wing and rotary wing aircraft.

The sound absorption in air is very dependent upon frequency and relative humidity and hence local air conditions will contribute significantly to the sound transferred into the water column. Appendix B Figure 2.6 shows the dependence of sound transmission through air on relative humidity and frequency. Low frequencies are transmitted well in air with typical attenuation values of 4dB/km at 1 kHz and 130dB/km at 10 kHz (Efroymson, Rose et al. 2000).

Sound from an airborne source is generally reflected from the water surface except for a cone of sound with a half angle of 13 degrees from the vertical. Much of the sound energy is reflected from the surface but sound pressure doubles as it transfers through the air to water interface. As the aircraft height increases the base area of the cone increases and the sound pressure level arriving at the water surface decreases. The zone of effect of an aircraft passing over an area of water induces sound into a strip of water the dimensions of which are proportional to the aircrafts height. Wave motion will add a variable which will extend the strips width. However for low frequency noise, generally, the sound wavelength is large compared to the wave height such that the water appears as a smooth surface, (Richardson 2006). See notes in Appendix A on acoustic impedance section 1.

Ice does not appreciably attenuate aircraft sounds at frequencies below 500 Hz (Efroymson, Rose et al. 2000).

Underwater sound caused by an overhead airborne source will be highest at the surface and decrease with depth. This seems also true for hovercraft (Richardson 2006). There is evidence that when the aircraft is not directly overhead sound levels may be higher at mid depths rather than close to the surface (Richardson, Greene et al. 1995).

At medium to long ranges the bottom reflection will be the dominant path by which an airborne source will reach a shallow hydrophone; this greatly extends the duration of the sound of the aircraft over a receiver in shallow water (Urick 1972).

The standard of altitude measurement for aircraft noise measurement in air is 300 m and Richardson suggests that this should be considered as the measurement altitude for the effect of aircraft generating underwater noise, however due to the few underwater measurements available and their lack of altitude information no standard seems to be applicable. In the study of helicopter noise for the proposed Lamma Island Heliport, BMT normalise their helicopter measurements to 150m. This may be a more meaningful altitude for helicopter measurements although too low for aircraft. A considerable amount of literature is available on the in air measurements of aircraft noise, in the absence of measured underwater data it is possible to estimate from the in air measurements the likely levels of underwater noise (see note in section 3.1.4).

3.1.1 Aircraft noise

Rotary turbines are likely to create sounds characterised by tones from several hundred Hz to above 1 kHz (Richardson, Greene et al. 1995) which are the fundamental and harmonics of the engine and proportional to the rotation speed and the number of blades on the turbine.

$$f = B * RPM / 60 \qquad (3.1)$$

Where f is the fundamental frequency Hz

B is the number of blades

RPM the revolutions per minute of the turbine

The other major sources of noise are propellers or rotors, these also produce fundamentals and harmonics in accordance with formula (3.1) however the tones are usually below 500Hz (Richardson, Greene et al. 1995). In general, for reciprocating engine driven propeller aircraft a number of tones will be present relating to engine speed and propeller or rotor speed. The absence of rotary components in jet aircraft leads to a broadband noise extending to 5 kHz and higher, (Blackwell and C.R.Greene 2002).

3.1.2 Fixed Wing

The contribution of noise from fixed wing aircraft to the underwater noise generated by oil industry cannot easily be quantified but the contribution is most likely generated by the increased movement of transport planes or personnel into coastal airstrips. In general aircraft generate more noise on take off than cruising or landing. (Richardson 1995)

Few measurements are available for relevant aircraft however all details of measurements made on fixed wing aircraft available are presented in table 3.1.1 Not all the information available indicates the height of the aircraft above sea level however the comparison between the in air measurement and the underwater measurement is of interest and has been used to show a simplistic relationship between in air and in water measurements.

3.1.3 Rotary Wing

From 1976 up to year-end 2002, just over 48 million passengers were transported to and from offshore installations on the UKCS (UK Continental Shelf). Over 6 million sectors were flown taking about 2.7 million flying hours. In 2002 some 160,000 sectors were flown transporting over 1.5 million passengers offshore, and sector flight times averaged just over 30 minutes (UK HSE 2002). Given this level of activity it is surprising that few measurements have been made of the underwater noise generated by helicopters.

Helicopter noise tends to have a pulsating quality caused by the blade passing frequencies of the rotors. Under certain conditions, this can become pronounced and is termed ‘blade slap’.

The forward motion of a helicopter in normal flight results in variations of blade speed through the air during each rotation formed by a combination of the forward speed of the aircraft and the rotation of the blade. This variation of blade speed through the air results in complex noise propagation. This effect applies to both the main and tail rotor. There is also an interaction between noise produced by main and tail rotors.

The main contribution of helicopters to underwater noise is likely to be on the approach to and take off from platforms or large vessels with helicopter pads. Again information is sparse however (Richardson 1995) gives some information on helicopter noise which is given in table 3.1.2.

The data available does not reflect current helicopters in use by the oil industry (table 3.1.3) however some information is available on in air noise levels from current helicopters making an assessment of the underwater noise impact possible but speculative. Table 3.1.4 gives a list of in air measurements of two helicopters measured near Hong Kong International Airport on a concrete helipad.

Table 3.1.1 Fixed Wing Aircraft

Aircraft detail	In air measurement[1 2] dBA Reference Unit = 20 mPa	In air measurement bandwidth Hz	Underwater [3]measurement broadband dB re 1 µPa rms	Underwater measurement bandwidth Hz	Aircraft Position[4]	Tones	Reference
F-15	95	20 to 18000	134	4 to 20000	Overhead (90 degrees)		(Blackwell and C.R.Greene 2002)
Boeing 737	84	20 to 18000	110	4 to 20000	45 Degrees		(Blackwell and C.R.Greene 2002)
Boeing 747	95	20 to 18000	123	4 to 20000	60 Degrees		(Blackwell and C.R.Greene 2002)
C-5		20 to 18000	111	4 to 20000	70 Degrees		(Blackwell and C.R.Greene 2002)
DC-6	86	20 to 18000	119	4 to 20000	25 Degrees		(Blackwell and C.R.Greene 2002)
DC-10	84	20 to 18000	124	4 to 20000	Overhead (90 degrees)		(Blackwell and C.R.Greene 2002)
B-N Islander			142 dB re 1 µPa rms m measurement details unknown		Altitude 152m	Propeller 68 -74 Hz Piston engine 102 Hz	(Richardson, Greene et al. 1995)
Twin Otter			147 dB re 1 µPa rms m measurement details unknown		Altitude 457 m	Propeller 82-84 Hz	(Richardson, Greene et al. 1995)
P-3 Orion			162 dB re 1 µPa rms m	50 to 5000	Altitude 76 m	Propeller 68 Hz	(Urick 1972)
Grumman Turbo Goose						Propeller 68 Hz	(Richardson 1995)

[1] Measured at 1.5 to 2m above water surface
[2] A weighted dB re 20 µPa

Table 3.1.2 Rotary wing aircraft

Aircraft detail	In air measurement dBA	In air measurement bandwidth Hz	Underwater measurement broadband dB re 1 μPa rms	Underwater measurement bandwidth Hz	Aircraft Position	Tones Hz	Reference
Bell 212			149 dB re 1 μPa rms m		Altitude 152 m	10.8 + harmonics	(Richardson 1995)
Bell 214 ST						11.8 + harmonics	(Richardson 1995)
Sikorsky 61						68 and 102	(Richardson 1995)

[3] Hydrophone depth of 10 or 6m
[4] Angle relative to the horizon, 90 degrees being overhead.

Table 3.1.3 Helicopters in service in 2002. Source (UK HSE 2002)

TYPE	WEIGHT CLASS	INTRODUCED	WITHDRAWN
Bell 212	Medium	Pre 1975	2000
Bell 214 ST	Heavy	1982	Still in Service
Boeing BV234 (Chinook)	Extra Heavy	1980	1989
Eurocopter B105	Light	1977	2001
Eurocopter AS330 (Puma)	Medium	1977	1985
Eurocopter AS332 (Super Puma)	Heavy	1982	Still in Service
Eurocopter AS365 (Dauphin)	Medium	1979	Still in Service
Sikorsky S58	Medium	Pre 1975	1980
Sikorsky S61	Heavy	Pre 1975	Still in Service
Sikorsky S76	Medium	1980	Still in Service
Westland 30	Medium	1982	1991
Westland Wessex 60	Medium	1975	1981

Table 3.1.4 In air helicopter noise

Aircraft Type	Operation	Maximum values in air Normalised to 150m Lmax dB(A)[5]	Reference
EC155 B1	On ground idling	80	(BMT 2005)
	Hovering	86.3	(BMT 2005)
	Touch down	80.2	(BMT 2005)
	Lift off	87.7	(BMT 2005)
Super Puma AS332 L2	On ground idling	82	(BMT 2005)
	Hovering	90.6	(BMT 2005)
	Touch down	Not available	(BMT 2005)
	Lift off	89	(BMT 2005)

The frequency analysis of the helicopter underwater noise show apparently harmonically related components however due to the complex and unsteady interaction of the rotor blade vortices frequency characteristics rapidly change with time. (Dwyer 1984)

From table 3.1.1 it can be seen that typically, the noise level in water (dB re 1 μPa broad band) is approximately 33 dB +/-7dB above the level measured in air (dB (A) re 20 μPa). This is close to the theoretical value of 32dB which is:

6dB at air to water interface + 26 dB change in reference level (20 μPa to 1 μPa) = 32 dB

This only applies for a limited frequency range due to the A weighting scale of the in air measurements, which attenuates sound at frequencies <1 kHz. A-weighting emphasizes sounds at frequencies between 1 and 6 kHz, further affecting the comparison.

3.2 Construction

This topic covers the following areas; pile driving, trenching, rock placement, tugs, pipe-laying and diving support. Shore based construction work has few measurements, these are considered in section 3.8 (Sites).

As the construction activities often directly interact with the seabed and geological structures, sound is often transmitted directly through the seabed and can be identified as a separate pressure wave arriving before the water borne noise.

The majority of information on construction activities relate to pile driving in a wide range of environments and with many types of pile. Different piles driven by different methods into a variable sea bed give rise to a wide range of results, in general the larger the diameter of the pile

[5] Measurements were made above a hard concrete surface

the higher the noise level produced, see figure 3.2.3. Two main types of pile driving are reported, impact and vibratory although others exist, limited measurements are available.

3.2.1 Impact pile driving

Impact pile driving has three sub categories; drop weight, diesel, and hydraulic.

a) Drop Weight, a mass with approximately the weight of the pile is raised a suitable height and released to strike the pile head which may be cushioned.
b) Diesel, the diesel hammer employs a ram which is raised by explosion of injected diesel in the base of the ram cylinder, just as in a diesel engine.
c) Hydraulic, a hydraulic ram is used to increase the effect of the drop weight.

The noise generated by impact pile driving extends in frequency from 10 Hz to 120kHz (McHugh, McLaren et al. 2005). The noise from the pile driver may vary by as much as 18dB at 2000m from the source depending upon the sea-bed conditions (Maxon and Nielsen 2000). The rms values seem constant with depth (water depth 95m) however peak values vary with depth (McHugh, McLaren et al. 2005). Pulse duration is related to, and increases with distance from the pile (Blackwell, Greene et al. 2004). Figure 3.1 shows an impact pile driver being prepared for operation in Milford Haven.

It should be noted that the pressures associated with pile driving can be both positive and negative, for example a peak positive pressure of 130 kPa can be associated with negative pressures of -85kPa (measured ar 1m). (Vagle 2003)

Figure 3.1 Impact pile driver being prepared to be placed onto pile

A summary of measured underwater sound levels near marine pile driving for activities in the USA is given in table 3.2.1 (Hastings and A.N.Popper 2005) and a review of published papers is given in table 3.2.2. The impact pile driving table is arranged in order of ascending pile diameter.

3.2.2 Vibratory pile driving

A vibratory pile driver is usually hydraulically powered although some electrically driven units are available. The majority of vibrators operate at frequencies between 20 and 40 Hz and can generate centrifugal forces of up to 4 000 kN.

The driving unit consists of contra-rotating eccentric masses which are in a housing attached to the pile head. These devices are used for normal circular piles as well as sheet steel piles. The intensity of ground vibrations which can occur under unfavourable conditions when using incorrect driving procedures or inappropriate equipment, can be a limiting factor. A summary of the information available is given in table 3.2.3. Figure 3.2 shows vibratory pile driving in progress in shallow water in Milford Haven.

Figure 3.2 Vibratory pile driving in progress

3.2.3 Mitigation of pile driving activities

As with all forms of waterborne activity there is a possibility that tones will be present from depth sounders or underwater instrumentation associated with vessels operating in the area. (see section 3.9)

The use of bubble curtains reduces the sound level transmitted through the water column (Wursig, Greene et al. 1999). These have been evaluated showing that the largest reduction in sounds (8 to 20 dB) were over the range 400 to 6400 Hz (David 2006) although mixed results were obtained by (Vagle 2003), suggesting that the use of bubble curtains is uncertain. Marine mammal observers and passive acoustic monitoring may be required for mitigation before and during the pile driving activity

3.2.4 Other construction activities

Data for other construction activities is scarce, however table 3.3.4 gives some information on trenching, rock laying, pipe-laying and tug activity associated with crane manoeuvring. In general, the noise associated with thrusters used for manoeuvring vessels or machinery are the most significant levels of noise (Blackwell and Greene 2005). Section 3.6 considers thruster noise levels in detail

Table 3.2.1 Construction: Various Impact Pile Driving Measurements

Summary of Measured Underwater Sound Levels Near Marine Pile Driving (Hastings and A.N.Popper 2005)

Pile Type	Distance from Pile (m)	Peak Pressure (dB re 1 μPa)	RMS (impulse) Pressure (dB re 1 μPa)	SEL (dB re 1 μPa2-s)	Extrapolated Peak to peak (dB re 1 μPa)
- Various Projects					
Timber (12-in) Drop	10	177	165	157	203
CISS[6] (12-in) Drop	10	177	165	152	203
Concrete (24-in) Impact (diesel)	10	188	176	166	214
Steel H-Type Impact (diesel)	10	190	175	-	
CISS (12-in) Impact (diesel)	10	190	180	165	216
CISS (24-in) Impact (diesel)	10	203	190	178	229
CISS (30-in) Impact (diesel)	10	208	192	180	234
- Richmond-San Rafael Bridge					
CISS (66-in) Impact (diesel)	4	219	202	-	237
CISS (66-in) Impact (diesel)	10	210	195	-	236
CISS (66-in) Impact (diesel)	20	204	189	-	236
- Benicia-Martinez Bridge					
CISS (96-in) Impact Hydraulic)	5	227	215	201	247
CISS (96-in) Impact (Hydraulic)	10	220	205	194	246
CISS (96-in) Impact (Hydraulic)	20	214	203	190	246
- SFOBB East Span[7]					

[6] CISS is Cast In Steel Shell pile.

[7] SFOBB is San Francisco-Oakland bay Bridge

CISS (96-in) Impact (Hydraulic)	25	212	198	188	246
CISS (96-in) Impact (Hydraulic)	50	212	197	188	252
CISS (96-in) Impact (Hydraulic)	100	204	192	180	250

3.2.2 Construction: Impact Pile Driving

Source Type	**Type**	**Size**	**Repetition rate** Blows/sec	**Water depth m**	**Measurement**	**Measurement Bandwidth** kHz	**Extrapolation**[8] dB re 1 μPa m peak to peak	**Characteristic**	**Reference**
Pile driving Impact	Hammer	0.75m diameter steel 22m long	0.38	95	153db rms @ 0.535 km 168dB peak @ 0.535 km	? to 100	216[9]	Mean pulse duration 200ms[10] Duty cycle 7.83%	(McHugh, McLaren et al. 2005)
Pile driving Impact	Hammer (Menck MHU500T)	4m diameter steel wall thickness 35mm length 50m	0.55	9	262 dB re 1 μPa m Peak to peak	0.01 to 150	262	Pulse duration est. at 300ms at 1881m Tonal content prob. due to ringing of pile. Most of energy is between 40Hz and 1 kHz	(Nedwell, Turnpenny et al. 2003)
Pile driving Impact				5	204 dB re 1 μPa Peak @ 30m	0.001 to 20	236		(Maxon and Nielsen 2000)
Pile Driving Impact	Hammer			180	246 dB re 1 μPa Source level		255		(Nedwell and Edwards 2004)
Pile driving Impact	Hammer 1000kJ	2.4m diameter steel			240 dB re1 μPa Source level		249		(Nedwell and Edwards 2004)
Pile driving Impact	Hammer 1000 kg Drop 4m (max) 80kJ	0.2m diameter cedar	0.2	2	32000 Pa peak to peak @ 1m	0.050 to 22.050	210		(Vagle 2003)
Pile driving Impact	Hammer 1000 kg Drop 4m (max) 80 kJ	0.2m diameter steel 4.7 mm thickness	0.2	2	31000 Pa peak to peak @ 1m	0.050 to 22.050	210		(Vagle 2003)
Pile driving Impact	Hammer 1000 kg Drop 4m, 80 kJ	0.3m diameter steel		3m to 15m down slope	32000 Pa peak to peak at 50 m	0.050 to 22.050	208		(Vagle 2003)
Source Type	**Type**	**Size**	**Repetition rate Blows/sec**	**Water depth m**	**Measurement**	**Measurement Bandwidth**	**Extrapolation**[11] **dB re 1 μPa m peak to peak**	**Characteristic**	**Reference**
Pile driving Impact	Hammer 7000 kg Drop 3m typical	0.508m diameter			79000 Pa peak to peak at 1m	0.050 to 22.050	217		(Vagle

	210 kJ typical								2003)
Pile driving Impact		1m diameter steel Closed end			250000Pa peak to peak		228	Pulsed	(Vagle 2003)
Pile Driving Impact	Hammer (Menck) Hydraulic Impact Hammer		0.33	Shallow river Tidal Water	192 dB re 1 µPa Peak Source level		198	Pulsed	(Nedwell and Edwards 2002)
Pile Driving Impact		2.5m dia 8mm thick 50m long	0.42	133	241 dB re 1 µPa positive peak at 1m	0.002 to 20	247	Pulsed	(Barbagelata 2004)
Pile driving Impact		4.7m diameter		10m	250 dB re 1 µPa peak to peak		250	Pulsed	(Parvin 2006; Parvin and Nedwell 2006)
Pile driving Impact	BSP357/9 Hydraulic drop hammer			Shallow water		0.005 to 120	194	Pulse	(Nedwell, Turnpenny et al. 2003)
Pile driving Impact	Driving steel sheets by land based equipment			Shallow water	136.1 dB re 1 µPa peak 124.7 dB re 1 µPa rms at 730m	0.02 to 10	172	Impulsive[12]	(Greene, Blackwell et al. 2007)
Pile Driving Impact		1.5m diameter	1	30	228 dB re 1 µPa 0 to peak	0.03 to 20	234	Pulsed Peaks at 125, 315 and 1000 Hz	(Thomsen, Ludemann et al. 2006)
Source Type	**Type**	**Size**	**Repetition rate Blows/sec**	**Water depth m**	**Measurement**	**Measurement Bandwidth kHz**	**Extrapolation[13] dB re 1 µPa m peak to peak**	**Characteristic**	**Reference**
Pile Driving Impact	DelMag D62-22 Diesel Driven hammer of 12930kg Energy per blow 224 kJ	0.51 diameter pipe	0.6 to 0.833	9	174.5 dB re 1 µPa 0 to peak @ 1m 171.7 dB re 1 µPa SPL @	0.04 to 10	180	Pulsed Peak Sound pressure between 20 and 40 Hz Falling at approx 40dB per decade	(Blackwell, Lawson et al. 2004)

					1m 170.1 dB re 1 µPa SEL @ 1m			Pulse duration related to distance	
Pile Driving Impact	DelMag D62-22 Diesel Driven hammer of 12930kg Energy per blow 224 kJ	1.07m diameter pipe	0.6 to 0.833	9	199.6dB re 1 µPa 0 to peak @ 1m 195.7 dB re 1 µPa SPL @ 1m 190dB re 1 µPa SEL @ 1m	0.04 to 10	206	Pulsed Peak Sound pressure between 20 and 40 Hz Falling at approx 40dB per decade Pulse duration related to distance	(Blackwell, Lawson et al. 2004)
Pile driving[14] hydraulic	Driving steel sheets by land based equipment			Shallow water	113 dB re 1 µPa rms at 1m average 127 dB re 1 µPa rms at 1m peak	0.02 to 150	122 Average 136 Peak		(Nedwell, Macneish et al. 2005)

Prediction of impact pile driving noise levels may be thought to depend upon size of the pile, energy with which the impact occurs and geological conditions. However by plotting the extrapolated values of the peak to peak sound pressure level at one metre and the pile diameter an approximate relationship can be seen (figure 3.3) which corresponds to the equation:

$$P = 230.25 * D^{0.0774} \quad (3.2)$$

Where P is peak to peak pressure in dB re 1mPa at 1m
D is the pile diameter in m

Whilst this approximation is not tested it appears to match the reported measurements reasonably well as shown in figure 3.3.

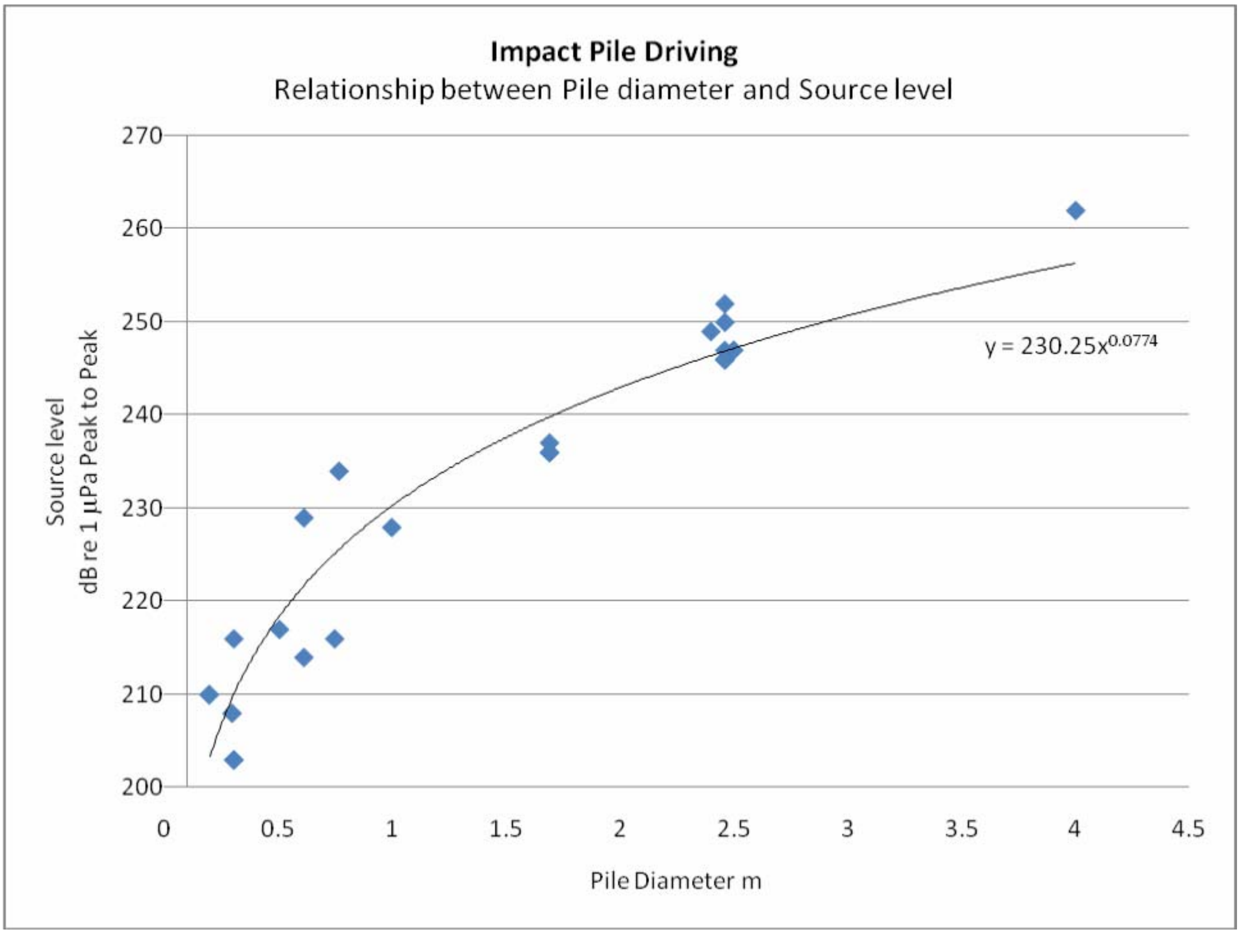


Figure 3.3. The relationship between pile diameter and peak to peak sound pressure level (x is the pile diameter in metres and y is the peak to peak sound pressure)

Table 3.2.3 Construction: Vibration Pile Driving.

Source Type	Type	Size	Vibration frequency	Water depth	Measurement	Measurement Bandwidth m	Extrapolation[15] dB re 1 μPa m peak to peak	Characteristic	Reference
Pile driving Vibration	PVE 2316 VM			Shallow water		0.005 to 20	Below noisy ambient conditions at 417m	Continuous	(Nedwell, Turnpenny et al. 2003)
Pile Driving Vibration	PTC 60 HD Vibro Driver		27 Hz	Shallow river Tidal Water	152dB re 1 μPa rms @24m		161[16]	Continuous Dominant frequency 27Hz, the vibratory frequency of the pile driver	(Nedwell and Edwards 2002)
Pile Driving Vibration	Driving steel sheets by land based equipment		24 Hz	12 m	143 dB re 1 μPa rms @ 100m		182	Continuous Tone at 24Hz	(Greene, Blackwell et al. 2007)

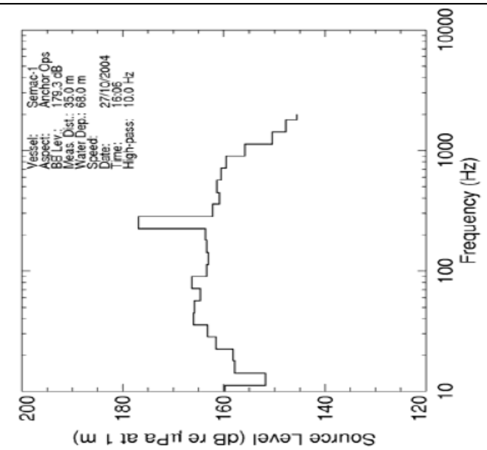
Insufficient data is available to draw any conclusions as to the relationship between pile size, geology, vibration levels and extrapolated sound levels.

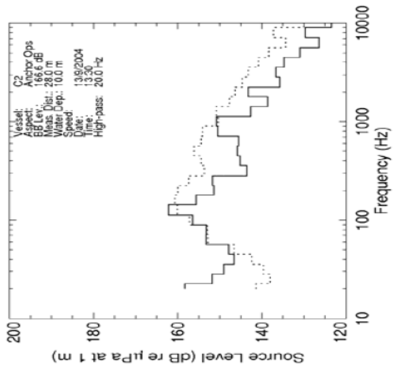
Table 3.2.4 Construction: other activities

Source Type	Type	Size	Activity	Water	Measurement	Measureme	Extrapolation[17]	Reference

				depth m		**nt Bandwidth kHz**	dB re 1 µPa m peak to peak	
Trenching (cable)				Very shallow	123 dB re 1 µPa SPL @ 160m	0.01 to 150	160	(Nedwell, Langworthy et al. 2003)
Rock Placement	Rock placement in 60 to 70 m			60 to 70	Measurement below ambient noise			(Nedwell and Edwards 2004)
Tugs	Manoeuvring Sealift barge			shallow	144dB dB re 1 µPa @ 60m[18]		170	(Richardson 2006)
Pipe laying	Pipe carrying ability of 15000 tons			Approx 30		0.001 to 100	Noise peaks at 200Hz probably thruster related	(Nedwell and Edwards 2004)
Pipe laying barge	Semi submersible	188m length 54.9m beam 12 anchor points each 22 tons	Winch pulling in AHT[19] Anchor Pull out Winching Forward Normal operations	68	182.2 dB rms re 1 µPa @ 1m Peak at 250 Hz during anchor manoeuvring 180.9 dB rms re 1 µPa @ 1m Peak at 250 Hz during anchor manoeuvring 174.2 dB rms re 1 µPa @ 1m 170.2 dB rms re µPa @ 1m	0.01 to 10	191 190 183 179	(Austin 2004) See figure 3.5
Source Type	**Type**	**Size**	**Activity**	**Water depth m**	**Measurement**	**Measurement Bandwidth kHz**	**Extrapolation[20] dB re 1 µPa m peak to peak**	**Reference**
Pipe Lay Vessel	Self propelled crane and pipe-lay vessel	191m long 35m beam		65.5	182.32 dB rms re 1 µPa @ 1m Highest level measured during	0.01 to 20	191	(MacGillivray and Racca 2006)

					operation of crane. Propulsion system not measured			
Dive Support Vessel	Dynamically positioned	107m long 35m beam		60	178.2 dB rms re 1 µPa @ 1m Thrusters operating at 20% to 30% of maximum thrust which is a typical level	0.01 to 20	187	(MacGillivray and Racca 2006)

Pipe lay for deepwater - *Semac*	Semi-submersible pipe lay barge held on station with an anchor spread. Requires dedicated support from AHTS and supply vessels. Two AHTS vessels required to maintain lay rate, if vessels reduced then pipe lay duration increases. Spread is usually supported by a survey vessel.	 1/3-octave source levels of *Semac* performing anchor winch out.

 *One*	*Figure 3.4 Source (Austin 2004)*	**BROADBAND LEVEL (dB re 1 µPa) = 179.3**
Pipe lay -for shallow water *Castoro*  *II*	Mono-hull pipe lay barge held on station with an anchor spread. Requires dedicated support from one AHTS and supply vessel, with a 2nd AHTS kept on standby to assist in the event of storms. See *Semac One* for description of pipe lay support vessels. *Figure 3.5* *Source (Hannay, MacGillivray et al. 2004)*	 1/3-octave source levels abeam of *Castoro II* during line winch operations. **BROADBAND LEVEL (dB re 1 µPa) = 166.6**[21]

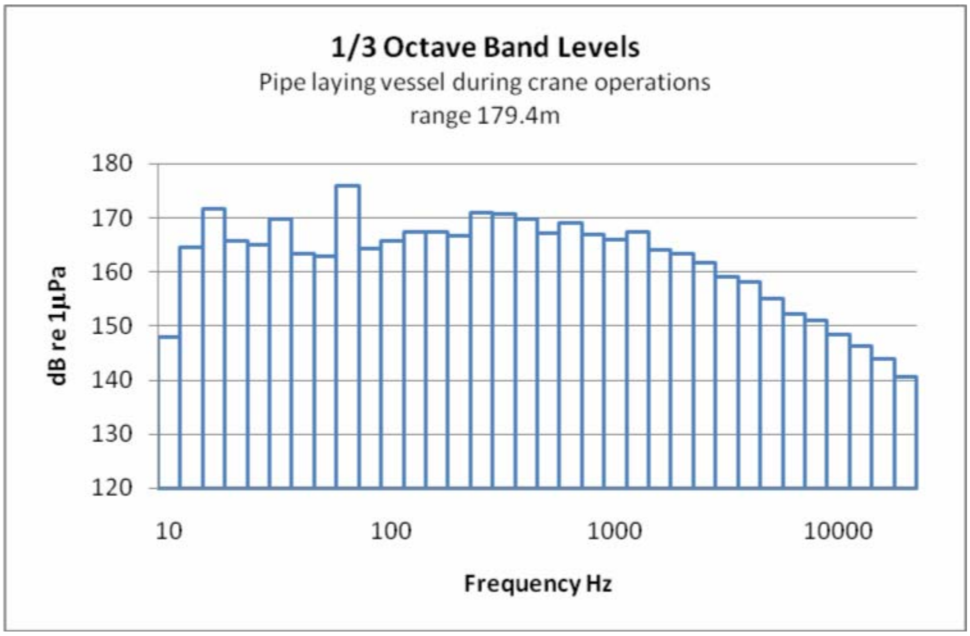


Figure 3.6 Third octave band analysis of pipe laying barge during crane operation(MacGillivray and Racca 2006)

3.3 Dredging

Dredgers can be categorised into three broad classifications (Mason 2004):

Mechanical dredges
Hydraulic dredges
Mechanical /hydraulic dredges which utilize both elements in combination.

3.3.1 Mechanical dredges

These use mechanical gear to lift up level sections of the sea bed, typically these include:

Grab or clamshell and dragline
Backhoe
Dipper
Bucket ladder
Propeller wash
Bed leveller

The most detailed underwater sound information is on grab or clamshell dredging which is given at the end of table 3.3.1.

The sounds generated by the bucket dredging operation can be characterised by a series of repetitive sounds (Dickerson, Reine et al. 2001);

Variable sound as winch operates and derrick and bucket swing into position
Impact as bucket hits sea bed
Grinding sound as bucket is closed and dredged material removed
Noise associated with closure of bucket jaws
Variable sound as winch operates and derrick and bucket swing into position over barge
Material being dumped into barge

3.3.2 Hydraulic dredges

Hydraulic dredges use pumps to provide the excavating and transport force to carry slurry solids from the excavation site to a discharge site or barge.

Typically these include:

Transfer dredges, which are moored and extend suction pipes to the sea bed and discharge into a barge or pump to another site.
Dustpan
Water injection

3.3.3 Mechanical/Hydraulic Dredges

These are the main dredges in use and are of two types:

a) Cutter head and bucket wheel dredges.

These use a cutter head to loosen the sea bed and then a suction pipe to pump the slurry to a discharge site.

b) Trailing suction hopper dredges.

These vessels use suction pipes to remove the sea bed and then store the slurry in hoppers on the vessel, it then moves to empty the hoppers at the discharge site.

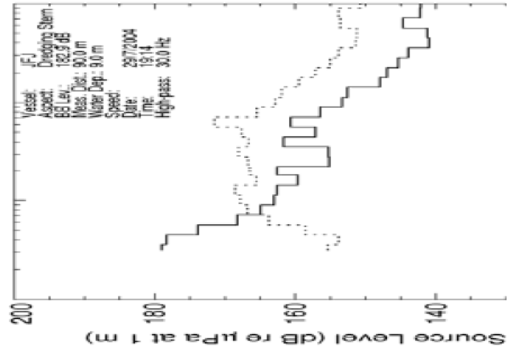
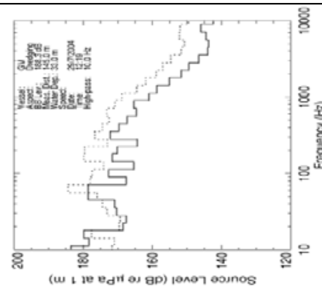
3.3.4. Noise variation

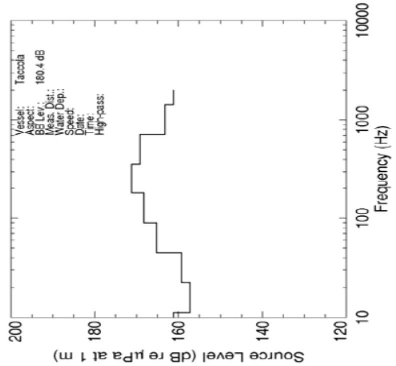
The noise produced by the dredgers depends on their operational status, sea bed removal, transit and dumping. The table includes a column stating the activity of the dredger during the measurement. In general the noisiest activity is associated with the seabed removal.

Table 3.3.1 Dredging noise

Source Type	Description	Capacity	Activity	Water depth m	Measurement re 1 μPa	Measurement Bandwidth kHz	Extrapolation[22] dB re 1 μPa m peak to peak	Characteristic	Reference
Transfer dredge	Cutter suction	60 – 100 k m^3 per day	Dredging	13	133 dB rms @ 0.19 km[23]	0.020 to 1	176		(Greene 1987)
Transfer dredge	Cutter suction	100 k m^3 per day	Dredging	46	140 dB rms @ 0.2 km	0.020 to 1	189		(Greene 1987)
Hopper dredge	11.1 MW power	8000 m^3	Loading	20	142 rms @ 0.93 km	0.020 to 1	194	Continuous No strong tones Roll off 20dB/oct above 1kHz	(Greene 1987)
Hopper dredge	11.1 MW power	8000 m^3	Underway	20	127 rms @ 2.4 km	0.020 to 1	183	Continuous Tones at 55,, 278, 1030 Hz	(Greene 1987)
Hopper dredge	11.1 MW power	8000 m^3	Pumping out	13	117 rms @ 13.3 km	0.020 to 1	180	Continuous No strong tones Roll off 20dB/oct above 1kHz	(Greene 1987)
Hopper dredge		8000 m^3	Loading	21	138 rms @ 0.43 km	0.020 to 1	187	Continuous	(Greene 1987)
Hopper dredge		8000 m^3	Underway (loaded)	25	150 rms @ 0.46 km	0.020 to 1	200[24]	Continuous Tone at 811Hz	(Greene 1987)
Hopper dredge		6000 m^3	Dumping	12	131 rms @ 1.5 km	0.020 to 1	183	Continuous No tones or strong peaks Dip at LF [25]	(Greene 1987)
Bucket Dredge (clamshell dredge)		Working on gravel	Bucket striking Channel bottom Bucket digging	10	124 rms at 1m 112 to 122[26] rms at 1m	0.020 to 20	133 121 to 131	Repetitive Peak at 163 Hz Peak at 40 Hz	(Dickerson, Reine et al. 2001)

Source Type	Description	Capacity	Activity	Water depth m	Measurement re 1 μPa	Measurement Bandwidth kHz	Extrapolation[22] dB re 1 μPa m peak to peak	Characteristic	Reference
			Bucket closing		99 rms at 1m		108	Peak at 316 Hz	
			Winching in/out		116 rms at 1m		125	33 to 56 Hz	
			Dumping material into barge		109 rms at 1m Variable with material in barge		118 Variable with material in barge	Peak at 82 Hz	

JFJ de Nul Cutter Suction Dredger 	Mechanical method of dredging, permitting CSD to work in harder soils/rock. Vessel can work in shallow Water to water depths of over 30m. Used normally for shore approaches. Vessel held on station by vertical pins which stab into the seabed, and are also used to pull the vessel forward. *Figure 3.7 Source (Hannay, MacGillivary et al. 2004)*	 1/3-octave source levels at stern of *JFJ de Nul* while dredging. **BROADBAND LEVEL (dB re 1 μPa) = 182.9**
Gerardus Mercator: Trailer Hopper Suction Dredger 	Trailer Hopper Suction Dredger (Hopper size: 18,000m^3) using suction to remove large volumes of soil to excavate the seabed. Soil is stored on the side of the trench and is returned once pipeline has been installed. Vessel uses thrusters to maintain station. 27 *Figure 3.8 Source (Hannay, MacGillivray et al. 2004)*	 1/3-octave source levels at broadside of *Taccola* while dredging (Langworthy *et al.* 2004) **BROADBAND LEVEL (dB re 1 μPa) = 180.4**

Taccola: Trailer Hopper Suction Dredger 	Trailer Hopper Suction Dredger Smaller version of Geradus Mercator (Hopper size: 4,400m3).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 3.9 Source (Hannay 2004)*	 **Figure:** 1/3-octave source levels at broadside of *Taccola* while dredging (Langworthy *et al.* 2004) **BROADBAND LEVEL (dB re 1 Pa) = 180.4**
James Cook: Trailer Hopper Suction Dredger 	Ice class Trailer Hopper Suction Dredger (Hopper size:1,870m3)[28]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 3.10 source (Hannay 2004)*	1/3-OCTAVE SOURCE LEVELS NOT AVAILABLE

3.4 Drilling

The descriptive information below is adapted from the overview of offshore gas and exploration activities published by the UK Department of Trade and Industry (DTI), (DTI 2006).
There are three types of drilling operations:

3.4.1 Drill-ship

These are based on a ship's hull adapted with a moon pool to allow the deployment of the drill though the hull. They are typically self powered and are not dependent on tugs maintaining position with DP and/or anchors. Drill-ships can operate in deep water however, because of the hull shape, they are more affected by wind and wave movement than semi-submersible rigs, and as a consequence would be more likely to suffer from weather down time. Exploration rigs are self-contained with their own power generation, utilities and accommodation facilities. Supplies are brought to the rig and wastes returned to shore by supply boat. Crew are transferred on and off the rig by helicopter. For safety reasons, a stand by vessel is deployed in the field for the duration of the drilling programme. A drilling derrick above the drill floor bears the weight of the drill string, which is a series of 9m long sections of hollow drill pipe screwed together and to the bottom of which the drill bit is attached. Additional sections of drill pipe are added to the drill string as the well is drilled deeper. The lower part of the drill string, adjacent to the drill bit, is comprised of a series of heavy drill collars to give added weight to the drill bit. The drill bit is rotated either by rotating the whole drill string by means of a rotary table on the drill floor/topdrive system, or by a down hole turbine powered by the flow of mud pumped down the hollow drill pipe.

Nedwell reports that the majority of noise from an operational drill ship was found to be in the band 40 to 600Hz, when measured at a range of 500m to 2km. At a range of 5km there was no perceptible noise above ambient, (Nedwell and Edwards 2004).

3.4.2 Jack-up rigs

Jack-up rigs are based on a buoyant steel hull with 3 or more lattice legs on which the hull can be "jacked" up and down. The rig is towed to location by 2 or more tugs with the legs jacked up so the hull floats. On reaching the drilling location the rig jacks its hull up the legs until the base of the legs are firmly in contact with the sea floor and its deck positioned above wave height. The rig's position is maintained by the legs which are in firm contact with the sea floor. No anchors are deployed, although in areas of strong seabed currents where sediment scour may be expected, gravel or rock may be dumped around the base of the legs to stabilise the sediments. Jack-up rigs are depth limited and can only operate in water depths of around 100m or less. These are the rigs which are most often used in the shallower waters of the southern North Sea.

3.4.3 Semi-submersible rigs

Semi-submersible rigs float at all times on pontoons and are the most likely rig type to be used in deep waters, mainly off the North sea. The rig is towed to location by two or more tugs. The pontoons contain ballast tanks, and the height of the deck above the sea surface can be altered by pumping ballast (sea) water in or out of the pontoons. During drilling operations, the deck is lowered but still kept above wave height. Rigs used in deep water or harsh environments, maintain position over the drilling location either by anchors (and where fitted, with rig thruster assistance as necessary) or by dynamic positioning using a series of computer controlled thrusters. Rig anchoring typically involves the deployment by anchor handler vessel, of eight or more 12 tonne high efficiency seabed penetrating anchors. The anchors are attached to the rig by cable and near the anchor by chain, of which a proportion (a minimum of 100m) lies on the seabed (the catenary contact). Hauling in of the cables by the rig "sets" the anchors in the seabed after which minor adjustments to the rig position can be made by hauling in or paying out cable. The precise arrangement of anchors around a rig is defined by a mooring analysis which takes account of factors including water depth, tidal and other currents, winds and seabed features. The typical radius of anchor patterns for a semi-submersible drilling rig operating in a water depth of 100m is 1300 - 1400m. Anchors are retrieved by anchor handler vessels by means of pennant wires which slide down the cable towards the anchor allowing a more or less vertical retrieval, facilitating anchor breakout from the seabed. A semi-submersible rig is shown in figure 3.7.

Nedwell reports that drilling noise measured in 100m of water around a platform has been in the order of 10 to 20 dB above ambient noise over the frequency range 20Hz to 100Hz with clear evidence of tones at 130, 200, 350 and 600Hz which probably originated from resonant frequencies of the drill shaft. No noise from drilling could be detected below 10Hz. (Nedwell and Edwards 2004). When used, thrusters generated variable noise in the 2 to 30Hz band, the blade rate of the thrusters could clearly be identified.

Figure 3.11 The Molikpaq – A converted drilling rig that was first used in Arctic waters offshore Canada

3.4.4 Drill Island

Drill Islands are man-made structures in shallow water generally consisting of a reinforced steel and concrete construction with a surface deck containing living quarters, drilling rig and power units. Underwater detectable tones tend to be produced by power plant on the islands. (Blackwell, Greene et al. 2004), (Richardson et el. 1995)

Source Type	Description	Capacity	Activity	Water depth m	Measurement Broad band re 1 µPa	Measurement Band width kHz	Extrapolation[29] dB re 1 µPa m peak to peak	Characteristic[30]	Reference
Drill ship	114.9 m long displacement 13 137 tons	7 diesel engines each 840 kW	Logging	17	125 dB rms @ 0.17 km	0.02 to 1	169	Continuous Tones up to 1850 Hz	(Greene 1987)
Drill ship	114.9 m long displacement 13 137 tons	7 diesel engines each 840 kW	Drilling	27	134 dB rms @ 0.2 km	0.02 to 1	180	Continuous with strong tones at 277 Hz	(Greene 1987)
Drill Ship	250m long		Drilling		195 dB rms at 1m	0.001 to 139	195	Continuous Majority of energy in 100 to 400Hz band	(Nedwell and Needham 2001)
Drill Barge	Conical drilling barge 80m diameter		Drilling	31	143 dB rms @ 0.98 km	0.02 to 1	197	Continuous No significant tones above 90Hz	(Greene 1987)
Drill Island	Caisson retained island		Drilling	29	130 dB rms @ 0.22 km	0.02 to 1	177	Continuous Extensive tones up to 5300Hz	(Greene 1987)
Drill Island	Gravel Island with production and drilling activities		Drilling	Under ice 12	124 dB rms @ 1km	0.01 to 10	155.5	Tones associated with power generation	(Blackwell, Greene et al. 2004)
Drill island	Concrete Island Drilling Structure		Idle	15	131 dB rms @ 1m	0.02 to 1	140[31]		(Hall and Francine 1991)
Drill island	Concrete Island Drilling Structure		Drilling	15	124 dB rms @ 0.259 km	0.02 to 1	157[32]	Continuous Strong tones at 1.375 to 1.5Hz[33]	(Hall and Francine 1991)
Drill rig	Exploration drilling rig		Working but not drilling	110	117 dB rms[34] @125m	0.01 to 10	167	Continuous Machinery above waterline Noise due to various mechanical plant on deck	(McCauley 1998)
Source Type	**Description**	**Capacity**	**Activity**	**Water depth m**	**Measurement Broad band re 1 µPa**	**Measurement Band width kHz**	**Extrapolation[35] dB re 1 µPa m peak to peak**	**Characteristic[36]**	**Reference**
Drill Rig	Exploration drilling rig		Drilling	110	115 dB rms[37] @405m	0.01 to 10	170	Tones produced by drill string in 31 and 62Hz 1/3 octave bands	(McCauley 1998)
Drill Rig	Exploration drilling rig		Rig positioning tenders operating thrusters	110	137 dB rms[38] @405m	0.01 to 10	192	Broadband noise produced by thrusters or main propellers under load	(McCauley 1998)
Semi-submersible	Drilling , oil production, and water injection		Generators and pumps	35	162.3 dB rms @ 1m	0.01 to 10	171	Broadband noise	(Hannay, MacGillivray et

Drill rig			operating continuously						al. 2004)

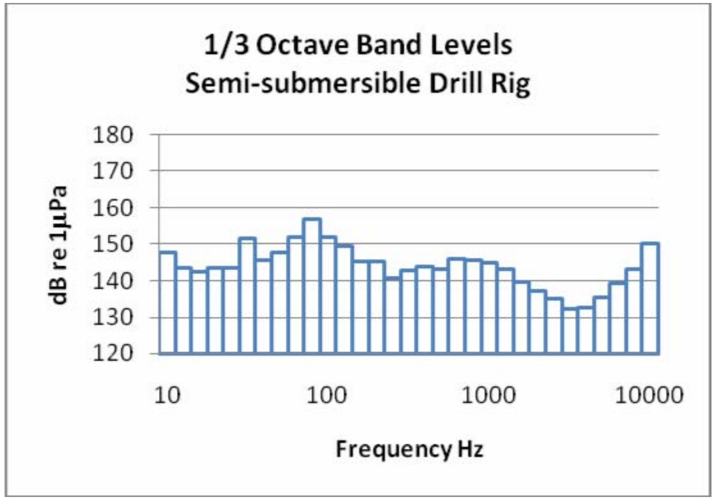


Figure 3.12 Third octave band levels for semi-submersible drill rig

3.5 Explosives

3.5.1General Use

Explosives are now rarely commercially used as an acoustic source; they are however used in construction projects for rock blasting and sometimes well head removal at the end of an oil rigs life

When an explosion is initiated a pressure wave propagates into the surrounding water. The shock wave is normally followed by a series of bubble pulses caused by successive oscillations of the gas volume that remains after the explosion. Bubble pulses do not occur if the gas bubble breaks the surface or if it is contained within a case. The pressure signature of an explosion consists of a shock wave followed by a series of smaller decreasing bubble pulses. In far field measurements the waveform is received after a surface reflection and therefore includes a negative going pulse as reflection of the initial shock pulse. The bubble oscillation frequency remains detectable at considerable distances. (Urick 1967), (Sulfredge, Morris et al.)

For unconfined TNT charges in deep water the peak pressure and impulse are given by:

$$Peak\ pressure = 2.16*10^4*(w^{1/3}/r)^{1.13} \quad (3.3) \quad \text{(Urick 1967)}$$

w is charge weight in pounds, r is range in feet and $Peak\ pressure$ is in pounds per square inch

Converting equation 3.3 to SI units gives

$$Peak\ pressure = 5.26*10^7*(w^{1/3}/r)^{1.13} \quad (3.4)$$

Where: w is charge weight in kgs, r is range in m and $Peak\ pressure$ is in Pascals

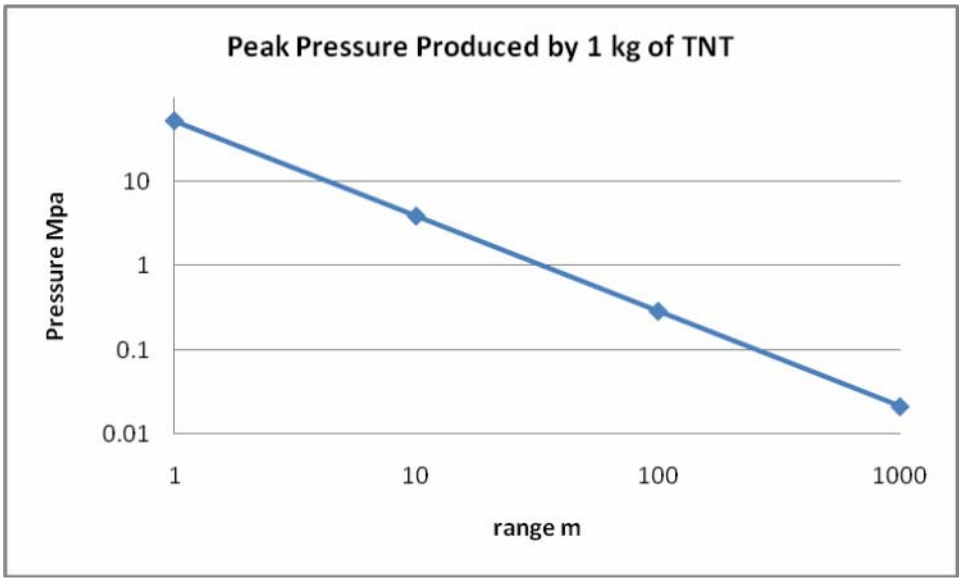


Figure 3.13 Peak pressure produced by 1Kg of TNT

The Impulse produced by a charge is given by the equation

$Impulse = 6 * 10^3 w^{0.63} r^{-1.13}$ Pa sec   (3.5)   (Nedwell and Edwards 2004)

Where: w is the charge weight in kgs, r is range in m and $Impulse$ is in Pascal seconds

For confined charges (such as boreholes)

$Peak\ pressure = 2.5 * 10^6 * w^{0.27} * r^{-1.13}$ Pa (3.6)

$Impulse = 1.8 * 10^3 w^{0.63} r^{-0.89}$ Pa sec   (3.7)

It should be noted that the peak pressure is proportional to the weight (w) of the charge to the power of 0.27 such that the weight of the charge has a relatively small effect on the peak pressure. Nedwell reports that from experience these results tend to significantly overestimate levels for shallow water (measured values typically 30% to 37% lower than calculation for unconfined charges).

Measurements reported by Nedwell in table 3.5.1 show the sound pressure levels received from a series of buried explosive charges in shallow water. The complex propagation path, being both water and seabed propagation makes any accurate determination of source level problematic. Significant variability is a normal feature of the received levels of explosive detonations, (Nedwell and Edwards 2004).

Nedwell also found that charges placed in well head pipes behaved more like unconfined charges than confined charges. The following tables summarise measurements made under various conditions in which the charge was buried below the sea bed.

Table 3.5.1 Sound pressure levels at two ranges produced by various charge sizes and depths in boreholes in the sea bed (Nedwell and Edwards 2004).

Charge weight kg	Charge depth m	SPL at Range 470m dB re1 μPa	SPL at Range 1900m dB re 1 μPa
0.2	3	169.3	n/d[39]
0.4	11	172.2	n/d
0.6	6	146.2	n/d
0.6	2	163.1	n/d
0.6	6	168	n/d
0.6	3	171.1	n/d
0.8	15	172.2	n/d
1	?	171.6	142.0

Table 3.5.2 Sound Pressure level produced by a small explosive charge

Charge weight	Charge type	Measured SPL dB re 1 µPa at 1m	Extrapolated Peak to peak dB re 1 µPa at 1m	Source
25g	Perchlorate based	226.9	236	(Nedwell and Edwards 2004)

Table 3.5.3 Measurements made of seabed surface placed charges (Nedwell and Edwards 2004)

Charge Kg	Water depth m	Measurement Range m	Peak Pressure 6m depth kPa	Peak Pressure 12m depth kPa	Peak to Peak pressure 6m depth 1000m range dB re 1 µPa	Peak to Peak pressure 12m depth 1000m range dB re 1 µPa
2	22	1000	7	5.8	203	201
2	22	1000	8.4	7.2	204	203
2	22	1000	5.9	6.1	201	202
2	22	1000	5.5	7.7	201	204
4	22	1000	8.8	8.2	205	204
4	22	1000	7.8	9.1	204	205
4	22	1000	8.4	10.2	204	206

3.5.2 Well head decommissioning

The removal of well heads is carried out using explosives or using cutting tools. No measurements of noise have been found for the use of cutting tools However in 2000 to 2001 Nedwell (Nedwell and Edwards 2004) reports on measurements made during explosive severance in the North Sea in water depths of 91 to 116 m using a charge of approximately 45kg. The slave station was a sea bed mounted instrument. The experimental results are closer to an unconfined explosive charge rather than a confined charge. The measurements are given in table 3.5.4.

Connor gives a detailed report on the explosive decommissioning of a hydrocarbon production platform in the Gulf of Mexico, (Connor 1990). Two types of explosive placements were used in open ended pipes (end above water level) and below water level ends. All the below bottom severance detonations produced direct shock wave pulse and a pulse from the explosion product bubble collapse. The peak overpressure of the direct shock was found to be two to ten times greater than the bubble pulse.

Table 3.5.4 Explosive charges used for well head decommissioning.

Range m	Charge size Kg	Receiver 1 depth m	Peak pressure kPa	Receiver 2 depth M	Peak pressure kPa	Slave station Depth m	Slave station peak kPa	Peak to peak At given range dB re 1 μPa
75	45					116	236	227
125	45					87	201	226
200	45					110	169	225
300	45					91	392	232
300	45					84	312	230
400	45					108	147	223
575	45	30	37					211
575	45			25	36			211
600	45	40	47					213
600	45	35	51					214
600	73	30	100					220
600	81	30	53					214
600	45	30	52					214
600	81			25	57			215
600	45			25	50			214
650	73	25	198					226
650	45	40	63					216
650	45	35	75					218
650	45	40	83					218
650	45			35	80			218
650	45	40	54					215
650	45			35	68			217
650	45	40	115					221
650	45	35	130					222
650	36	30	118					221
650	36			25	130			222
650	45	30	77					218
650	45			25	74			217
800	36	30	117					221

Based on measurements by (Nedwell and Edwards 2004)

3.5.3 Mitigation.

Bubble curtains were experimented with by Nedwell on a rock blasting site in Spain. The report does not give detail information on the bubble curtain but states that it was not as effective as hoped, (Nedwell and Edwards 2004). In general mitigation is by the use of Marine Mammal Observers (MMO) and by passive acoustic monitoring.

Under the E & P sound and marine life programme the Joint Industry Programme (JIP) are sponsoring Mitigation & monitoring procedures.

3.6 Seismic Exploration Sound Sources

Seismic exploration sound sources may be used to investigate shallow subsoil structure for engineering site work, or deeper structures usually in the search for oil. The returning signals from the sources are detected by hydrophones trailed behind the survey vessel in known locations relative to the position of the source. The recorded signals are then subjected to specialist analysis and processing to yield information on the subsea-bed structure.

The type of source is chosen to suit the survey requirement;

Low frequency sources (such as air guns) produce low frequency energy which penetrate the seabed to considerable depths (many kilometres) and is then reflected by the geological layers and then received by the survey hydrophone arrays. This type of source is used for oil exploration

High frequency sources such as sparkers and boomers do not penetrate the sea bed to a significant extent (typically hundreds of metres) but produce high resolution information about the sub surface properties of the seabed. These sources are used for high resolution surveys of the sea bed for placement of structures etc.

A brief summary of the most common sources is given below.

3.6.1 Airgun sources

These are the most common and the most powerful of the low frequency sound sources used for seismic exploration. The air guns produce high levels of low frequency sound by releasing controlled volumes of high pressure air into the water creating an oscillating bubble which produces 90 per cent of its energy in the band 70 to 140 Hz (van de Sman 1998). The air guns are formed into an array to produce a low frequency beam of energy toward the sea floor. It is likely that other beams of energy are formed in various directions depending on frequency at a range of frequencies up to 100 kHz.

The frequency spectrum generated by the airguns will be dependent upon the depth at which they are deployed. The high acoustic impedance of the water surface to air interface creates a mirrored signal of opposite phase and destructive interference will occur where the direct signal and the surface reflected signal are out of phase in shallow deployment giving broader bandwidth but reduced total energy output the normal operating depth for air gun arrays is between 5 and 7 m (Gausland 1998)

Evidence shows that the air guns produce energy above background noise up to frequencies in excess of 22 kHz at range of 2 km and frequencies in excess of 8 kHz at ranges of 8 km (Goold and Fish 1998)[40] . There is evidence that the low frequency content of air gun pulses can be detected at ranges of 3000km (Nieukirk, Stafford et al. 2004).

The levels of noise measured around the air guns will depend greatly on the air gun array configuration and the local ocean conditions, (DeRuiter, Tyack et al. 2006). It is likely that the sound propagation will vary considerably from site to site and detailed knowledge of the geographic and oceanographic parameters will be required for accurate modelling (McCauley, Fewtrell et al. 2000). Each exploration company may use a number of gun array configurations, depending upon the survey requirements, and as such the source values must be considered as indicative only.

The relationship between the total volume of air discharged and the resulting Sound Pressure Level (SPL) is of the nature

$$SPL = kV^{2.4} \qquad (3.8)$$ (Nedwell, Needham et al. 1999)

where k is a constant and V is the total volume of air

And / Or

$$SPL = KPNV^{1/3} \qquad (3.9)$$ (Hildebrand 2006)

Where: K is a constant, P is the air pressure, N is the number of guns and V is the total volume of air

The Rayleigh Willis equation for the bubble oscillation period is given by

$$T = k\frac{P^{1/3} + V^{1/3}}{\left(P_{atm} + \rho gD\right)^{5/6}} \qquad (3.10)$$

Where T is bubble oscillation period, P is the gun pressure, V is the gun volume, P_{atm} is atmospheric pressure, ρ is the density of water, g is gravitational acceleration, D is the depth of the gun, and k is a constant.

A set of experimental data on a three string 3147 cu inch seismic survey in the Chukchi Sea gives a comprehensive study of the sound output from an airgun array, (Patterson, S.B. Blackwell et al. 2007). The study used bottom mounted hydrophones in 42m of water. The table below relates Peak pressures, Sound Pressure Levels (SPL) and Sound Exposure Levels (SEL) for Bow, stern and broadside measurements

Table 3.6.1 Table of sound output of a 3147 cubic inch air gun array (Patterson, S.B. Blackwell et al. 2007).

		dB re 1m	Measurement Ranges	Sample size
Bow	Peak	266.4	0.35 to 30.6 km	391
	SPL	249.5		
	SEL	224.6		
Stern	Peak	249.8	0.3 to 33.9 km	232
	SPL	247.2		
	SEL	221.0		
Broadside	Peak	253.5	0.52 to 5.16 km	54
	SPL	239.7		
	SEL	222.9		

3.6.1.1 Variation of received sound with depth

In experiments where multiple hydrophones have been deployed to measure the far-field nature of the sound (Greene and Richardson 1988), the hydrophones close to the surface (3m) show 7 dB lower levels than those at greater depths (9m and 18m).

3.6.1.2 Variation received sound with range

Increasing range generally leads to a decreasing sound pressure level. The attenuation rate of the sound pressure level generally follows a cylindrical or spherical spreading law depending primarily on the water depth. The measured results often fall between the two spreading functions and some measurements show spreading at greater levels than spherical spreading sometimes termed hyperspherical spreading. Section 6 gives more information on spreading and absorption coefficients.

Pulse duration tends to increase with range and the pulse shape is modified to give a downward frequency sweep characteristic of pulsed sound propagation in shallow water, (Greene and Richardson 1988).

As the nature of the pulse changes in duration and magnitude with distance from the source so the relationship between SPL and SEL changes with distance from the source as shown in the table 3.6.2.

Table 3.6.2 Relationship between SPL and SEL with distance.

SPL-SEL	Range
Approx 10dB	300m
Approx 8.5 dB	300m to 3km
Difference is negative as pulse has been stretched by propagation characteristics to 1 sec or larger	10 to 16 km

3.6.1.3 Directionality

It should be noted that the design aim of the air gun array is to produce as much energy as possible focused in a vertical beam into the seabed. However most measurements are necessarily taken at some distance more or less in the horizontal plane, thus measuring not the main beam of the array but the side lobes and the reflections of the main beam from the seabed and sea surface which may be larger than the direct arrival in the horizontal axis.

There is conflicting evidence of directionality of air gun arrays. Received levels from a three sub array of 3147 cu inch showed little aspect dependence whereas a single string of 1049 cu inch (one of the three sub-arrays) showed stronger aspect dependence with the broadside having the highest peak values and the stern the lowest peak values, (Patterson, S.B. Blackwell et al. 2007). Modelling of a 3959 cu inch array showed an 8.5 dB variation from broadside to end-fire aspects, the frequency range of the model was not stated, (LePage, Malme et al. 1995). The modelled variation was measured and validated by LePage on a similar air gun array, (LePage, Malme et al. 1996). The same type and level of variation is reported by Nedwell, (Nedwell and Edwards 2004).

It is most likely that the directionality of the airgun array depends upon the layout of the air guns, their firing times and the frequency band of measurement and this will vary from survey to survey.

3.6.2 Water gun sources

Water guns operate in a similar way to airguns however high pressure water is vented into the surroundings when the gun is triggered and there is consequently no air bubble oscillation. The spectrum of the water gun pulse is considerably wider than the air gun being reduced only 10 dB at 200Hz , (Gausland 1998).

The variation of signal with depth and the array directional properties are those as the air gun arrays discussed above.

3.6.3 Sparker sources

The sparker is a relatively high powered sound source (typically 215 dB source level). It is dependent on an electrical arc that momentarily vaporizes water between positive and negative electrodes. The collapsing bubbles produce a broad band (50 Hz - 4 kHz) omni-directional pulse which can penetrate several hundred meters into the subsurface. It can operate only in salt water in order to meet the conductivity requirements of the system.

3.6.4 Boomer sources

The boomer is a broad-band sound source operating in the 300 Hz – 3 kHz range. By sending electrical energy from the power supply through the wire coils, spring loaded plates in the boomer transducer are electrically charged causing the plates to repel, thus generating an acoustic pulse. This system is commonly mounted on a sled and towed behind the boat.

Dependant on subsurface material types, resolution of the boomer system ranges from 0.5 to 1 m, penetration from 25 to 50 m. The reflected signal is received by a towed hydrophone streamer.

Source Type	Volume Cu inch	Pressure PSI	Water Depth m	Measurement	Measurement Bandwidth kHz	Extrapolation dB re 1 µPa m peak to peak [41]	Characteristic	Reference
Water Gun (Hydroshock) single				238 dB re 1 µPa m Peak to peak[42]	0 to 2	238	Pulsed	(Bouyoucos 1981)
Sleeve exploder array 12 guns Propane oxygen mix			15 to 30	153 dB rms re 1 µPa @ 8km	0.02 to 1	214	Pulsed 6 second interval Duration 250ms at 8km Duration 400ms at 29 km	(Greene and Richardson 1988)
Open bottomed gas guns			9 to 11	177 dB rms re 1 µPa @ 0.9km	0.02 to 1	225	Pulsed Interval unknown Duration 200ms at 0.9 km Most energy at 72Hz	(Greene and Richardson 1988)
Sparker Single 8kV 1mm gap				92 dB re 1 µPa @ 1m peak		92[43]	Pulsed++	(Nedwell 1994)
Squid Minisparker[44] Squid 500				209dB rms 215 dB rms[45]	0.15 to 1.7	218 224	Repetition rate 4 to 6 sec Pulse duration 0.8 mSec (typical)	(USGS 2000)
Huntec Boomer[46]				205 dB rms	0.5 to 8	214	Repetition rate 0.5 to 1 sec Pulse duration 0.34mSec (typical)	(USGS 2000)
Air gun single	40	2000	15	129 dB rms re 1 µPa @ 5km	0.020 to 20	186[47]	Pulsed Interval unknown	(Greene and Richardson 1988)
Air gun Single Bolt 1900B	40	1500 2000	Shallow Shallow	191 dB rms re 1 µPa @ 1m 193 dB rms re 1 µPa @ 1m		200 202	Pulsed	(Nedwell and Edwards 2004)
Air gun array 4 guns	4 * 70 cu inch guns 280 cu inch total		48	242.7 dB re 1 µPa @ 1m peak	0.005 to 20	249	Pulsed Interval unknown	(Patterson 2007)
Air gun array 3 guns	330		34	167 dB rms re 1 µPa	0.020 to 20	226	Pulsed Interval unknown	(Greene 1988)

Source Type	Volume Cu inch	Pressure PSI	Water Depth m	Measurement	Measurement Bandwidth kHz	Extrapolation dB re 1 µPa m peak to peak [41]	Characteristic	Reference
				@ 3km				
Air gun array 8 Guns, Single Line	1049	2000	42	Bow 260.4 dB re 1 µPa peak Stern 245.7 dB re 1 µPa peak Broadside 247.2 dB re 1 µPa peak	0.005 to 20	266 252 253	Pulsed Interval unknown	(Patterson 2007)
Air gun array	1404		130	119 dB rms re 1 µPa @52km	0.020 to 20	196[48]	Pulsed Interval unknown	(Greene 1988)
Air Gun array	1709		20	179 dB rms re 1 µPa @ 1.9km	0.020 to 20	233	Pulsed Interval unknown	(Greene 1988)
Air gun array 12 air guns	2869		20	160 dB rms re 1 µPa @ 12km	0.020 to 20	222[49]	Pulsed Interval unknown	(Greene 1988)
Air Gun Array[50] 24 Airguns	3147	2000	42	Bow 266.4 dB peak re 1 µPa at 1m Stern 249.8 dB peak re 1 µPa at 1m Broadside 253.5 dB peak re 1 µPa at 1m	0.005 to 20	272 256 259	Pulsed 10 Second intervals	(Patterson 2007)
Airgun array 18 air guns	3955		100	Source level of 262.9 dB rms re 1 µPa @ 1m[51]		271	Pulsed	(Nedwell 2004)
Airgun Array[52] 18 air guns	3959		53 to 201	193.6 dB peak re 1 µPa at 180m	High pass at 5Hz	244 (239 to 246)	pulsed	(LePage 1995)

The measured results for the air gun arrays are plotted on the figure 3.14. Together with the two equations from section 3.6 used to calculate the sound pressure level can be seen that eqn 3.8 (Hildebrand 2006) is a close fit, whereas eqn 3.9 (Nedwell, Needham et al. 1999) consistently overestimates the SPL.

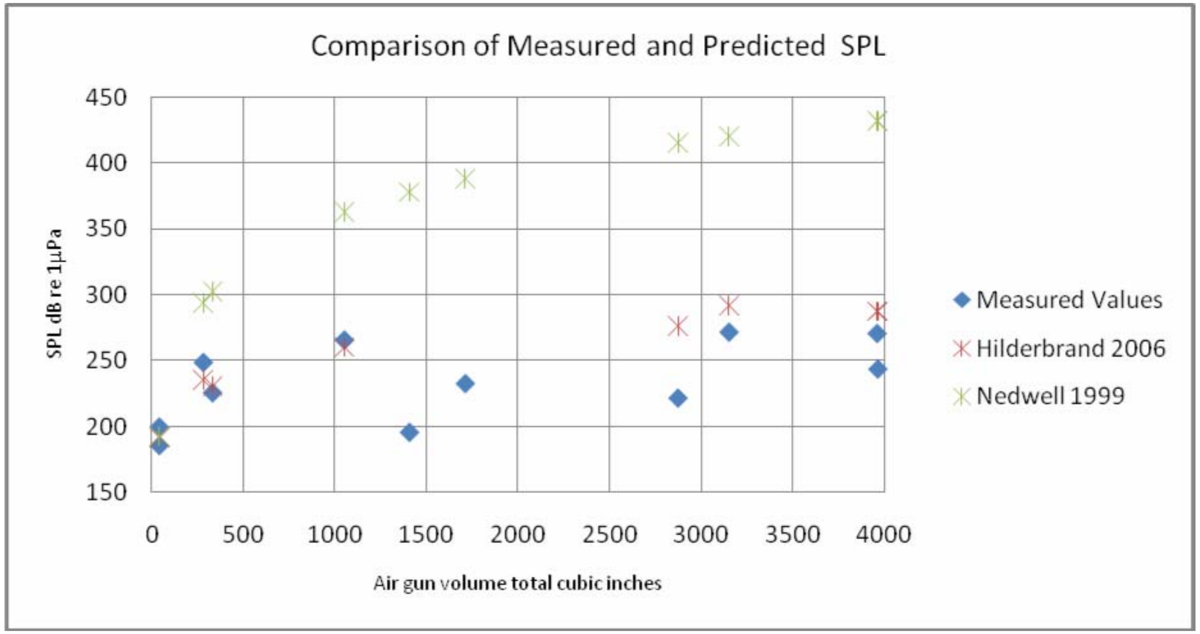


Figure 3.14 Comparison of measured and calculated air gun SPL.

3.7 Shipping and Small Vessel Noise

3.7.1 General

Every vessel has its own unique noise characteristic depending upon propulsion unit, machinery, hull size and shape. These characteristics will change with vessel speed and weather conditions and loading, thus generalisations are required to represent typical vessels as well as reporting measurements of individual vessels.

Shipping noise is generally within the 50 to 300Hz band and is a major contributor to noise near shipping lanes and generally in deep water, it is the dominant noise source between 20 Hz and 500 Hz (Urick, R. J. (1967). Principles of underwater sound, Peninsula Publishing). Average deep water, ambient spectra is shown in appendix 2 section 6. Hull vibrations induce low frequency noise (below 15Hz) for large vessels (see section 3.7.3)

There is evidence to show that low frequency noise has increased at a rate of approximately 3dB per decade in the period from 1950 to 1998 (McDonald, Hilderbrand et al. 2006). This noise is thought to be primarily due to the increase in propeller driven vessels. A simple relationship can be shown between the increase in gross domestic product and the increase in low frequency ocean noise (Frisk). A significant proportion of this noise is due to the activities of the oil and gas industries, which account for nearly 50% of the gross tonnage but only 19% of the total number of vessels in the world’s commercial fleet (McDonald, Hilderbrand et al. 2006). In the St Lawrence Seaway about 6000 merchant ships per annum transport cargo along the 300 km long route between the great lakes and the Atlantic. This amount of sea going traffic produces significant continuous noise and causes masking of Blue and Fin whale calls. (Simard, Roy et al. 2006)

A relationship between the increase in total gross tonnage of shipping and the increase in low frequency noise in the ocean has been proposed, (NRC 2003).

Change in shipping noise (dB) = 20 log (final gross tonnage/initial gross tonnage)

Whilst this equation may be a simplification and is untested, it fits historical data well. Figure3.11 shows the increasing tonnage of oil carried by tankers over the last 30 years.

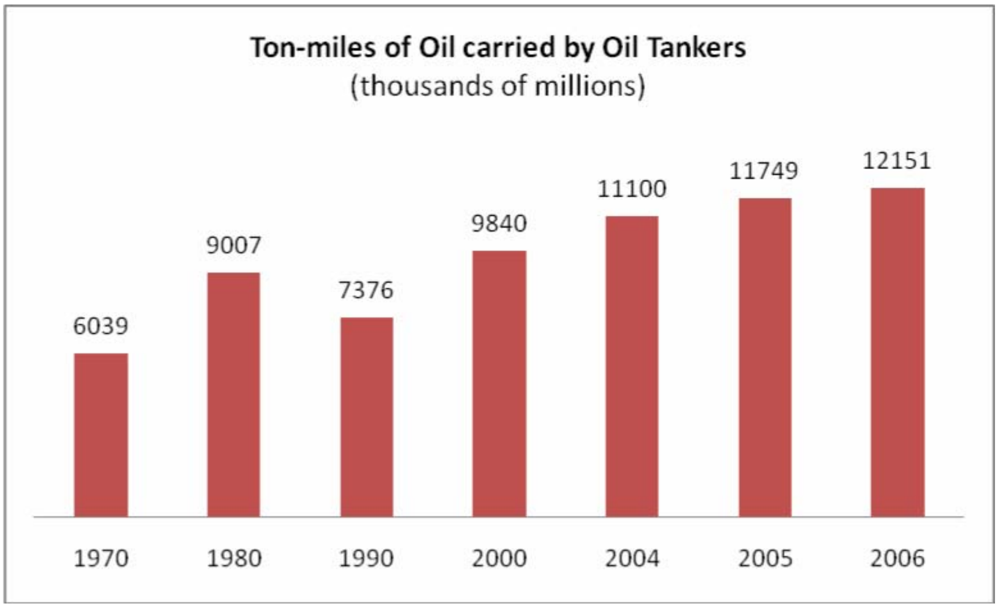


Figure 3.15 Movement of oil by tankers. Source UNCTAD calculation

Shipping produces narrowband and broadband underwater sound typically due to engine, machinery and propeller related noise. All vessels which use propellers for propulsion have the potential to produce cavitation noise which is at higher frequencies and is broadband in nature (Kipple and Gabriele 2003). It is estimated that 85% of vessel noise results from propeller cavitations, this sound represents wasted energy in moving ships through water (Barlow and Gentry 2004).

The horsepower required to power a ship increases with the ship's size and is proportional to the cube of the ships speed (Cybulski 1977). Increasing size, power and speed produces increasing radiated broadband and tonal noise primarily radiated by cavitations of the propeller.

3.7.2 Water depth

Shallow water acts as a high pass filter with the cut off frequency increasing with decreasing depth. In very shallow waters distant shipping makes little or no contribution to ambient noise (Harland and Richards 2005).

The domination of ship noise in the frequency band 20 to 500 Hz in the deep ocean may be attributable to traffic at distances of 1000 miles or more. (Cybulski 1977), (Urick 1967).

3.7.3 Noise Characteristics

The classical model proposed by Ross (Ross 1976) states that the ship noise is proportional to a base line spectrum with a constant of proportionality raised to a power proportional to the length and speed of the vessel. Other models give a closer match between modelled and actual ship noise (Wales and Heitmeyer 2001). An approximation of the high frequency emissions of a vessel can be taken as "red" noise (or $1/f^2$ noise) and the low frequency noise assumed to be "white noise" as an average of smoothing the ships tonal noise (Hazelwood 2005). The transition point between the two characteristics varies typically between 100 and 1000 Hz but may be lower for large vessels such as super tankers. Noise tends to rise at the lower frequencies (below 15 Hz for large vessels possibly due to radiation by hull vibrations (Wright 1983).

Measurements of the noise associated with three super tankers was carried out in 1977 (Cybulski 1977). The water depth for the measurements was in excess 4000m with a surface duct between 20 and 34m. Tones emitted by the propeller were calculated based on

$$(RPM * B / 60) * n \text{ Hz}$$

where B is the number of Propeller blades
n is the harmonic number.

Table 3.7.1 Fundamental shaft and propeller tones

Dead weight Tons	Length m	Beam M	Draft m	Speed Knots	Horsepower	Propeller blades	rpm	Fundamental Blade rate	Fundamental Shaft tones	SPL Cavitations induced Narrow band radiation
271034	337.4	53.6	21	16	38000	5	87	7.25 Hz	1.44 Hz	181.4
312212	351.4	55.5	22.3	15.1	30000	4	80	5.3 Hz	1.33 Hz	179.4
102960	265.8	39	19.6	15.5	22550	4	113	7.5 Hz	1.89 Hz	181.5

The measurements show a good correlation between measured tonal lines and calculated tonal lines. Up to 42 out of 55 lines for the shaft rotation could be matched between theory and actual measurements.

(Cybulski 1977) reports that directionality, 7dB higher from bow to stern measurements, was measured during the transit of one of the vessels the origin of the directionality could not be determined although wake or seabed reflections were suggested.

Models are available for predicting vessel noise, these are discussed in detail in Ocean Noise and Marine Mammals (NRC 2003). The graph below shows modeled spectral densities from the RANDI (Research Ambient Noise Directionality) noise model. The ships are based on mean values of ship length and ship speed for each class of vessel.

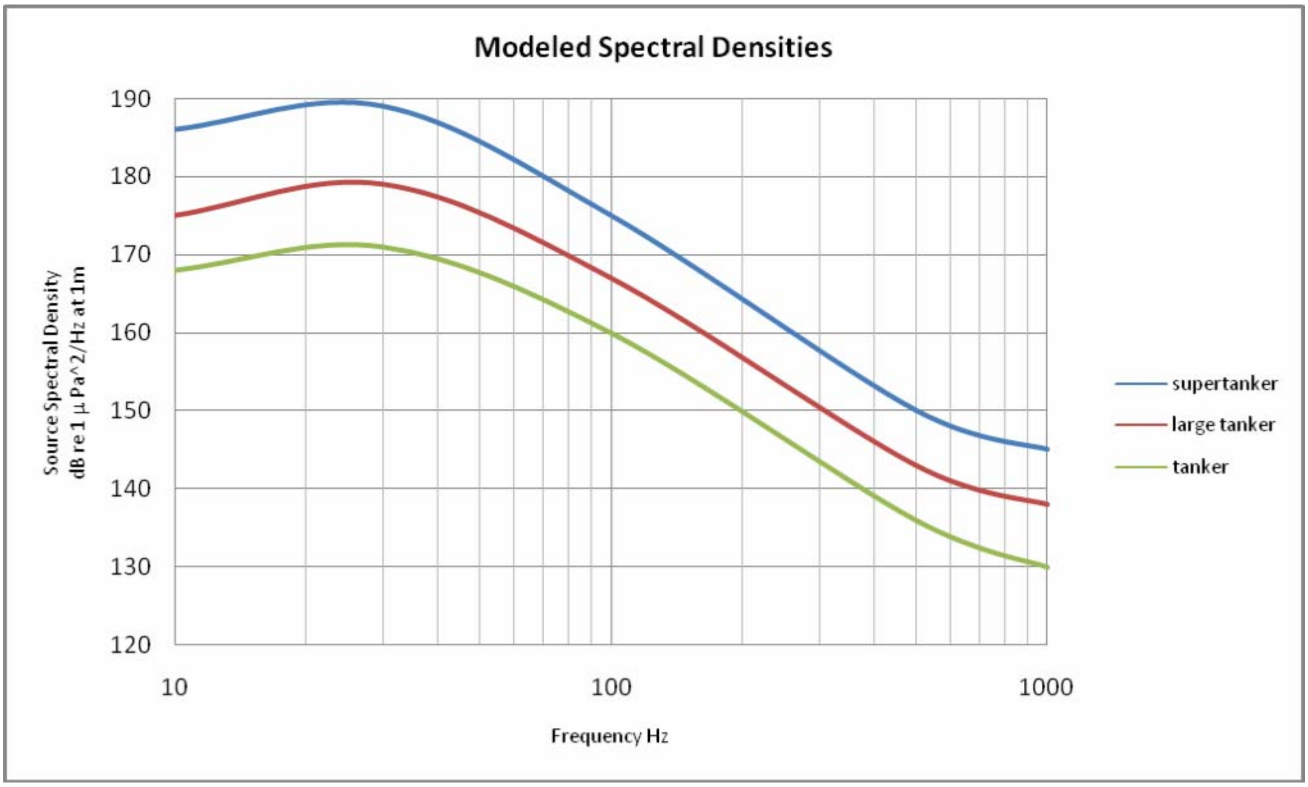


Figure 3.16 Modelled spectral densities of a range of tanker sizes

3.7.4 Thruster acoustic characteristics

Cavitations of the impellor are the major noise source for vessels using dynamic positioning systems, unless they excite a ship resonant response. Blade passage rate (rpm * number of blades) and cavitation induced noise depend to a large extent on the hydrodynamic and hyrdo-acoustic design of the impeller. (Fischer 2000)

Measurements of thruster noise for an offshore supply vessel are given in the table 3.6.2 below and shown graphically in figure 3.13.

Table 3.7.2 Measurements of thruster noise for an offshore supply vessel Source (Austin 2005)

Engine	Propeller Power	Thrusters	Thruster Propeller Power	Broadband Source Level	Extrapolated value
On	100%	Off	0%	187.76	197
On	75%	Off	0%	183.89	193
On	50%	Off	0%	182.27	191
On	25%	Off	0%	178.98	188
On	0%	Off	0%	173.31	182
On	0%	On	0%	173.94	183
On	0%	On	100%	181.75	191

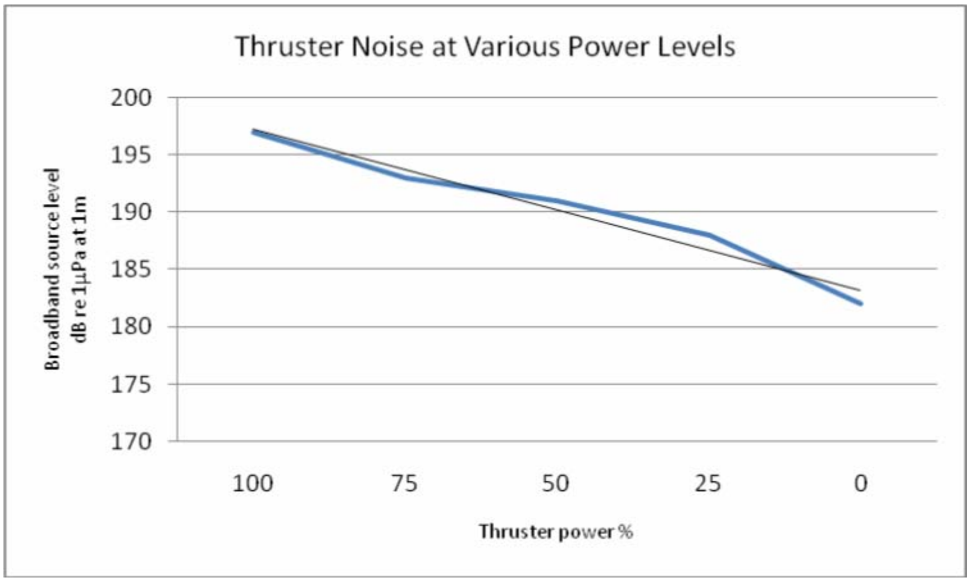


Figure 3.17 Thruster noise. Adapted from (Austin 2005)

The table shows that the maximum thruster noise is below the main propulsion noise at full power. The graph shows that the thruster noise has an approximate linear relationship with the power level supplied.

Where cavitation is the main source of noise it may be reduced by improved propeller design. The onset of cavitation is clearly shown in figure 3.14 below which shows a thruster before and after modification to reduce underwater radiated noise. Thruster cavitation was reduced until onset was at around 250 RPM. Note that the measurements units are not distance calibrated. (Brown, Dai et al. 2001)

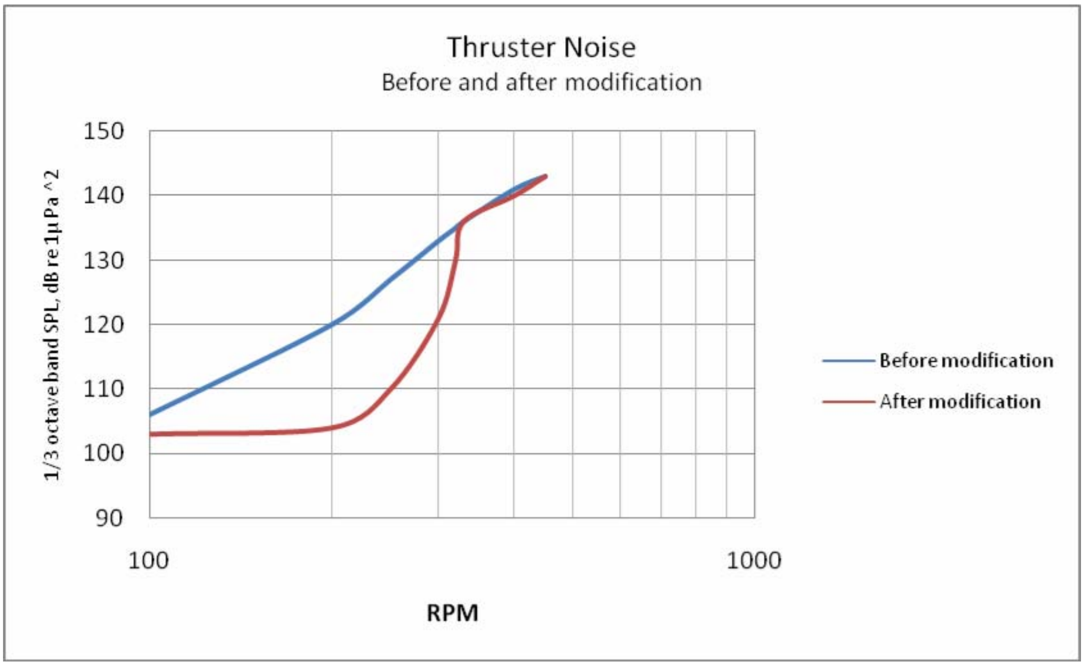


Figure 3.18 Thruster Noise showing onset of cavitation at around 250 RPM (Brown, Dai et al. 2001)

3.7.5 Effect of vessel speed

A report from Glacier Bay shows that sound level and sound peaks generally increased by between 4 and 6dB when increasing speed from 10 to 20 knots, although in one case the noise levels dropped due to low frequency propulsion system noise components (Kipple 2002).
A small increase in speed from 4.9 knots to 5.8 knots of a laden self propelled barge showed a 5 dB increase in SPL (Zykov and Hannay 2006).

Hydrodynamic flow over the ship's hull and appendages is an important broadband noise generating mechanism especially with increased speed (Hildebrand).

As ship increases speed broadband noise such as propeller cavitation and hull vibration noise become dominant over machinery noise (NRC 2003).

3.7.6 Vessel size

Large vessel noise is generally higher at low frequencies, small high powered (greater than 100 HP) propeller driven craft often exceed large vessel noise at frequencies above 1 kHz and at 2.5 kHz may be 13 dB above large ship noise (Kipple 2002).
Small vessels do not contribute to the global ocean acoustic environment but may be important localised sound sources. Smaller vessels can produce significant sound levels relative to their size as their speeds are typically higher than large vessels and they produce higher frequency (Zykov and Hannay 2006) noise which propagates better in shallow water than the low frequencies typical of larger craft

The passage of small vessels through swells in rougher sea states can lead to cyclic changes in sound level by up to 8 dB above and below the average sound level. This effect will increase the local maximum levels but may be mitigated over longer ranges by increased scattering from the sea surface. (Zykov and Hannay 2006)

3.7.7 Hovercraft

Underwater hovercraft noise is dominated by the blade rate of the thrust propeller rather than, as may be expected, the lift fan. (Richardson 2006). The sound level is higher near the surface (1m) than at a deeper point (7m). This is probably due to the fact that all the sources of noise are in the air and then coupled into the water via the air/water interface.

3.7.8 Note on tables

Due to the scarcity of measurement information about the vessels used by the oil and gas industries a range of vessels outside the industry have been included in the tables. The tables have been structured with the largest vessels by gross tonnage first, down to the small vessels by length last.

Table 3.7.3 Shipping and small vessel noise

Vessel Type	Displacement Tonne	Length m	Propulsion	Activity	Measurement	Measurement band kHz	Extrapolation dB re 1 µPa m peak to peak	Reference
Cruise Ship	78200 (77000 tons)	260	Diesel Electric	Underway 9.9 knots Underway 5.6 knots	177 dB rms re 1 µPa at 1yd 177 dB rms re 1 µPa at 1yd	0.01 to 40	185 185	(Kipple 2002)
Cruise Ship	77000 (78200 tons)	260	Diesel Electric	Underway 10.8 knots Underway 14.2 knots	175 dB rms re 1 µPa at 1yd 183 dB rms re 1 µPa at 1yd	0.01 to 40	183 191	(Kipple 2002)
Cruise Ship	55900 (55000 tons)	219	Diesel Electric	Underway 10.8 knots Underway 18.0 knots	181 dB rms re 1 µPa at 1yd 183 dB rms re 1 µPa at 1yd	0.01 to 40	189 191	(Kipple 2002)
Cruise Ship	50800 (50000 tons)	230	Direct Diesel	Underway 10.0 knots Underway 19.2 knots	176 dB rms re 1 µPa at 1yd 195 dB rms re 1 µPa at 1yd	0.01 to 40	184 203	(Kipple 2002)
Cruise Ship	49800 (49000 tons)	241	Diesel Electric	Underway 10.5 knots Underway 15.3 knots	185 dB rms re 1 µPa at 1yd 184 dB rms re 1 µPa at 1yd	0.01 to 40	193 192	(Kipple 2002)
Cruise Ship	23400 (23000 tons)	188	Steam Turbine	Underway 10.0 knots Underway 15.5 knots	178 dB rms re 1 µPa at 1yd 178 dB rms re 1 µPa at 1yd	0.01 to 40	186 186	(Kipple 2002)
Cargo bulk	25515	173	Low speed diesel direct drive	Underway at 16 knots 140 rpm	192 dB rms re 1 µPa @ 1 m		201	(Arveson and Vendittis 2000)
Cargo bulk				Held in dock using two tugs	188.8 dB rms re 1 µPa @ 1 m	0.01 to 20	198	(Blackwell and C.R.Greene 2002)
Cargo freight				In dock loading and unloading	133.5 dB rms re 1 µPa @ 1 m	0.01 to 20	142	(Blackwell and C.R.Greene 2002)
Container Vessel				Loaded	181 dB rms re 1 µPa @ 1 m	0.01 to 10	190 100 to 5400 Hz	(Galli, Hurlbutt et al. 2003)
Large gravel carrier	19853 (gross tonnage)	219	9464 BHP	Underway	117.6 dB rms re 1 µPa @ 134m 156.66 dB rms re 1 µPa @ 1m	0.02 to 20	166	(Carr, Laurinolli et al. 2006)
Tanker				50% Loaded	180 dB rms re 1 µPa @ 1 m	0.01 to 10	189 100 to 6700 Hz	(Galli, Hurlbutt et al. 2003)
Ice Breaker	6264 (6166 tons)	100	Diesel Electric	Bubbler Noise	201 dB re 1 µPa @ 1 m Source level (95th percentile)	0.1 to 20	210 Continuous White noise most energy below 5kHz	(Erbe and Farmer 2000)
Ice Breaker	6264 (6166 tons)	100	Diesel Electric	Propeller cavitation noise during ramming of ice	205 dB re 1 µPa @ 1 m Source level (95th percentile)	0.1 to 20	214 Sharp pulses at 11 Hz	(Erbe and Farmer 2000)
Rig tender	2600	64	4 engines each 2000 HP	Underway at 11 knots	136 dB rms re 1 µPa @ 400 m		182	(McCauley 1998)

Vessel Type	Displacement Tonne	Length m	Propulsion	Activity	Measurement	Measurement band kHz	Extrapolation dB re 1 μPa m peak to peak	Reference
Seismic Survey Vessel	3779 (gross tonnage)	84.9 (279 ft)	5 Diesel electric engines A total of 10123 BHP	Seismic Survey	125 to 132 dB rms re 1 μPa @ 500m	0.01 to 20	Aspect dependent	(Patterson, S.B. Blackwell et al. 2007)
Tug/ supply/fire fighting vessel	1894 gross tonnage	67 (218 ft)	4 main engines with total output 10600 kW 2* 600Hp thruster 1*800 HP thruster	Offshore support vessel	187.76 dB rms re 1 μPa @1m[53]	0.001 to 10	197	(Austin, MacGillivray et al. 2005)
Icebreaking Tug and supply vessel	1190 (gross tonnage)	62.5 (205 ft)	2 G.M. 20-645-E7 turbocharged diesel engines Total of 7200 BHP	Seismic survey support	127 to 135 dB rms re 1 μPa @ 500m	0.01 to 20	Aspect dependent	(Patterson, S.B. Blackwell et al. 2007)
Tug	783 (gross tonnage)	47 (153 ft)	4 caterpillar V6 D399 diesel engines Total of 4500 BHP	Seismic survey support	122 dB rms re 1 μPa @ 500m 160.8 dB rms re 1 μPa @ 1 m[54]	0.01 to 20	170	(Patterson, S.B. Blackwell et al. 2007)
Tug with Barge[55]	Tug Gross tonnage 104	19.5 (64 ft) Beam8.2 (27 feet) Draft 1 (3.5 feet)	Main engine 1095 hp diesel 1.01 diameter propeller 5 blades	Unloaded Speed 7.4 knots Unloaded Speed 8.7 knots Partial load Speed 6.4 knots	173 dB re 1 μPa @ 1 m Source level 182 dB re 1 μPa @ 1 m Source level[56] 177 dB re 1 μPa @ 1 m Source level	0.01 to 20	182 Broadband 10 to 2500 Hz with broad peak between60 and 600Hz 191 Lower LF content, broadband 50 to 5000 Hz 186 Lower LF content, broadband 50 to 5000 Hz	(Zykov and Hannay 2006)
Tug				Pushing gravel barge	163.8 dB rms re 1 μPa @ 1 m	0.01 to 20	173 Most of energy in 100 to 2000Hz band with tones at multiple of blade rates	(Blackwell and C.R.Greene 2002)
Tug				Docking gravel barge	178.9 dB rms re 1 μPa @ 1 m	0.01 to 20	188	(Blackwell and C.R.Greene 2002)
Offshore fishing		20	Single V12 450 Hp	Underway at 12.5 knots	139 dB rms re 1 μPa @ 30 m		174	(McCauley 1998)
Self Propelled barge		42.7 (140 ft) Beam 12 (40ft)	Two 220 hp diesel engines Two 1.016m propellers	Unloaded at 2.8m/sec Partial loading At 2.8m/sec	173 dB rms re 1 μPa @ 1 m 174 dB rms re 1 μPa	0.01 to 20	181 183 Broadband noise between 10 and	(Zykov and Hannay 2006)

Vessel Type	Displacement Tonne	Length m	Propulsion	Activity	Measurement	Measurement band kHz	Extrapolation dB re 1 µPa m peak to peak	Reference
					@ 1 m		5000 Hz	
Self Propelled barge		42.7 (140 ft) Beam 12 (40ft)	Two 220 hp diesel engines Two 1.016m propellers	Unloaded at 2.8m/sec Full loading At 2.5m/sec Full loading At 3m/sec	163 dB rms re 1 µPa @ 1 m 168 dB rms re 1 µPa @ 1 m 174 dB rms re 1 µPa @ 1 m	0.01 to 20	172 177 183	(Zykov and Hannay 2006)
Cabin cruiser		9.1 to 10.3 (30 and 34 ft)	Diesel Jet drive 420 & 2*310 HP	Underway 10 knots Underway 20 knots	160 dB rms re 1 µPa at 1yd 167 dB rms re 1 µPa at 1yd	0.01 to 40	169 176	(Kipple 2003)
Crew boat		8.5 (28 feet)	Two 285 inboard engines and two 773 Hamilton jet pumps	Underway 13 knots	166 dB rms re 1 µPa @ 1 m	0.01 to 20	175	(Zykov and Hannay 2006)
Cabin Cruiser workboats		6.7 to 19.7 (22 to 65 ft)	350 to 375 HP various	Underway 10 knots Underway 20 knots	165 dB rms re 1 µPa at 1yd 182 dB rms re 1 µPa at 1yd	0.01 to 40	174 191	(Kipple 2003)
Boston Whaler		6.4 (21 feet)	250 Hp Johnson 2 cycle outboard	Full speed	147.2 dB rms re 1 µPa @ 1 m	0.01 to 20	156	(Blackwell and C.R.Greene 2002)
Skiff		5.77 (19 ft)	4 stroke outboard 115HP	Underway 10 knots Underway 20 knots	172 dB rms re 1 µPa at 1yd 174 dB rms re 1 µPa at 1yd	0.01 to 40	181 183	(Kipple 2003)
Skiff		4.9 (16 feet)	50 Hp 4 stroke outboard.	Underway 13 knots	166 dB rms re 1 µPa @ 1 m	0.01 to 20	175	(Zykov and Hannay 2006)
Skiff		4.25 to 5.5 (14 to 18 ft)	2 or 4 stroke outboard 25 to 40 HP	Underway low speed Underway 20 knots	157 dB rms re 1 µPa at 1yd 169 dB rms re 1 µPa at 1yd	0.01 to 40	166 178	(Kipple 2003)
Flat bottom workboat			90 Hp Outboard	Idle Full Speed	141 dB rms re 1 µPa @ 1 m 163 dB rms re 1 µPa @ 1 m	0.01 to 10	150 500 to 1700 Hz 172 100 to 3000Hz	(Galli, Hurlbutt et al. 2003)
Small work boat			Twin Caterpillar inboard, 210 HP	Idle Full Speed	148 dB rms re 1 µPa @ 1 m 162 dB rms re 1 µPa @ 1 m	0.01 to 10	157 200 to 1800 Hz 171 200 to 4600Hz	(Galli, Hurlbutt et al. 2003)

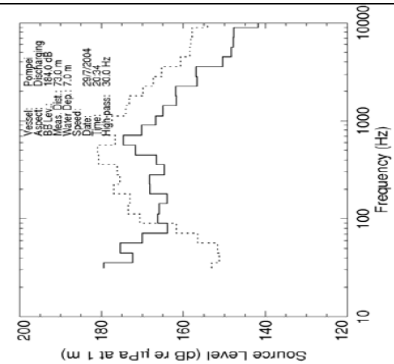
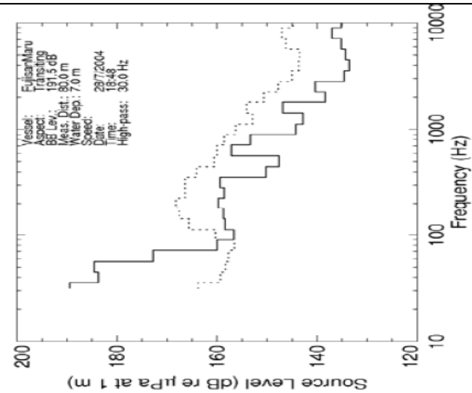
Vessel Type	Displacement Tonne	Length m	Propulsion	Activity	Measurement	Measurement band kHz	Extrapolation dB re 1 μPa m peak to peak	Reference
Avon rubber boat		5.4 (18 feet)	80 Hp 4 cycle engine	Full Speed 57.6 k/hr 31 knots	155.9 dB rms re 1 μPa @ 1 m	0.01 to 20	165	(Blackwell and C.R.Greene 2002)

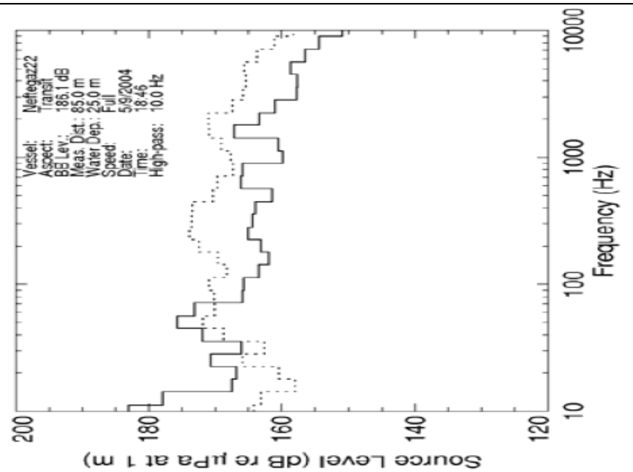
Table 3.7.4 Hovercraft

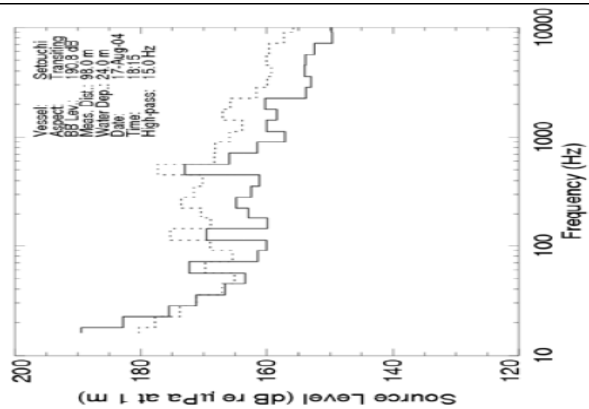
Vessel Type	Displacement Tonne	Length m	Propulsion	Activity	Measurement	Measurement band kHz	Extrapolation dB re 1 μPa m peak to peak	Reference
Hovercraft	Griffon 2000D 2268 kg payload	11.9	12 blade lift fan Blade rate 420Hz Thrust propeller blade rate 92Hz	Underway 20knots	133 dB rms at 6.5m (1m depth) 131 dB rms at 7m depth	0.01 to 10	158	(Richardson 2006) (Blackwell and Greene 2005)
Hovercraft	AP.1-88		1800 or 2100 RPM	Underway over Ice covered river	141 dB rms at 16m (1.5 to 0.5m hydrophone depth below ice layer)			(Roof and Fleming 2001)

Table 3.7.5 Snowmobile

Type	Activity	Measurement	Measurement band	Extrapolation dB re 1 μPa m peak to peak	Reference
Snowmobile	In progress over Ice covered river	140 dB rms at 3m (1.5 to 0.5mhydrophone depth below ice layer)			(Roof and Fleming 2001)

Support vessel – *Pompei* 	Support vessel to the CSD, principal duties to hold the end of the floating hose and tow the pipe in event of storm. Normal operations are on DP but can operate on anchors *Figure 3.19*	 1/3-octave source levels abeam of *Pompei* while discharging spoil. **BROADBAND LEVEL (dB re 1 µPa) = 184.0**
Support vessel – Tug (*Fujisan Maru*) 	Support vessel to the CSD, used to keep the floating hose on station in event of rougher weather.[57] *Figure 3.20 (Hannay, MacGillivray et al. 2004)*	 1/3-octave source levels abeam of *Fujisan Maru* while transiting. **BROADBAND LEVEL (dB re 1 Pa) = 191.5**

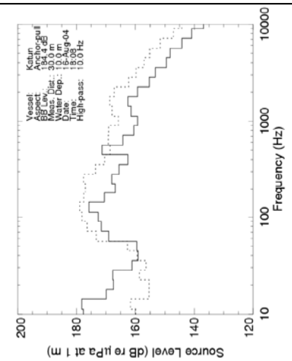
Supply vessel 	Supply of food, supplies and consumables to pipe lay spread. Vessel located along side pipe lay barge or off location getting supplies from shore. Picture typical of vessel type. *Figure 3.21 (Hannay, MacGillivray et al. 2004)*	 1/3-octave source levels for *Neftegaz 22* transiting at full speed. **BROADBAND LEVEL (dB re 1 Pa) = 186.1**

Setouchi Surveyor 	Survey vessel to support pipe lay operations. Route is surveyed before dredging operations, before pipe lay operations and after pipe lay. *Figure 3.22 (Hannay, MacGillivray et al. 2004)*	 1/3-octave source levels to the side of the *Setouchi Surveyor* while transiting. **BROADBAND LEVEL (dB re 1 Pa) = 190.8**

AHTS - Anchor Handler Tug Supply Vessel

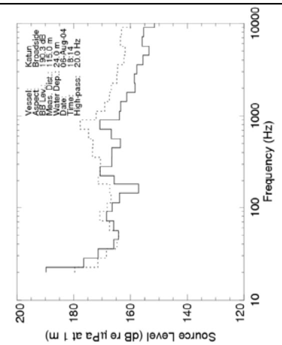
Dedicated anchor handler vessels for the pipe lay barge. Vessels used to reposition the anchors required to keep pipe lay barge on station. Alternative vessels for Castoro 2 are being considered (see DH Delta catamaran)[58]

Figure 3.23 (Hannay, MacGillivray et al. 2004)



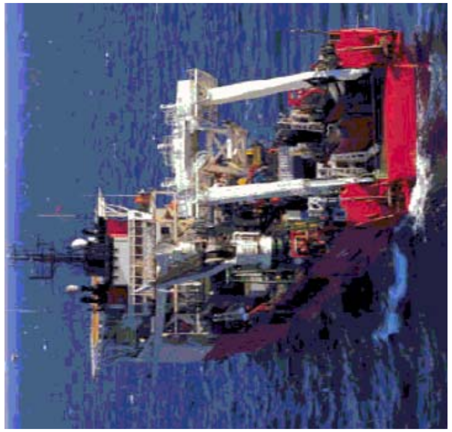
1/3-octave source levels of *Katun* while performing anchor pull.

BROADBAND LEVEL (dB re 1 Pa) = 184.4



1/3-octave source levels abeam of *Katun* while transiting.

BROADBAND LEVEL (dB re 1 Pa) = 190.3

Anchor handling for pipe lay spread - DH Delta 	As alternative to conventional anchor handlers. Vessels are more weather sensitive. *Figure 3.24*	REPRESENTATIVE VESSEL NOT MEASURED – 1/3-OCTAVE SOURCE LEVEL PLOT NOT AVAILABLE NOISE PRODUCED BY THIS TYPE OF VESSEL WOULD LIKELY BE SIMILAR TO THAT SHOWN FOR THE DN43 (SEE ABOVE HISTOGRAM).
Diving Support Vessel – Bar Protector 	Diving support vessel used to perform the tie-in and commissioning of the pipelines. Vessel is usually kept on station with dynamic positioning, however it can be moored using anchors *Figure 3.25 (Hannay, MacGillivray et al. 2004)* [59]	REPRESENTATIVE VESSEL NOT MEASURED – 1/3-OCTAVE SOURCE LEVEL PLOT NOT AVAILABLE NOTE: PRIMARY NOISE PRODUCED BY SUCH A VESSEL WOULD LIKELY BE ATTRIBUTED TO THE ONBOARD POWER PLANTS AND WINCH SYSTEM, NOT TO THE PROPULSION SYSTEM AS THE VESSEL WOULD BE ANCHORED AND NOT TRANSITING OR EMPLOYING THRUSTERS.

3.8 Sites

Noise from production platforms or construction sites is very variable and generally depends upon vessels operating around the site (Richardson 2006) (Swift and Thompson 2000) where crew boats, self propelled barges and tugs are the main contributors to the sound field. The vessel noise may be detected at ranges up to 30km from the site. Without vessels the broadband noise of the Northstar site reached background levels at a range between 1 and 4 km with vessel activity the background level was reached at a range of between 30 and 40 km (Blackwell and Greene 2005).
Narrow band noise events have been associated with gas turbine use on FPSO (Floating Production Storage and Offloading vessel) and valve and compressor problems again on an FPSO (Swift and Thompson 2000).

The noise from Douglass oil and gas facility was found to vary significantly from time to time. The deeper hydrophones showed higher levels of sound (Nedwell 2003).

The most significant amount of literature is available on the gravel island production site “Northstar” in the Beaufort sea. (Richardson 2006), (Spence 2006), (Blackwell, Greene et al. 2004) and (Blackwell and Greene 2005).

During the construction phase of the ice road, gravel trucks trenching and other operations produced broad band noise levels (10 – 10000 Hz) in the order of 124 dB at 100m. (Greene, Blackwell et al. 2007). It was found difficult to isolate individual pieces of machinery as, in general, multiple activities were in progress during measurements.

During production the prime noise path is a direct sound path through the gravel of the Island, a second path was found to be direct radiation from systems connected directly to the sea. The sounds produced by “Northstar” were found to comprise a variety of tones which were intermittent in nature, probably associated with the use of large machinery on the island. Two tones 30Hz and 60Hz were found to be continuous.

Measurements of the Phillips oil platform also revealed a number of tones mainly below 500Hz the most prominent being around 80Hz (Blackwell and C.R.Greene 2002).

The noise investigations of the “Northstar” were inconclusive as to the generation of noise by the buried pipeline. (Spence 2006), however (Richardson 2006) suggests that the source of unknown noise incurred whilst measuring the Northstar production island, may be due to turbulent flow within the oil well.

Decommissioning

The removal of structures from the seabed may be carried out by cutting, using disc cutters or by explosives. Little documentation on either of these processes is available, however a recent report describes detailed modelling techniques for calculation of impact zones during explosive removal of offshore structures, (Dzwilewski and Fenton 2003).

Type	Activity	Water Depth m	Measurement	Extrapolation dB re 1 μPa m peak to peak	Characteristics	Comments	Reference
Douglass oil and gas platform		9		195.6 at depth of 5m 225.7 at depth of 10m	Strong Tonal components from machinery	Rig support vessel in attendance.	(Nedwell 2003)
Northstar oil production island	Construction & production		Max 141 dB rms Min 81 dB rms @ 550m	177 117	Constant tones at 30, 60 & 87Hz	Vessels in attendance	(Richardson 2006)
The Phillips oil Platform in Cook Inlet		25m	107 dB rms @0.34 km	130[60]	Tones below 500Hz Prominent tone at 80Hz		(Blackwell and C.R.Greene 2002)
General Digger operations	Removing concrete & welding noise	Shallow	113 dB rms @ 1m average 119 dB rms @ 1m peak	122 average peak 128 dB		Activity during hydraulic piling	(Nedwell, Macneish et al. 2005)
Gravel trucks on ice road	23m^3	Shallow water/ice	123dB rms at 100m		Broadband 10 to 10000Hz Centre of strongest 1/3 OB 160 Hz	Construction of ice road	(Greene, Blackwell et al. 2007)
Ditch witch	Ice cutting equipment	Shallow water/ice	122dB rms at 100m		Broadband 10 to 10000Hz Centre of strongest 1/3 OB 20 Hz	Construction of ice road	(Greene, Blackwell et al. 2007)
Trenching with backhoe		Shallow water/ice	125 dB rms at 100m		Broadband 10 to 10000Hz Centre of strongest 1/3 OB 10 Hz	Construction of ice road	(Greene, Blackwell et al. 2007)
Dozer		Shallow water/ice	114 dB rms at 100m		Broadband 10 to 10000Hz Centre of strongest 1/3 OB 10 Hz	Construction of ice road	(Greene, Blackwell et al. 2007)

3.9 Sonars and acoustic devices

Passive sonar is the use of hydrophones (underwater microphones) to listen for noise in the ocean and has no impact other than the towing vessel noise, on the environment.

Active sonar is the use of underwater sound for locating and surveying within the ocean and is used extensively by the oil and gas industries as well as all other vessels using the oceans.

Other acoustic transmitting devices are used to activate release mechanisms, discourage seals and other marine life from approaching fish farms, fish nets or other potentially hazardous areas.

Sonar can be grouped into three categories (Tasker 2005; Tasker, Clark et al. 2005);

Low Frequency, sounds produced below 1000 Hz

Mid Band, sounds in the band 1 to 10 kHz

High frequency, sounds in the band 10 kHz upwards

Low frequency sonar is used by the military for long range detection of quiet submarines using a large Low Frequency Array (LFA), (SURTASS-LFA) and by oceanographers for Acoustic Thermometry of Ocean Climate (ATOC) (section 4.1). The oil industry’s seismic survey process uses low frequency impulses for geological profiling, this is detailed in section 3.5.

Mid band sonar is typically used for finding and tracking of underwater targets. Bathymetric sonar uses mid band frequencies for wide area low resolution surveys.

High Frequency sonar is used for depth sounders and fish finding, they generally use low power and narrow beam widths. Most vessels used by the oil and gas industry will be fitted with some form of high frequency sonar to measure water depth.

A typical survey of the seabed and sub-surface geology before placement of a drilling rig or pipe line might include high resolution seismic survey, side scan sonar and multibeam bathymetry.

Unlike seismic pulses the duration of sonar chirps are not observed to increase with range (Patterson, S.B. Blackwell et al. 2007).

Table 3.9.1 Sonars and acoustic devices

Sound Source	Typical frequency	Duration mSec	Source Levels dB re 1 μPa m	Extrapolation dB re 1 μPa m peak to peak	Bandwidth	Beam angle Beam width degrees[61]	Reference
Bottom Profilers	0.4 to 30 kHz	0.1 to 160	200 to 230	209 to 239		150	(Heathershaw, Ward et al. 2001)
Sub surface imaging	1 to 12 kHz Typically 3.5 kHz	Sweep or chirp	204	213			(O'Brien, Arnt et al. 2002) (Gordon, Gillespie et al. 2002) (Tasker, Clark et al. 2005)
Chirp Sonar Datasonics chrip11	2 to 7 or 8 to 23 kHz	Pulse interval 0.25 to 5 sec	189.2 peak 184 SPL 171 SEL	195			(Patterson, S.B. Blackwell et al. 2007)
Underwater telephone	5to 11 kHz	Continuous	180 to 200	189 to 209			(Heathershaw, Ward et al. 2001)
GLORIA	6 to 7 kHz						(Tasker, Clark et al. 2005)
Acoustic releases	7 to 50 kHz	Pulses 1	192 dB 0 to peak	198		omni	(O'Brien, Arnt et al. 2002)
Navigation transponders	7 to 60 kHz	3 to 40	180 to 200	189 to 209			(Heathershaw, Ward et al. 2001)
Fugro Sea Floor Survey Type SYS09	9 and 10 kHz		230	239			(Tasker, Clark et al. 2005)
Silent Scrammer	9.7 kHz	3.3 to 14mSec	Max Source Level 191	199			(Lepper 2007)
Acoustic Harassment Devices (AHD)	10kHz	Typically 0.5 to 2s Duty Cycle 50%	Typically 185 to 190dB	194	600 Hz	omni	(Roussel 2002) (Liss, Briggs et al. 2005)

Sound Source	Typical frequency	Duration mSec	Source Levels dB re 1 µPa m	Extrapolation dB re 1 µPa m peak to peak	Bandwidth	Beam angle Beam width degrees[62]	Reference
Acoustic Deterrent Devices (ADD)	Typically 12 – 17 kHz But maybe up to 160kHz	Typically 300ms	Typically between 120 and 140dB	129 to 149		omni	(Roussel 2002)
Depth sounders	12 to 36kHz	pulse	180 to 220	189 to 229		6 Directly below vessel	(Heathershaw, Ward et al. 2001)
Depth sounder Atlas Hydrosweep DS-2	15.5 kHz	pulse	220	229		Directly below vessel	(Tasker, Clark et al. 2005)
Acoustic Doppler current profilers	38 to 150 kHz	Continuous					(O'Brien, Arnt et al. 2002)
Sidescan Sonar	50 to 500kHz	0.01 to 0.1	220 to 230	229 to 239			(Heathershaw, Ward et al. 2001)

3.10 Tools

Minimal information is available on the use of underwater tools. The only published work available is Nedwell 2004 which gives very brief information.

Table 3.10.1 Underwater Tools

Type			**Activity**	**Water Depth** m	**Measurement**		**Extrapolation** dB re 1 μPa m peak to peak	**Comments**	**Reference**
Diver Tools			Drills, wrenches, grinders, bolt gun, jack hammer		Peak source level 200 dB re 1 μPa m		206		(Nedwell 2004)

4 Other Sounds in the Oceans

The following tables are listed for comparative purposes and give examples of the range of sounds the man made, geological and meteorological noise sources and biological noise.

Table 4.1 Man made noise sources

Sound Source	**Sound Pressure level dB re 1 μPa m**	**Ping Energy dB re 1 μPa ^2s**	**Ping Duration**	**Duty Cycle**	**Peak Frequency**	**Band Width**	**Directionality**	**Source**
Underwater Nuclear Device	328		1000s	Intermittent	Low	Broad	Omni	(Liss, Briggs et al. 2005)
Ship Sock Trial	299		100s	Intermittent	Low	Broad	Omni	(Liss, Briggs et al. 2005)
Military Sonar Surtass / Low Frequency Active (LFA)	235	233	60 to 100s		100 to 500 Hz			(Liss, Briggs et al. 2005)
Military Sonar (AN /SQS-53C)	235	232	0.5 to 2.5s	6%	2600 to 3300 Hz	Narrow	Horizontal	(Liss, Briggs et al. 2005)
Military Sonar (AN /SQS-56)	223				2600 to 3300 Hz			(Tasker, Clark et al. 2005)
Research Sonar ATOC	195		20 min	8%	75 Hz	37.5	Omni	(Liss, Briggs et al. 2005)

Table 4.2 Geological and meteorological noise sources

	Maximum Source Level[63] dB re 1 μPa m	**Frequency range**		**Extrapolation**		
		Hz		dB re 1 μPa m peak to peak		
Undersea earthquake	272	20 to 1000	Magnitude 4.0 on Richter scale (energy integrated over 50Hz bandwidth)	281		(Heathershaw, Ward et al. 2001)
Seafloor volcanic eruption	255	20 to 1000	Massive steam explosions	264		(Heathershaw, Ward et al. 2001)
Lightning strike on sea surface	250	20 to 1000	Random events during storms	259		(Heathershaw, Ward et al. 2001)

Table 4.3 Biological Noise

	Maximum Source Level[64] dB re 1 μPa m	**Frequency range**		**Extrapolation**		
		Hz		dB re 1 μPa m peak to peak		
Bottlenose Dolphin	226	40 to 140 kHz	Echolocation Clicks	235		(Harland and Richards 2005)
Fin whale	200	20 to 1000	Vocalisations; pulses, moans	209		(Heathershaw, Ward et al. 2001)
Humpback whale	192	20 to 1000	Fluke and Flipper slaps	201		(Heathershaw, Ward et al. 2001)
Bowhead whale	189	20 to 1000	Vocalisations ; songs	198		(Heathershaw, Ward et al. 2001)
Blue whale	188	20 to 1000	Vocalisations ; low frequency moans	197		(Heathershaw, Ward et al. 2001)
Right whale	187	20 to 1000	Vocalisations ; impulsive signal	196		(Heathershaw, Ward et al. 2001)
Gray whale	185	20 to 1000	Vocalisations ; moans	194		(Heathershaw, Ward et al. 2001)
Harbour Porpoise	170	40 to 140 kHz	Echolocation Clicks	179		(Harland and Richards 2005)
Open ocean ambient noise	74 to 100	20 to 1000	Estimate for offshore central California sea state 3-5.			(Heathershaw 2001)

5 Other Useful Literature

The following documents represent technical information relevant to underwater sound and the oil and gas industries.

5.1 Technical information and specifications

Technical documentation which has been used in the compilation of this report

Special Report of the SEG Technical Standards Committee	SEG standards for specifying marine seismic energy sources	(Johnston, Reed et al. 1988)
Seismic Energy Sources	1968 Handbook	(Kramer, Peterson et al. 1968)
The air gun impulsive underwater transducer	Bolt Beranek and Newman Inc	(Barger and Hamblen 1980)
Impact of seismic surveys on marine life	Leading Edge	(Gausland 2000)
Environmental Aspects of Airguns	Shell EXPRO	(van de Sman 1998)
Impacts of Marine acoustic technology on the Antarctic environment.	SCAR Ad Hoc group on marine acoustic technology and the environment	(O'Brien, Arnt et al. 2002)
The Environmental effects of Underwater Explosions with Methods to Mitigate Impacts	U.S. Army Corps of Engineers	(Keevin and Hempen 1997)

5.2 Reports relating to underwater noise and the oil industry

The environmental impacts of shipping: a whales eye view of ships	IFAW (International Fund for Animal Welfare)	(Leaper and Papastravrou)
Sound effect on the environment interview with Dr Leung	MER (Marine Engineers Review)	(Leung 2001)
An Overview of Offshore oil and gas exploration and production activities	Department of Trade and Industry (UK)	(DTI 2006)
A Review of the effects of seismic survey on marine mammals	Marine Technology Society Journal	(Gordon, Gillespie et al. 2003)
Oceans of Noise	Whale and Dolphin Conservation Society	(Simmonds, Dolman et al. 2004)
Underwater noise	IFAW & NRDC	(IFAW and NRDC 2004)
Sounding the depths 2	Natural Resources Defence Council	(Jasney, J.Reynolds et al. 2005)
Marine Seismic Surveys- A study of environmental implications	Centre for Marine Science and Technology Curtin University Perth	(McCauley, Fewtrell et al. 2000)
Mitigating, monitoring and assessing the effects of anthropogenic sounds on beaked whales	NOAA Southwest Fisheries Science centre	(Barlow 2006) (Barlow and Gisner 2006)
Potential impact of offshore human activities on gray whales	NOAA	(Moore and Clarke 2002)
Shunpiking	Margaree Environmental Association and the Save Our Seas Coalition	(Clark 2002)
Sonic Impact: A Precautionary Assessment of Noise Pollution from Ocean Seismic Surveys	Greenpeace	(Cummings and Brandon 2004)
Underwater Noise: Death Knell of our Oceans?	Dalhousie University	(Weilgart 2007)
Underwater Sound and Marine Life	Report of IACMST Working Group on Underwater sound and Marine Life	(Liss, Briggs et al. 2005)
The contribution of marine seismic surveys and their potential impacts on marine biota	An overview of noise sources in the ocean focussing on shipping and seismic exploration. Discusses an overall ocean noise budget	(Hildebrand 2006)
A review of the Impact of Anthropogenic Noise on Cetaceans	An overview including seismic exploration impact	(Perry)
Introduction to air guns and air gun arrays	Review of air guns and environmental issues	(Dragoset 2000)

Impact of Noise on the Marine Environment- a Regulatory Perspective	A presentation by the UK DTI and their stategic view of ocean noise.	{Soderstrom, #121}

5.3 Other literature relating to underwater sound

Sounds, source levels, and associated behaviour of humpback whales, Southeast Alaska.	Measurements of frequency band and signal levels of noise made by humpback whales	(Thompson, Cummings et al. 1986)
Marine Mammals and Noise	Reference work on noise sources and cetaceans	(Richardson 1995)
Assessment of Bioacoustic Impact of Ships on Humpback Whales in Glacier Bay, Alaska	Paper discusses propagation models, audiograms and impact assessment	(Richardson 1995)
Likely Sensitivity of Bottlenose Dolphins to pile-driving noise	Paper discusses pile driving noise and comments on the use of bubble curtains	(David 2006)
Underwater temporary threshold shift in pinnipeds: effects of noise and duration	Effects of underwater noise on pinnipeds and discussion of metrics for underwater sound	(Kastak 2005) (Kastak, Southall et al. 2005)
Policy on Sound and Marine Mammals	Report on an International Workshop	(Vos and Reeves 2005)
Background information on Marine Mammals for Strategic Environmental Assessment 6	Review of noise sources and impact	(Hammond, Northridge et al. 2005)
Ocean Noise and Marine Mammals	Review of noise sources and potential impact on Marine Mammals	(NRC 2003)
International Regulation of Undersea Noise	Review of International law relating to underwater noise pollution	(Scott 2004)
Anthropogenic sound and marine mammal Health: measures of the nervous and immune systems before and after intense sound exposure.	Reports on the nervous system activation and immune function in marine mammals when subjected to air gun and sonar signals	(Romano, Keogh et al. 2004)
Potential Impact of offshore human activities on gray whales (*Eschrichtius robustus*)	Review of all aspects of offshore activities and impact on gray whales	(Moore and Clarke 2002)

Appendix A

Definition of Metrics

A more comprehensive set of metrics is being developed by the Joint Industry Programme (JIP)

A.1 Acoustic Impededance

The speed of sound is related to frequency by the equation C = f λ

Where C = speed of sound in m/sec

F = frequency in Hz

and λ is the wavelength in metres

The particle velocity μ relates to the plane wave pressure p by the equation

$$p = \mu\ (\rho c)$$

The term ρc is known as the characteristic impedance. The large impedance contrast between air and water (approximately a ratio of 3600) implies that the sea surface behaves as an almost perfect reflector of internal sound

A.2 Signal Definitions

Quantity				Abbreviation	Definition
Amplitude					The maximum displacement from zero or mean position of a wave or oscillation
peak level or zero to peak				Peak or 0-p	Same as amplitude of a signal or the maximum value measured from the zero line
peak to peak level				p – p	The maximum displacement between the positive part of the signal and the maximum negative part of the signal
root mean square				rms	The root mean square of a signal (being $1/\sqrt{2}$ of the amplitude of the signal for a sine wave) averaged over the duration of the signal.

To remove doubt, the graph below shows a sinusoidal measurement. The vertical axis represents displacement and the horizontal axis time.

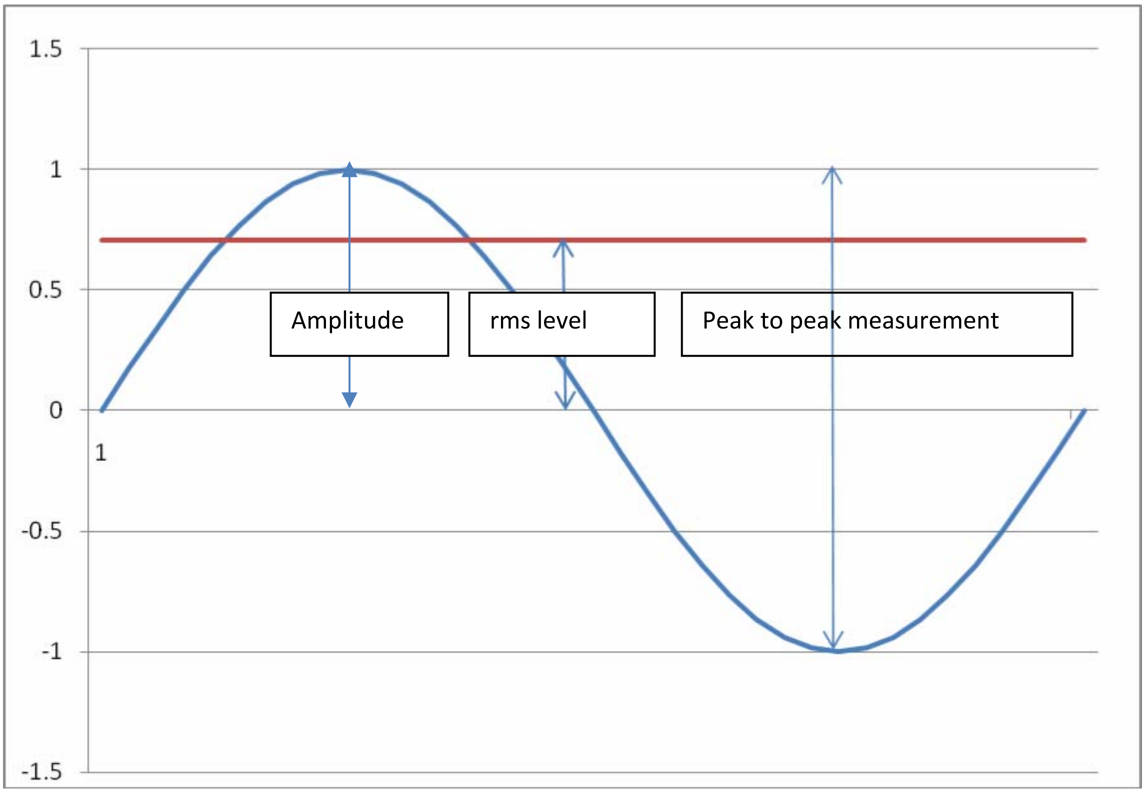


Figure A.1

Note that for a sine wave,

$$Peak\ to\ Peak = 2 * Amplitude$$

$$rms = Amplitude / \sqrt{2}$$

$$Peak\ to\ Peak = rms * \sqrt{2} * 2$$

$$Peak\ to\ Peak\ (dB) = rms\ (dB) + 3dB + 6dB$$

$$Peak\ to\ Peak\ (dB) = rms\ (dB) + 9dB$$

This is not necessarily true for other wave forms and impulsive sounds.

To compare peak levels with rms levels (for a sinusoid pressure wave only) multiply the peak level by 0.7071 to obtain the rms level. (Gausland 2000) (Horowitz 1996)

In describing seismic sources (Johnston 1988) “the source strength is the maximum acoustic pressure radiated by a marine seismic source measured in MPa-m (megapascals referenced to 1 m) in a stated pass band. The zero to peak value is used for near-field signatures. A peak to peak value is normally used for far field signatures.”

In practice a range of metrics have been used to define the source strength most of which are not readily comparable without significant assumptions.

Peak pressure, the instantaneous maximum of the absolute sound pressure, in dB re 1 μPa.

Pulse duration, defined as the time interval between the arrival of 5% and 95% of the total pulse energy measured in seconds.

Sound pressure level (SPL), is calculated by taking the (rms) value of pressure, over a specified period of time to the reference pressure. The SPL of a pulse is thus dependent upon the chosen duration of the pulse (the definition of rms includes an averaging period).

$$SPL = 20\log_{10}(P_{rms} / P_{ref})$$

Sound Exposure Level (SEL), represents the total amount of energy measured during a single noise event referenced to one second. SEL is defined as the squared instantaneous sound pressure integrated over the pulse duration in dB re $1\mu Pa^2 s$

Note that SEL is not influenced by the duration of a pulse as it is a measure of the total energy of the pulse regardless of its duration.

Equivalent Continuous Sound Level (L_{eq}) is the sound level of a steady state sound that has the same total energy as the time varying sound, over a specific time period.

$$L_{eq}(T) = SEL + 10\log(N / T)$$

Where T is the time in seconds and N is the number of events during the time period.

From experience RMS=SEL+10 to 15dB for airgun pulses depending upon amount of reverberation. (Demarchi, Bocking et al. 2006)

A.3 Extrapolation of data points

The extrapolated values are calculated on the basis of spherical spreading to within the water depth and then cylindrical spreading to the receiver position. This is a broad brush statement and gives values which are only indicative of the source level. A number of experimenters have produced a wide range of spreading and absorption coefficients dependent upon conditions local to the area of observation and the nature of the source (O'Brien, Arnt et al. 2002).

A.4 Measurement interpretation

The evaluation of the sources of underwater noise and its effect on marine biota can be assessed in many different ways, two of these are summarised below.

A.4.1 The dBht (species) levels.

The lowest level of sound that a species can perceive over its full range of hearing frequencies can be presented as an audiogram. This is, in effect the filter structure which defines the animals hearing. Levels of sound below the threshold for that species cannot be detected by that species. In the dBht(species) a frequency dependent filter is used to weight the sound. The suffix “ht” relates to the fact that the sound is weighted by the hearing threshold of the species. The dBht(species) level is estimated by passing the sound through a filter which mimics the hearing ability of the species and measuring the sound level after the filter. The level expressed is different for each species and corresponds to the perception of the sound by the species. In effect the scale can be thought of as a dB scale where the species hearing threshold is the reference unit (Nedwell 2003).

The noise level that may be perceived by a particular species can be calculated by applying the dBht filter to the source level across the frequency band.

A.4.2 The M-Weighting

There are major differences in the auditory capabilities of marine mammals, ideally audiograms would be available for all marine mammals, however few are established. The M weighting system places marine mammals into one of five groups based on their hearing function. These five groups are:-

Low frequency Cetaceans	typically Baleen whales
Mid Frequency Cetaceans	typically Beluga whales
High frequency cetaceans	typically porpoises
Pinnipeds in water	
Pinnipeds in air	

The impact of a sound on a marine mammal is assessed by passing the sound through the appropriate filter (one of the five above) and assessing the resulting levels impact on the mammal.

The M-weighting functions have been defined primarily for exposure to strong sounds, including pulsed sounds. This is similar to the C-weighting function used for human exposure to pulsed sounds. (Patterson, S.B. Blackwell et al. 2007)

Appendix B

Conversion tables and graphs

B.1 Cubic inches to Litres.

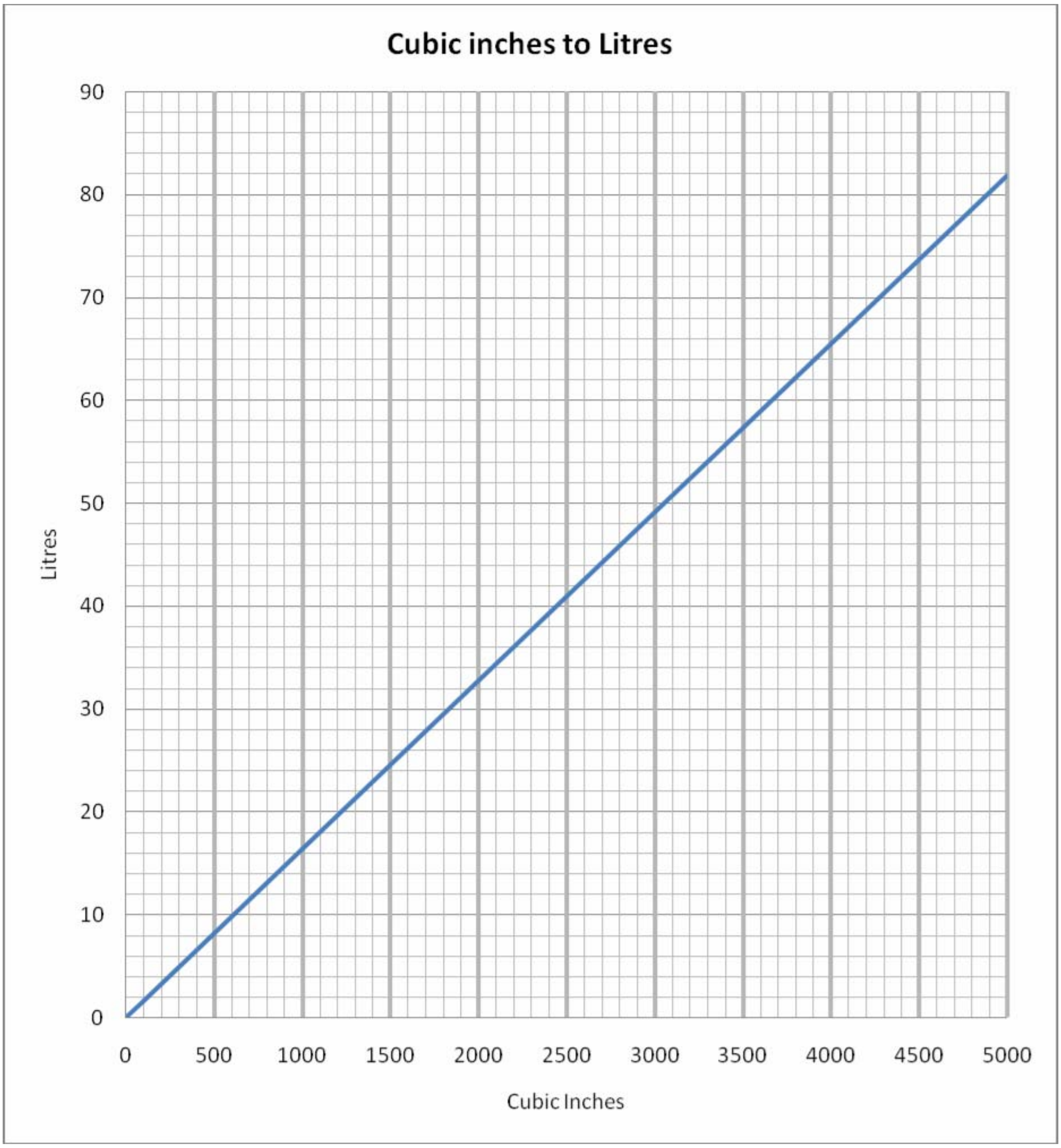


Figure B.1 Conversion of cubic inches to Litres

Conversion based on 1 cubic inch = 0.01638 litres

B.2 Conversion of PSI to Mpa

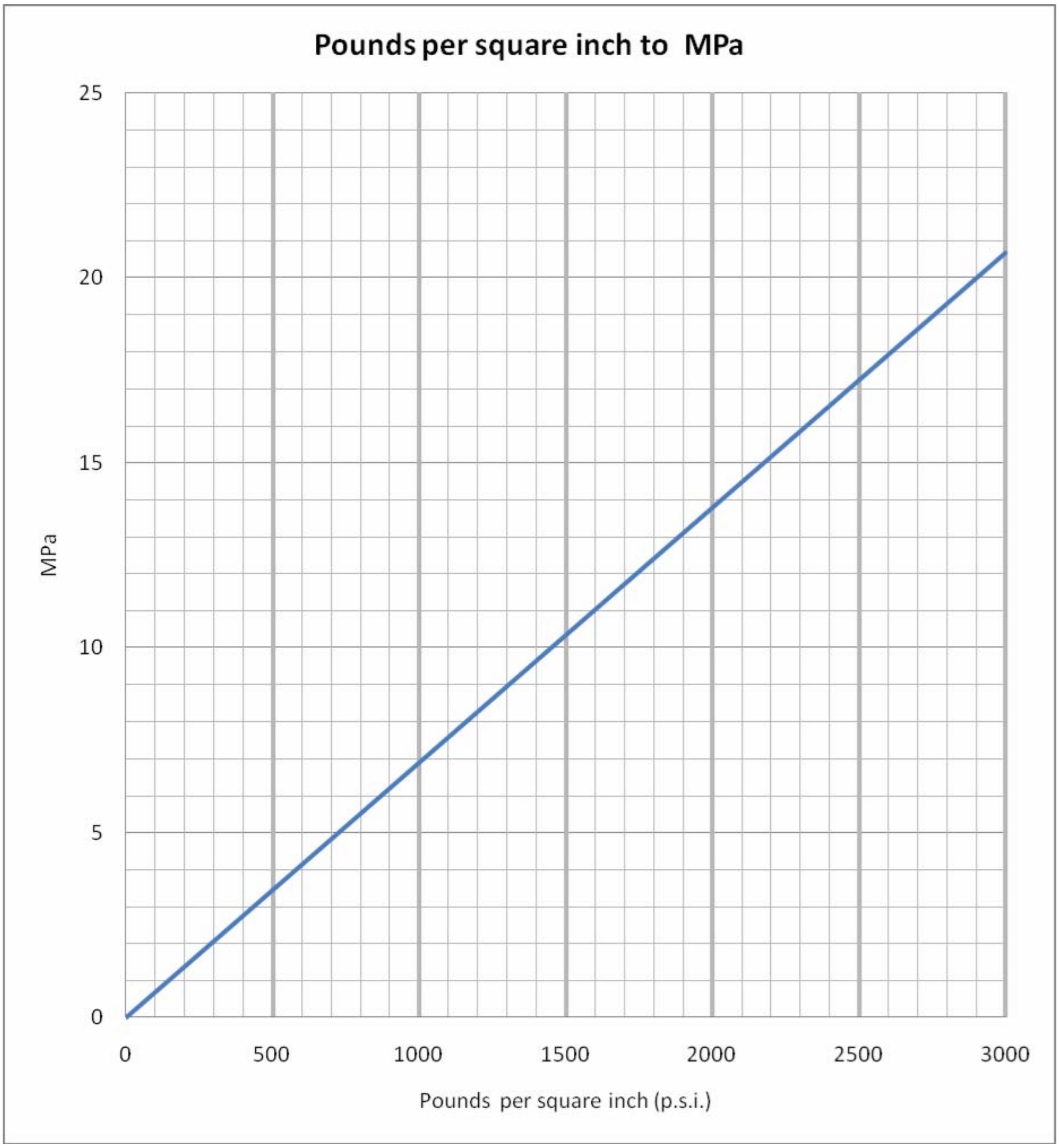


Figure B.2 Conversion of PSI to MPa

Conversion based on 1 psi = $6.894 * 10^3$ Pa

B.3 Sound pressure level conversion µV/µBar to dB re 1V/µPa

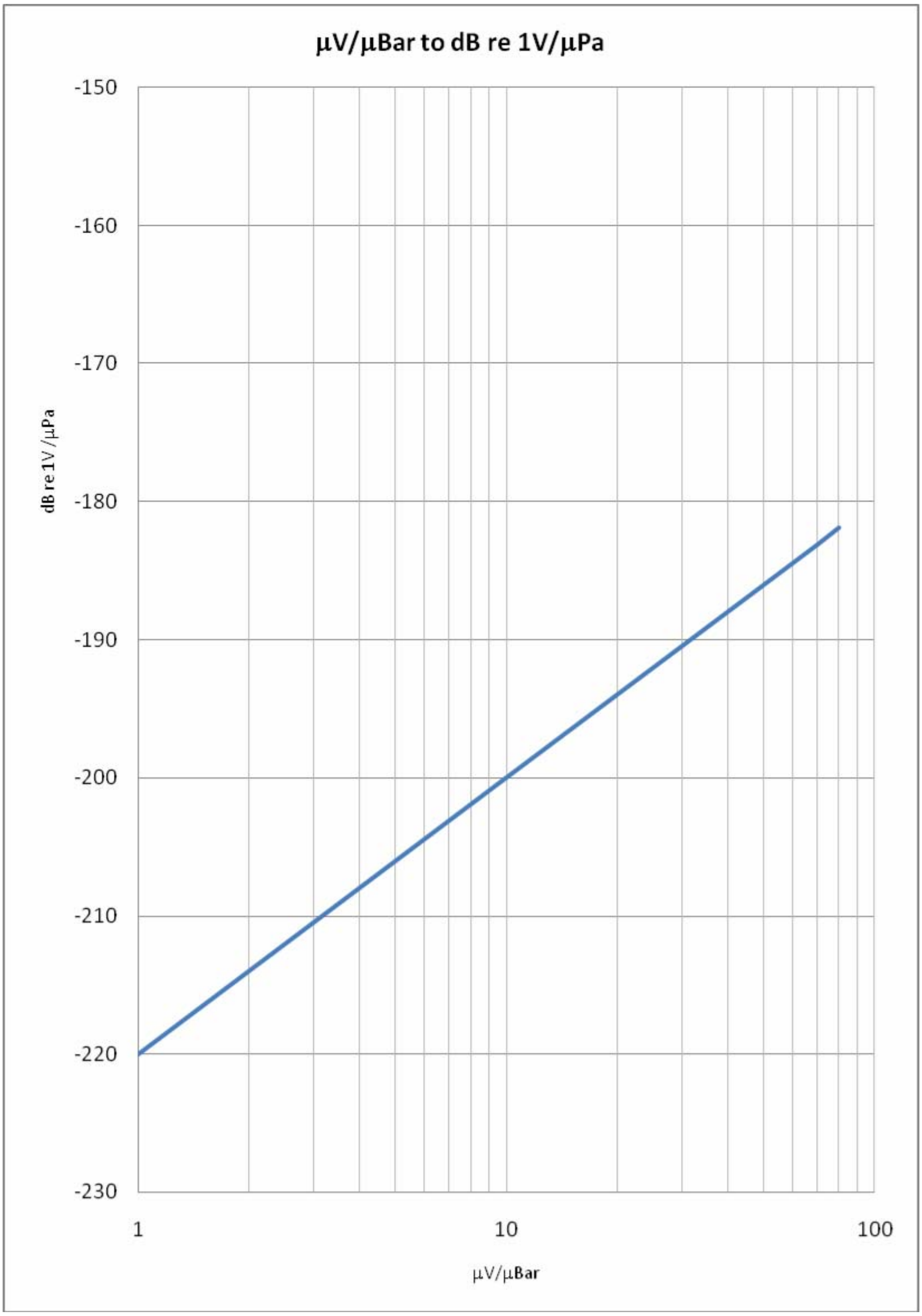


Figure B.3 Sound pressure level conversion µV/µBar to dB re 1V/µPa

Based upon $1\mu Pa = 10^{-5}\ \mu bar$

B.4 Conversion of knots to m/sec

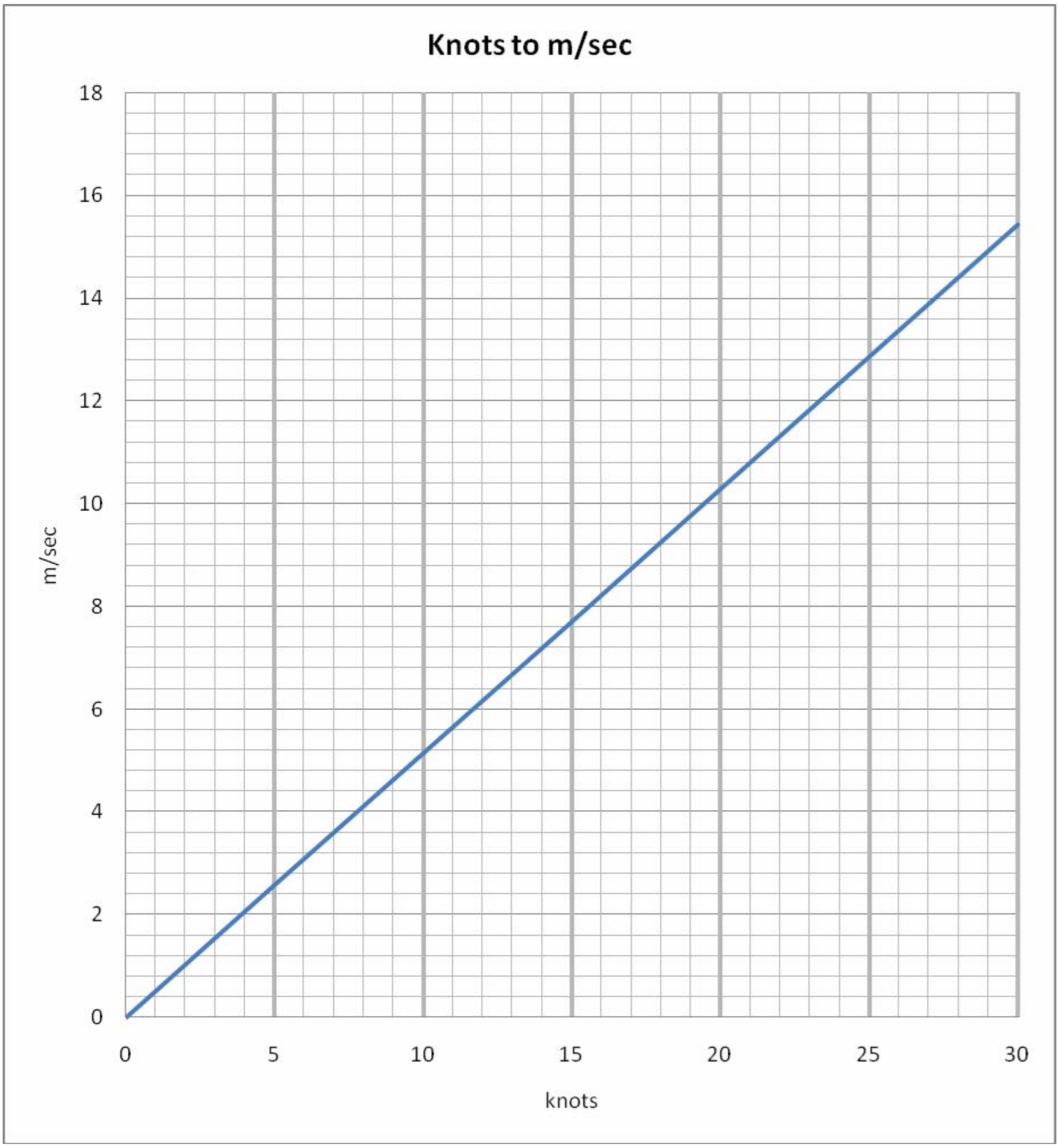


Figure B.4 Conversion of knots to m/sec

Based on conversion 1 knot = 6080 feet/hour = 1.688 ft/sec =0.513 m/sec

B.5 Sound attenuation properties of seawater

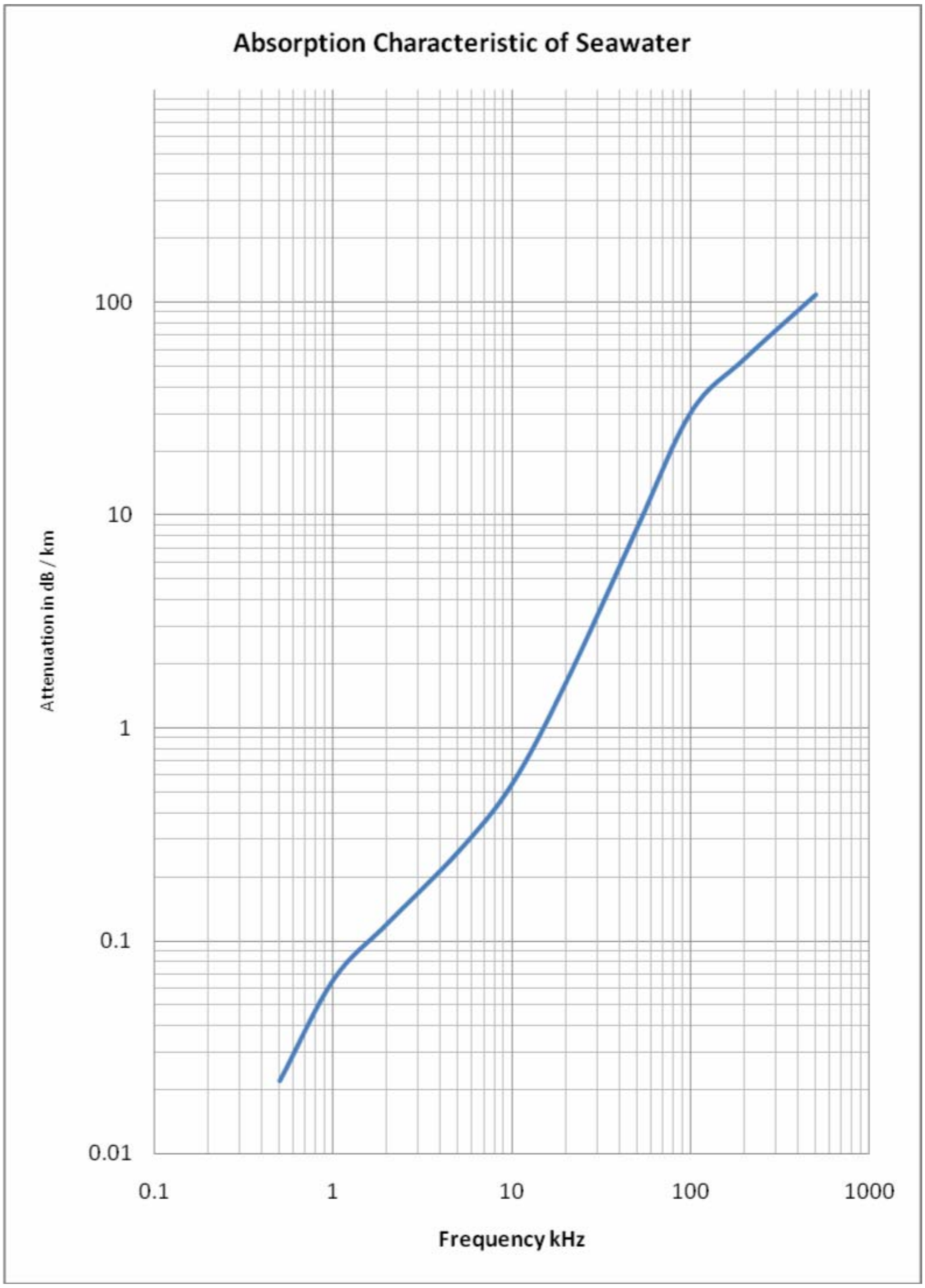


Figure B.5 Sound attenuation properties of seawater adapted from Urick (Urick 1967)

B.6 Ambient noise levels in the ocean

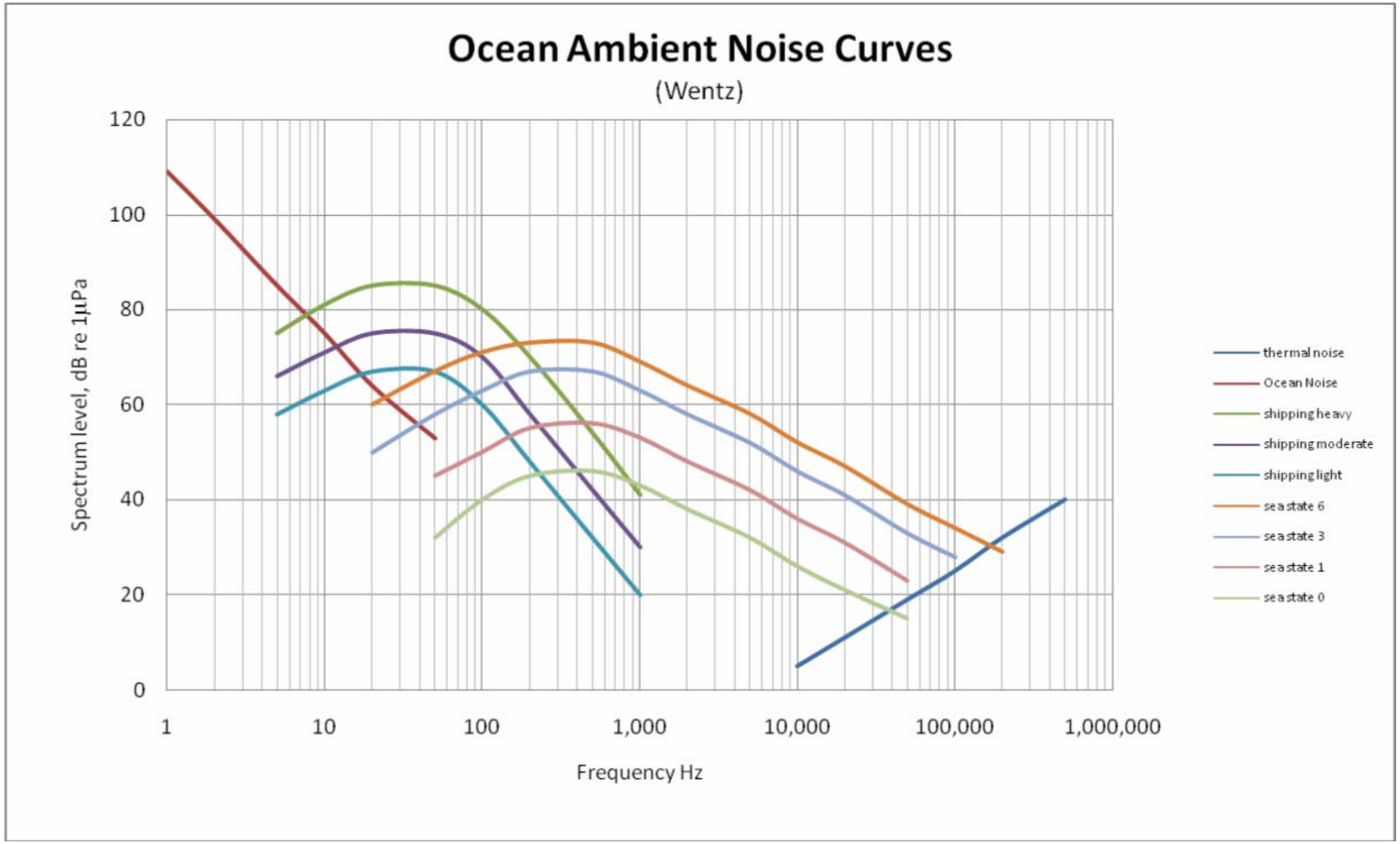


Figure B.6 Ambient noise levels in the ocean adapted from Wentz and Urick (Urick 1967)

B.7 Sound transmission through air

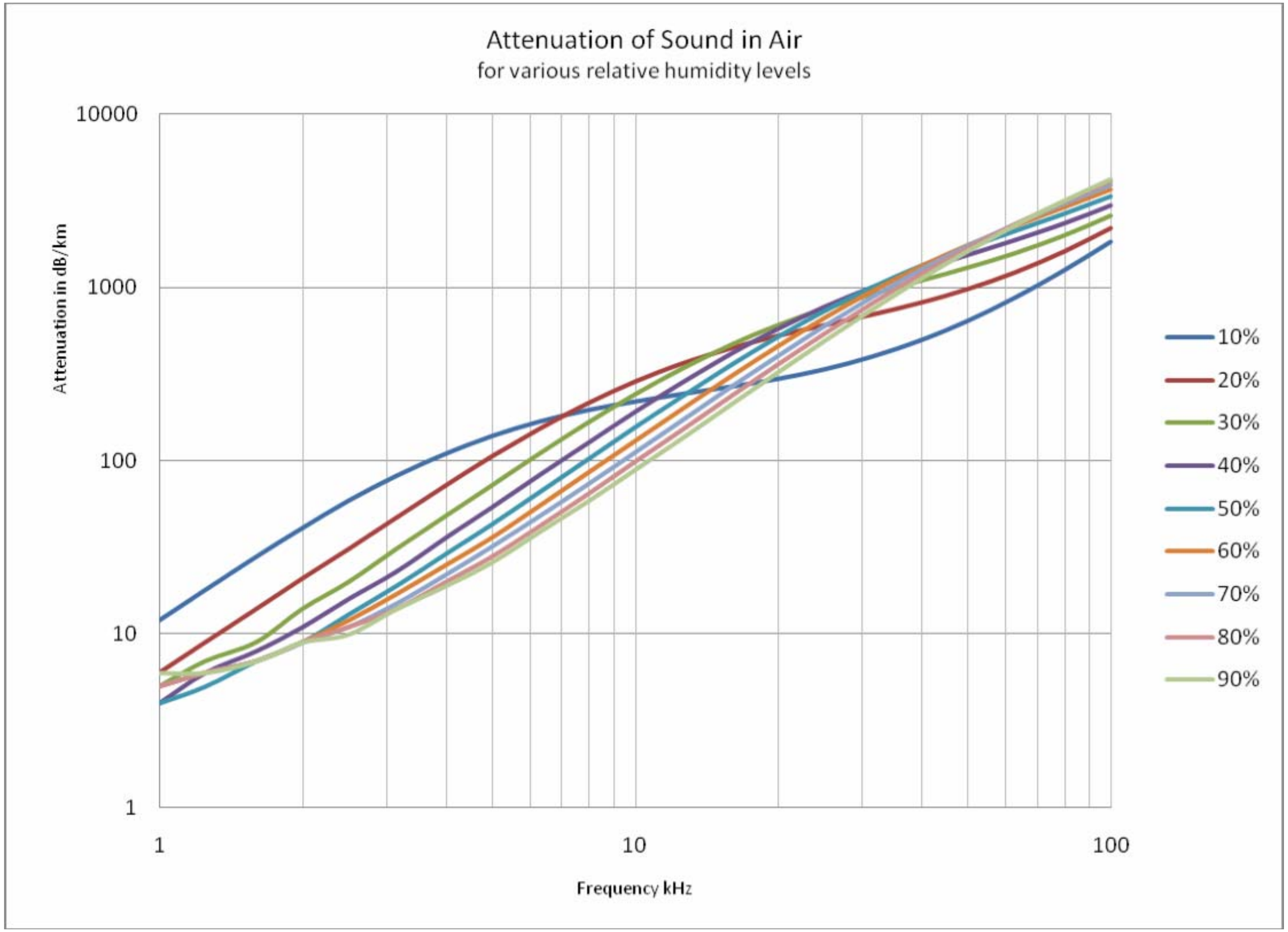


Figure B.7 Sound transmission through air adapted from (Kaye and Laby 1986)

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