SWAP 3D Seismic Survey - Underwater Sound Study

P D Ward

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Customer contact	Alison Williams
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Principal authors	
P D Ward	Award Environmental Consultants Ltd. Southampton SO16 6AA
	Tel: 023 8077 7021
	Email: pdward46@hotmail.com

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EXECUTIVE SUMMARY

The Shallow Water Absheron Peninsular (SWAP) Contract Area is located within the Azerbaijan sector of the Caspian Sea and extends across approximately 1,900km^2 from the coastline to a distance of approximately 25 km. A series of three dimensional (3D) seismic surveys are planned to be carried out over various depth zones within a number of Priority Areas (PA) in the SWAP Contract Area and the surrounding areas during the months of June through to October 2016. The VSGA array is to be deployed in waters of depth varying between 0 m and 2 m; the Bubbles array is to be used in water depths in the range 2 -5 m while the Geotiger array is for use in waters of depth greater than 5 m.

Underwater sound generated by the seismic source (airgun) array has the potential to impact ecological receptors (specifically seals and fish) in the marine environment. A study has therefore been conducted to determine the potential distances from the seismic sound source at which its sound decreases to below thresholds for potential injury and behavioural impacts.

Marine fauna known to be present within and in the vicinity of the 3D SWAP Seismic Area includes Caspian seals (a critically endangered pinniped species) and various species of fish including sturgeon (also critically endangered), kilka, shad, carp and mullet species. The international published literature has been reviewed in order to determine the most up-to-date advice on acoustic impact criteria relating to pinnipeds and fish being exposed to seismic sound. Subsequently, thresholds have been used in terms of both peak sound pressure level (SPL), root-mean-square (RMS) SPL, and sound exposure (energy) level (SEL) metrics. For fish, dual exposure criteria for Permanent Threshold Shift (PTS) and Temporary Threshold Shift (TTS) were based on those developed by Popper *et al*.[1] and given in terms of sound pressure level (SPL) and sound exposure level (SEL). The audiological sensitivities for different species of fish were accounted for by having a range of sound level thresholds at which potential impact may occur. For pinnipeds, dual exposure criteria for potential permanent and temporary hearing damage (PTS and TTS respectively) were based largely on the work undertaken by Southall *et al*.[2] Where appropriate, M-weighting functions relating to the auditory sensitivity of pinnipeds were used.

The output of a seismic sound source is typically characterised by a far-field signature. This is commonly modelled by back-propagating modelled estimates (which are calibrated to measurements) of sound pressure level made in the far-field back to a reference distance of 1 m. The underlying assumption is that in the far-field, SPLs from individual sound source elements add constructively and that this representation of sound level can be corrected or back-propagated to represent the source sound level at 1m distance from the source. However, this process over-estimates source levels in close

[1] Popper, A. N., Hawkins, A. D., Fay, R. R., Mann, D., Bartol, S., Carlson, T., Coombs, S., Ellison, W. T., Gentry, R., Halvorsen, M. B., Løkkeborg, S., Rogers, P., Southall, B. L., Zeddies, D., and Tavolga, W. N. (2014). "Sound Exposure Guidelines for Fishes and Sea Turtles: A Technical Report," ASA S3/SC1.4 TR-2014 prepared by ANSI Accredited Standards Committee S3/SC1 and registered with ANSI. Springer and ASA Press, Cham, Switzerland.

[2] Southall, B.L., Bowles, A.E., Ellison, W.T., Finneran, J.J., Gentry, R.L., Greene Jr., C.R., Kastak, D., Ketten, D.R., Miller, J.H., Nachtigall, P.E., Richardson, W.J., Thomas, J.A., Tyack, P.L., 2007. "Marine mammal noise exposure criteria: initial scientific recommendations". Aquatic Mammals 33, 411–521.

proximity to a spatially distributed source such as a seismic source array (in the near-field). Whilst sound propagation models typically require a single number value to represent source level, the back-propagated value does not give a realistic representation of sound levels within close proximity of the source. To address this, a simple model of a distributed acoustic source representing the individual source elements in the array has been developed in order to provide a more accurate estimate of the near-field acoustic source level for the array.

An analysis of the propagation of underwater sound from the seismic source array was undertaken in order to estimate distances at which sound levels are predicted to decrease below threshold levels.

Ranges to threshold criteria for potential impacts based on peak SPL metrics for fish are given in Tables ES.1. Tables ES.2 and ES.3 show results for both peak and RMS SPL metrics for pinnipeds in Priority Areas 2 and 4 respectively.

Table ES.1 suggests that peak SPLs fall below the threshold level for potential mortality in fish at a maximum distance of 40 m and below the threshold for potential recoverable injury at 60 m from the largest source array. Using the same metrics, Tables ES.2 and ES.3 suggests that peak levels fall below the threshold at which PTS may occur in pinnipeds beyond a maximum distance of 9 m and below the threshold at which TTS may occur beyond 32 m from the largest source array.

Impact	Threshold dB re 1 μPa	Distance		
		VSGA	Bubbles	Geotiger
Potential mortal injury in fish with low hearing sensitivity exposed to impulse sound Recoverable injury in fish with low hearing sensitivity exposed to impulse sound	213 dB peak	<1 m*	4 m*	27 m*
Potential mortal injury in fish with medium hearing sensitivity exposed to impulse sound Potential mortal injury in fish with high hearing sensitivity exposed to impulse sound Potential mortal injury in fish eggs and larvae exposed to impulse sound Recoverable injury in fish with medium hearing sensitivity exposed to impulse sound	207 dB peak	<1 m*	12 m*	42 m
Recoverable injury in fish with high hearing sensitivity exposed to impulse sound	203 dB peak	<1 m*	12 m*	60 m

Table ES.1: Summary of potential impact ranges for fish species exposed to seismic source array sound using peak level metrics

Potential Impact	Threshold dB re 1 μPa	Distance		
		VSGA	Bubbles	Geotiger
Permanent Threshold Shift (PTS) onset	218 dB peak	<1 m*	1 m*	9 m*
Temporary Threshold Shift (TTS) onset	212 dB peak	<1 m*	6 m*	32 m*
Avoidance Behaviour	190 dB RMS[1]	<1 m*	12 m*	51 m
Avoidance Behaviour	190 dB RMS[2]	<1 m*	20 m*	80 m
Limited disturbance	180 dB RMS[1]	<1 m*	30 m*	120 m
Limited disturbance	180 dB RMS[2]	1 m*	51 m	190 m
Limited disturbance	150 dB RMS[1]	14 m*	636 m	1.5 km
Limited disturbance	150 dB RMS[2]	20 m*	931 m	1.9 km
Background level	120 dB RMS[1]	153 m	3.4 km	4.7 km
Background level	120 dB RMS[2]	445 m	4.0 km	5.4 km
Background level	110 dB RMS[1]	664 m	8.1 km	6.0 km
Background level	110 dB RMS[2]	943 m	8.1 km	6.7 km
Background level	100 dB RMS[1]	1.5 km	8.1 km	7.4 km
Background level	100 dB RMS[2]	1.9 km	8.1 km	8.0 km

Table ES.2: Summary of potential impact ranges for pinnipeds in Priority Area 2 exposed to seismic source sound based on peak level and RMS metrics (* - maximum range derived from near-field source level model; [1] – based on Peak level – 15 dB; [2] - based on Peak level – 10 dB)

Potential Impact	Threshold dB re 1 μPa	Distance m		
		VSGA	Bubbles	Geotiger
Permanent Threshold Shift (PTS) onset	218 dB peak	<1 m*	1 m*	9 m*
Temporary Threshold Shift (TTS) onset	212 dB peak	<1 m*	6 m*	32 m*
Avoidance Behaviour	190 dB RMS[1]	<1 m*	12 m*	51 m
Avoidance Behaviour	190 dB RMS[2]	<1 m*	20 m*	80 m
Limited disturbance	180 dB RMS[1]	<1 m*	30 m*	112 m
Limited disturbance	180 dB RMS[2]	1 m*	51 m	153 m
Limited disturbance	150 dB RMS[1]	14 m*	1.13 km	3.3 km
Limited disturbance	150 dB RMS[2]	20 m*	2.22 km	6.6 km
Background level	120 dB RMS[1]	153 m	38.9 km	51 km†
Background level	120 dB RMS[2]	455 m	51 km†	51 km†
Background level	110 dB RMS[1]	976 m	51 km†	51 km†
Background level	110 dB RMS[2]	2.2 km	51 km†	51 km†
Background level	100 dB RMS[1]	3.9 km	51 km†	51 km†
Background level	100 dB RMS[2]	7.7 km	51 km†	51 km†

Table ES.3: Summary of impact ranges for pinnipeds in Priority Area 4 exposed to sound from seismic source arrays based on peak level and RMS metrics
(* - maximum range derived from near-field source level model; [1] – based on Peak level – 15 dB; [2] - based on Peak level – 10 dB; † - maximum extent of propagation modelling)

Limited behavioural disturbance thresholds are given using RMS metrics. The underlying quantitative evidence related to behavioural impacts is scarce[2] but historical studies suggest SPLs around 190 dB re 1 μPa (RMS) are likely to elicit avoidance behaviour reactions in pinnipeds. Similarly, the historical datasets support the contention that exposure to SPLs in the range 150 to 180 dB re 1 μPa (RMS values over the pulse duration) generally have limited potential to induce avoidance behaviour in pinnipeds. Accordingly, Tables ES.2 and ES.3 indicate that SPL RMS levels fall to below these thresholds at distances ranging from <1 m to 6.6 km depending on the source array/water depth used.

Distances over which sound from the seismic source is above background sound levels have been estimated. A range of background levels are assumed from 100 dB re 1 μPa (RMS) to 120 dB re 1 μPa (RMS). Accordingly, limiting distances vary between 153 m when background levels are high to 51 km when levels are low. It is noted that longer limiting ranges tend to occur during the month of October and this is attributed to the upward refracting nature of the sound speed profile. As a result, sound emitted from the sources is directed towards the sea surface rather than the seabed, and from where it subsequently propagates to greater distances.

In order to assess potential impacts using energy-level metrics (SEL), a moving animal or receptor/sound source scenario is modelled. This considers a receptor moving away from the sound source and consequently experiencing sound levels which vary over time. As the SEL accumulates over time, eventually it may or may not exceed a threshold level corresponding to the potential onset of PTS or TTS. Potential cumulative impact for an animal is dependent not only on its hearing sensitivity to the sound but also on its proximity and duration of exposure to a sound signal. Any result arising from a given receptor/sound scenario therefore is unique to that specific model scenario only. Nevertheless the results from modelling several scenarios provide some indications of boundary conditions for real-world receptor/sound source movement scenarios to inform an assessment using a cumulative SEL threshold criterion. A number of modelling scenarios were considered each involving multiple seismic source arrays separated by varying cross-line distances: these are summarised in Table ES.4.

Combined Scenario	Survey vessels and separations	Vessel/receptor movement relative to modelling axis
MS 1	Single source vessel	Vessel @270°, receptor @180°
MS 2	1000 m Geotiger separation with Geotiger 2 offset	Alternate vessels @270°/90°, receptor @180°
MS 3	2000 m Geotiger separation with Geotiger 2 offset	Alternate vessels @270°/90°, receptor @180°
MS 4	3000 m Geotiger separation with Geotiger 2 offset	Alternate vessels @270°/90°, receptor @180°
MS 5	4000 m Geotiger separation with Geotiger 2 offset	Alternate vessels @270°/90°, receptor @180°
MS 6	5000 m Geotiger separation with Geotiger 2 offset	Alternate vessels @270°/90°, receptor @180°
MS 7	8000 m Geotiger separation with Geotiger 2 offset	Alternate vessels @270°/90°, receptor @180°
MS 8	10000 m Geotiger separation with Geotiger 2 offset	Alternate vessels @270°/90°, receptor @180°
MS 9	12000 m Geotiger separation with Geotiger 2 offset	Alternate vessels @270°/90°, receptor @180°

Table ES.4: Modelling scenarios involving multiple sound sources

The results showed that the cumulative SELs experienced by a receptor when a single VSGA source array is used are lower than the threshold levels associated with potential impacts. Accordingly, for fish, cumulative SELs are lower than threshold levelsassociated with potential mortal injury (in the range 207-219 dB re 1 μPa^2.sec depending on hearing sensitivity), recoverable injury (in the range 207-216 dB re 1 μPa^2.sec) and TTS (186 dB re 1 μPa^2.sec). For pinnipeds, cumulatve SELs are lower than threshold levels relating to PTS (186 dB re 1 μPa^2.sec), TTS (171 dB re 1 μPa^2.sec) and significant behavioural reactions following exposure to a single pulse (171 dB re 1 μPa^2.sec).

A further scenario consisting of a receptor moving through an acoustic field generated by multiple sources was modelled. For this scenario, the Bubbles source vessel transits at a speed of 2.3 m/s on a bearing of 270° while both the Geotiger source vessels transit at the same speed in the opposite direction on a bearing of 90°. The Bubbles and each Geotiger source are separated by an initial cross line distance (on the modelling Y-axis) of 500 m while the two Geotiger sources are separated by an initial 1000 m. In addition, one of the Geotiger array sources is offset in the x-direction by 2000 m. A representative initial layout of the sources and receptor is shown in Figure ES.1.

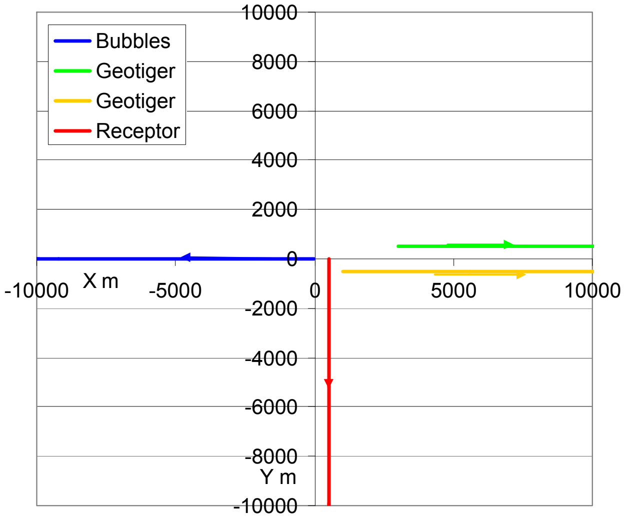

Figure ES.1: Relative locations and paths of receptor and source arrays for an initial Geotiger separation of 1000 m

The Geotiger separation in the Y-direction is systematically incremented and the overall SEL and SPL is noted at each stage. It is noted that as the receptor starts at a fixed location relative to the Bubbles source vessel transits through the acoustic field, the distance between the receptor and the Bubbles and each of the Geotiger sources changes and hence the main contributing sound source to the acoustic field also changes. At the commencement of the scenario, the dominant source is Bubbles. After a period of time varying between 150 seconds and 700 seconds (2.5 - ~11 minutes), the southernmost Geotiger becomes the dominant source. The scenario is modelled using source and sound propagation data relevant to each Priority Area (PA) and for each month over which the seismic survey is scheduled to take place. Results indicating maximum overall SPLs and cumulative SELs are summarised in Tables ES5 to ES.8.

The results indicate that for the given scenario involving fish as the receptor, the maximum overall SPLs are below threshold levels related to potential mortal injury (in the range 207-213 dB re 1 μPa peak depending on fish hearing sensitivity), and recoverable injury (in the range 203-207 dB re 1 μPa peak). When SEL is used as the metric, maximum SELs are above threshold levels related to the potential TTS TTS (186 dB re 1 μPa^2.sec) only for the closest Geotiger separations (1 km) when operating in PA2 during the month of August and in PA4 during the month of September. By October, SELs are above the TTS threshold for all Geotiger separations considered.

When pinnipeds are considered, overall peak SPLs are lower than the threshold levels for potential PTS and TTS (218 dB re 1 μPa peak and 212 dB re 1 μPa peak respectively). Similarly, RMS SPLs are lower than the threshold levels corresponding to potential avoidance behaviour (190 dB re 1 μPa rms). RMS SPLs that may cause limited behavioural disturbance reactions (in the range 150-180 dB re 1 μPa rms) occur for the smallest Geotiger cross-line separations during the months of June and July in PA2. As the survey season progresses, RMS SPLs are above threshold levels related to limited behavioural disturbance at increasingly greater cross-line separations between Geotiger sources. By October in PA4, RMS SPLs are above threshold levels for all separations considered.

When SEL is used as the criteria metric, maximum cumulative SEL is below the threshold level for potential PTS (186 dB re 1 μPa^2.sec) for all months except during October in PA4. While maximum cumulative SEL is above the TTS threshold level (171 dB re 1 μPa^2.sec) initially only for the smallest Geotiger separations (1 km) during June and July in PA2 but increasing to all separations during August in PA2 and during both September and October in PA4.

It is noted that, for the longer distance sound propagation, there is some seasonal variation with longer ranges occurring during the month of August in PA2 and during October in PA4.

Priority Area		**Geotiger separation**								
	Month	1 km	2 km	3 km	4 km	5 km	6 km	8 km	10 km	12 km
PA2	Jun	172.6	166.7	163.4	161.2	159.9	159.3	158.8	158.5	158.4
PA2	Jul	173.9	167.6	164.6	162.9	161.8	161.4	161.0	160.8	160.7
PA2	Aug	177.9	174.3	171.0	169.2	168.1	167.5	166.7	166.4	166.3
PA4	Sept	179.9	174.1	171.5	169.7	168.4	167.6	166.7	166.5	166.3
PA4	Oct	178.2	177.1	177.1	176.0	173.5	173.1	172.5	172.1	171.3

Table ES.5: Summary of maximum SPLs experienced by fish as a function of Geotiger separation

Priority		**Geotiger separation**

Area	Month	1 km	2 km	3 km	4 km	5 km	6 km	8 km	10 km	12 km
PA2	Jun	179.9	174.9	171.4	168.3	166.2	165.0	163.7	163.1	162.8
PA2	Jul	181.8	177.7	174.5	171.8	169.6	168.2	166.6	166.1	165.9
PA2	Aug	187.2	184.8	182.3	179.5	178.0	176.7	174.5	173.7	173.4
PA4	Sept	188.0	184.8	183.7	180.6	178.5	177.2	175.2	174.2	173.8
PA4	Oct	192.4	192.1	192.1	191.8	190.6	190.3	190.5	189.6	189.2

Table ES.6: Summary of maximum SELs experienced by fish
as a function of Geotiger separation

Priority Area		**Geotiger separation**								
	Month	1 km	2 km	3 km	4 km	5 km	6 km	8 km	10 km	12 km
PA2	Jun	166.9	159.4	157.0	156.5	156.3	156.2	156.2	156.2	156.2
PA2	Jul	170.5	163.6	160.6	159.7	159.5	159.4	159.4	159.4	159.3
PA2	Aug	176.1	173.2	170.1	168.5	167.5	166.9	166.2	165.8	165.7
PA4	Sept	178.5	173.0	170.8	169.0	167.8	167.0	166.2	165.9	165.8
PA4	Oct	176.5	176.4	176.6	175.7	173.4	173.0	172.4	171.9	171.0

Table ES.7: Summary of maximum SPLs experienced by pinnipeds
as a function of Geotiger separation

Priority Area		**Geotiger separation**								
	Month	1 km	2 km	3 km	4 km	5 km	6 km	8 km	10 km	12 km
PA2	Jun	173.1	165.9	161.9	160.3	159.7	159.5	159.3	159.3	159.3
PA2	Jul	177.6	171.5	167.4	165.4	164.7	164.5	164.4	164.4	164.4
PA2	Aug	185.5	183.5	181.2	178.6	177.3	176.1	174.0	173.2	172.9
PA4	Sept	186.5	183.6	182.9	179.9	177.8	176.7	174.7	173.7	173.3
PA4	Oct	191.8	191.7	191.8	191.6	190.5	190.2	190.4	189.5	189.2

Table ES.8: Summary of maximum SELs experienced by pinnipeds
as a function of Geotiger separation

1. INTRODUCTION

A three dimensional (3D) seismic survey is planned to be undertaken in the Shallow Water Absheron Peninsular (SWAP) Contract Area. The Contract Area is located within the Azerbaijan sector of the Caspian Sea and extends across approximately 1,900km^2 from the coastline to a water depth of approximately 25 m.

The Contract Area is divided into a number of Priority Areas and the locations of these within the Contract Area are shown in Figure 1.1. The seismic surveys are planned for commencement in 2016: a provisional schedule indicating deployment in each Priority Area (PA) is given in Table 1.1. Within each Priority Area, seismic sound sources (airguns) will be used; these are tuned specifically for use in shallow waters. The VSGA array will be used in water depths 0-2 m, the Bubbles array is appropriate for waters of depths 2-5 m while the Geotiger array will be used in water depths greater than 10 m. In the context of the current work, the modelling study will focus on Priority Area 2 (PA2) and Priority Area 4 (PA4).

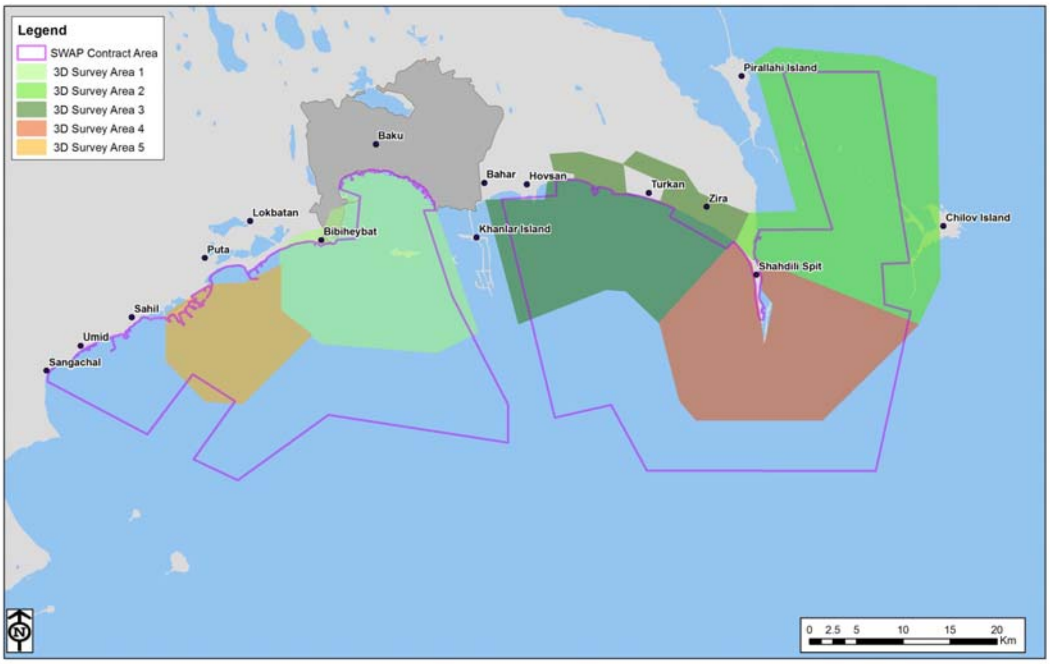

Figure 1.1: Location of Priority Areas within SWAP 3D Contract Area

Priority Area	Survey Duration (days)	Start date	End date
PA1	49	01-Mar-16	18-Apr-16
Block Move	5	19-Apr-16	23-Apr-16
PA3	46	24-Apr-16	08-Jun-16
Block Move	5	09-Jun-16	13-Jun-16
PA2	80	14-Aug-16	01-Sep-16
PA4	57	02-Sep-16	28-Oct-16
Block Move	5	29-Oct-16	02-Nov-16

Priority Area	Survey Duration (days)	Start date	End date
PA5	22	03-Nov-16	24-Nov-16

Table 1.1: Indicative schedule for survey activity in Priority Areas

Seismic surveys involve the generation and propagation of underwater sound, which may have potential to impact species of marine fauna in the vicinity of the survey.

This report has been prepared by Peter Ward of Award Environmental Consultants Ltd on behalf of AECOM Infrastructure & Environment UK Ltd in order to establish distances at which underwater sound levels associated with the SWAP 3D Seismic Survey meet relevant underwater sound thresholds developed for the protection of marine fauna.

This study comprises the following:

- Discussion on the source parameters relating to the seismic source arrays proposed for the survey, including a comparison of the derived near-field and back-propagated (based on far-field assumptions) source level.
- Summary of relevant sound threshold criteria related to potential impacts to marine fauna based on international published literature on studies of animal audiology, injury and behaviour, taking into account known marine fauna within the SWAP 3D Seismic Survey area.
- Description of the sound propagation modelling undertaken using the derived far-field source level for the seismic array to determine the maximum distances over which each threshold is met; and
- Discussion of the results obtained.

2. DESCRIPTION OF UNDERWATER SOUND AND ASSESSMENT METRICS

2.1. Introduction

This section provides a brief review of the metrics used to measure and assess underwater sound propagation in the marine environment. It is noted that a number of these definitions and parameters draw on the advice given in American National Standards Institute (ANSI) S12.7-1986[1].

A sound wave or signal may be defined as the periodic change in pressure from some equilibrium value. The unit of pressure is given in Pascals (Pa) or Newtons per square metre (N/m^2). Levels of sound pressure however cover a very wide range of values, typically from 1×10^{-3} Pa for the hearing threshold value of a human diver at 1 kHz to 1×10^{7} Pa for the sound of a lightening strike on the sea surface. For convenience therefore, sound levels are expressed on a logarithmic scale given by decibels (dB) relative to a fixed reference pressure commonly 1 μPa for measurements made underwater.

2.2. Peak Sound Level

For transient pressure pulses such as an impulse generated by a seismic source, the peak sound level is the maximum absolute value of the instantaneous sound pressure recorded over a given time interval. Hence:

$$\text{Peak Level (zero-to-peak)} = 20 \times \log_{10} (P_{peak} / P_{ref}) \qquad \text{eqn. 2-1}$$

When the pulse has approximately equal positive and negative parts to the waveform, the peak-to-peak level is often quoted and this is equal to twice the peak level or 6 dB higher.

2.3. RMS Sound Pressure Level

The Root-Mean-Square (RMS) Sound Pressure Level (SPL) is typically used to quantify sound of a continuous nature, from activities such as shipping, sonar transmissions, drilling or cutting operations, or background sea sound; however it has also been used to characterise impulsive sound signals such as that from seismic source arrays. RMS SPL is the mean square pressure level measured over a given time interval (t), and hence represents a measure of the average SPL over that time. It is expressed as:

$$\text{RMS Sound Pressure Level} = 20 \times \log_{10} (P_{RMS}/P_{ref}) \qquad \text{eqn. 2-2}$$

For a continuous sound, the time period over which measurements or calculations are made is not relevant as the calculation will give the same result regardless of the time period over which it is averaged. For impulsive sounds, the time period over which the calculation is averaged may vary and must be quoted as the RMS value will vary with the averaging time period: generally the longer the averaging period, the greater the RMS SPL. This is discussed further in Section 8.

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[1] ANSI S12.7-1986, "Methods for measurement of impulse noise", Issued by the American National Standards Institute, 20 February 1986

RMS SPL is often inferred by using a fixed correction factor relative to measurements or calculations made using other metrics such as Peak SPL.

2.4. Sound Exposure Level

A transient pressure wave may also be described in terms of the Sound Exposure Level (SEL) where the SEL is the time integral of the square pressure over a time window long enough to include the entire pressure-time history. The SEL is therefore the sum of the acoustic energy over a measurement period, and effectively takes account of both the level of the sound, and the duration over which the sound is present at a given receptor location in the acoustic environment. Sound Exposure (SE) is defined by the equation:

$$SE = \int_0^T p^2(t)dt \qquad \text{eqn. 2-3}$$

where *p* is the acoustic pressure in Pascals, *T* is the duration of the sound in seconds and *t* is time. The Sound Exposure is a measure of the acoustic energy and therefore has units of Pascal squared seconds (Pa^2-s).

To express the Sound Exposure as a logarithmic decibel, it is compared with a reference acoustic energy level of 1 μPa^2.s. The SEL is then defined by:

$$\text{SEL} = 10 \log_{10} \int_0^T \frac{p^2(t)dt}{P_{ref}^2} \qquad \text{eqn. 2-4}$$

For continuous sources, the RMS SPL and the SEL of 1 second duration are equal. Where a sound time period is less than a second the RMS SPL will be greater than the SEL. For signals of greater than 1 second, the SEL will be greater than the RMS SPL where:

$$\text{SEL} = \text{SPL} + 10 \log_{10} T \qquad \text{eqn. 2-5}$$

2.5. Cumulative Sound Exposure Level

Where multiple transient pressure wave events occur, the total or cumulative SEL from multiple events can be calculated by summing the SEL from a number of individual events. The events themselves may be separated in time or space or both. For instance, the events could be consecutive from a seismic source moving from site to site or else concurrent where seismic sources are active at the same time on neighbouring sites.

2.6. Source Level

The source level (SL) is the apparent strength of a sound source at a reference distance, given as 1 m, from the source. For example, a source may be quoted as having a source SPL of 180 dB re.1μPa at 1 m. In practice the sound output of a source are rarely measured at such a close range, and the source level is often inferred by back-propagating the sound from a number of far field measurements. While this technique works for a point source from which sound radiates uniformly in all directions, for a distributed source such as an array of seismic sound sources where the sound adds destructively in the immediate vicinity of the array, an over-estimation of source levels can result. This subject is explored further in Section 3.

2.7. Received Level

The Received level (RL) is the strength of the acoustic field at a given depth and range relative to the source. As the sound varies with range, it is important to state the range at which the measurement has been taken or the estimate has been made.

2.8. Transmission Loss

The transmission loss (TL) represents the loss in intensity or pressure of the acoustic field strength as the sound propagates from source to receptor. In general terms the transmission loss is given by:

$$TL = N \log(r) + \alpha r \qquad \text{eqn. 2-6}$$

where r is the range from the source, N is a factor for attenuation due to geometric spreading, and α (in $dB.km^{-1}$) is a factor for the absorption of sound in water. Hence, the received sound level at a range r from a source is given by:

$$RL = SL - TL \qquad \text{eqn. 2-7}$$

which can be written in the form :

$$RL = SL - N \log(r) - \alpha r \qquad \text{eqn. 2-8}$$

A more rigorous discussion of transmission loss is given in Section 6 where the acoustic propagation modelling for the SWAP 3D Seismic Survey is presented.

It is noted that the terms transmission loss and propagation loss (PL) are synonymous.

3. SOUND SOURCE CHARACTERISTICS

3.1. Introduction

Seismic surveys are an essential part of an oil and gas exploration programme. During a survey, impulsive, low frequency sound emitted from a seismic source array is used to produce a signal that is reflected back from the underlying geology to produce signal that are recorded and processed to provide an image the subsea rock formations that is used to identify potential hydrocarbon traps and reservoirs. For offshore surveys the reflections from the rock structures are recorded using hydrophones either towed behind the survey vessel or fixed on the seabed. The signals are then transmitted to the on-board processing equipment and analysed.

Seismic sound source arrays such as airgun arrays currently provide the most efficient and safe sound source that is commercially available for conducting seismic surveys. These are underwater pneumatic devices that expel a bubble of compressed air into the water. Compressed air is released in the water to form a bubble, the bubble collapses in on itself and may oscillate several times. The acoustic signal thus produced consists of a sequence of positive and negative pulses that are proportional to the rate of change of volume of the air bubbles.

A single seismic sound source produces an acoustic signal that is both non-directional and largely lacking sufficient power to penetrate far into the seabed. To achieve the required signal strength and directionality, an array of multiple source elements, often 10 to 30 or more, are used to form a source array which is distributed over a spatial area of up to 15m x 50m. Consequently, a highly directional, downward pointing acoustic signal is produced and this has the potential to penetrate the subsea geology to a depth of several kilometres.

The far-field signature output of a seismic source array may be modelled through the use of a number of industry-standard software packages[2,3]. The modelling programs require a number of input parameters including airgun types, pressure, spatial geometry and depth, from these, it is possible to determine the output sound signal response of the array in terms of beam directivity and source frequency spectrum.

From an acoustic modelling perspective the data thus derived require additional analysis and interpretation in order to correctly represent the signature of the array especially taking into account the distributed nature of the sound sources across the array itself. The sections below describe the steps required such that the SWAP 3D arrays are correctly characterised.

3.2. Source Level

The source level of a seismic source array may be estimated by either modelling or measuring underwater SPL at some far distance - often 100's m to several km - from the

[2] http://www.pgs.com/upload/Nucleus.pdf
[3] https://www.gundalf.com/

array itself and back-propagating to 1m. To allow for comparisons to be made between various source arrays, it is necessary to propagate the data back to a reference distance of 1 m from the array. The main assumption is that in the far-field a distributed source appears as a point source as SPLs from individual source elements add constructively and that this simple representation of the acoustic sound level can be corrected by back-propagating to represent source sound level. However, this process leads to an estimate of source level which can be in excess of the actual level by up to 20 dB as it does not consider the near field interaction effects between individual source elements. Acoustic propagation modelling tools typically use a single source level number as input data. Consequently there is a need to derive a more realistic near-field source level based on inputs from individual source elements as well as using the single far-field derived source level that can be input to the propagation modelling tools.

The underlying assumption while back-propagating the data, is that the source is ultimately a point source and that it radiates sound equally in all directions. When an array consists of a number of source elements positioned over a finite sized area, this simple description is no longer valid. In acoustic terms, the array is now a distributed source, that is, it consists of a number of individual acoustic point sources each with its own acoustic intensity and which all contribute to the overall acoustic field. Close to the array, the sound output from individual elements no longer add constructively as sound energy no longer arrives at a location at the same time due to the distributed nature of the array. In order to estimate a more appropriate source level for use at distances close to the array, an alternative approach is sought.

Provisional details on the source arrays to be used in the SWAP 3D seismic survey have been provided by BP based on GUNDALF reports[4]. Figure 3.1 shows the intended configurations for each of the SWAP 3D survey airgun arrays. The GUNDALF report also provided data on individual source element geometry, capacity and energy level for each of the source arrays. These data are summarised in Table 3.1. The entries in red (eg. source elements 1, and 4 for the Bubbles array) indicate that these are absorbing energy and do not directly contribute to the acoustic field. Energy-absorbing elements arise through the complex interactions of individual sources in an array[5]. The outcome of the process is that the overall energy efficiency of the array is increased.

[4] “GUNDALF array modelling suite – SWAP 2D array” (2015). BP– Pers. Comm.

[5] Laws R., G. Parkes, L Hatton, (1988), “Energy-Interaction: The Long-Range Interaction Of Seismic Sources”, *Geophysical Prospecting*, Volume 36, Issue 4, pages 333–348.

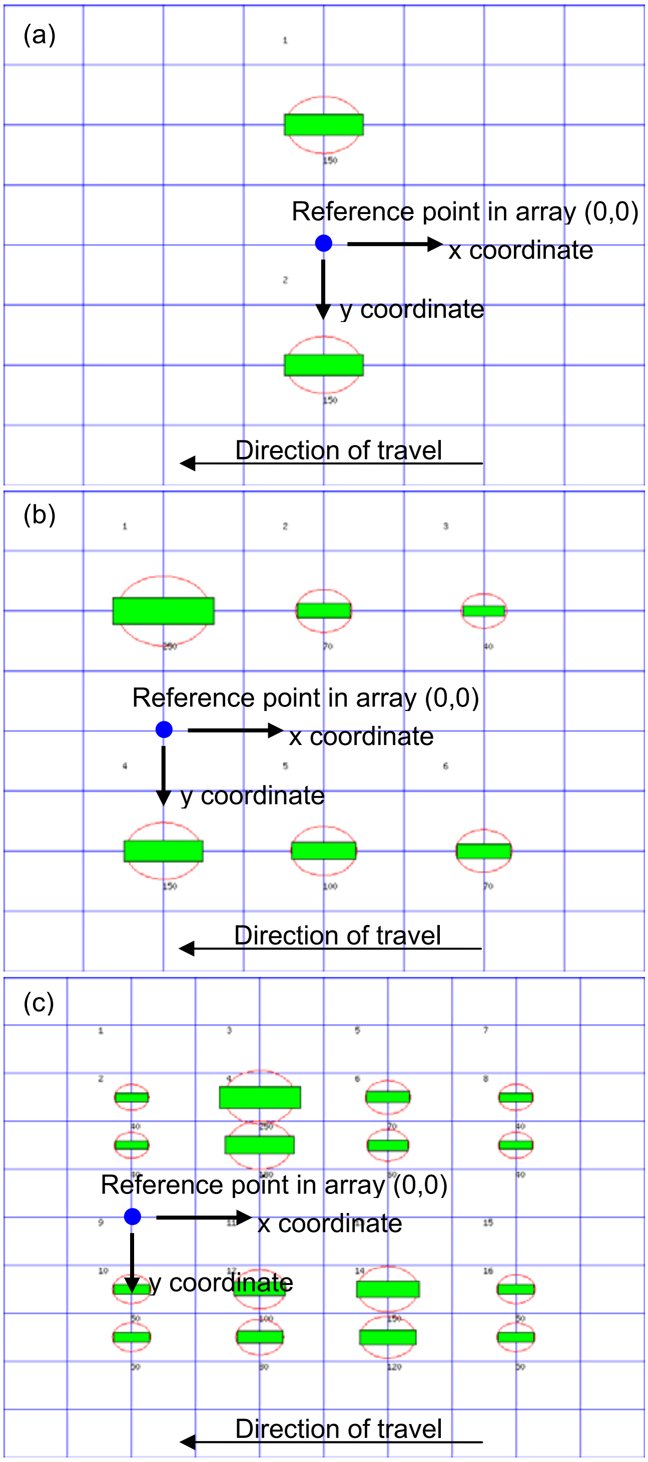

Figure 3.1: Schematic of seismic sound source array configurations for
(a) VSGA array for use in water depths 0-2 m;
(b) Bubbles array for use in water depths 2-5 m; and
(c) Geotiger array for use in water depths >5 m

It is noted that the source levels for each source element are given in energy units of Joules. Source levels in dB units may be estimated through converting energy to power by dividing by a representative time t. Subsequently, the source level in dB units is given by[6]:

$$SL = 170 + 10\log_{10}(Pw) \qquad \text{eqn. 3-1}$$

where Pw is the power in Watts.

VSGA						
Gun	Source volume	Location in array relative to reference point (see Figure 3.1)			Acoustic energy	Source level
No.	Cubic inch	x m	y m	z m	Joules	dB re 1 μPa at 1 m
1	150	2	-2	1	8.9	182.5
2	150	2	2	1	16	185.1
Bubbles						
Gun	Source volume	Location in array relative to reference point (see Figure 3.1)			Acoustic energy	Source level
No.	Cubic inch	x m	y m	z m	Joules	dB re 1 μPa at 1 m
1	250	0	-2	1.5	-28679.9	217.6
2	70	2	-2	1.5	11939.4	213.8
3	40	4	-2	1.5	7795.2	211.9
4	150	0	2	1.5	-1938.9	205.9
5	100	2	2	1.5	6502.4	211.1
6	70	4	2	1.5	11215.6	213.5
Geotiger						
Gun	Source volume	Location in array relative to reference point (see Figure 3.1)			Acoustic energy	Source level
No.	Cubic inch	x m	y m	z m	Joules	dB re 1 μPa at 1 m
1	40	0	-2.5	5	10992.1	213.4
2	40	0	-1.5	5	11735.7	213.7
3	250	2	-2.5	5	-47121.7	219.7
4	180	2	-1.5	5	-16096	215.1
5	70	4	-2.5	5	13552.2	214.3
6	60	4	-1.5	5	13958.1	214.5
7	40	6	-2.5	5	11888.3	213.8
8	40	6	-1.5	5	12073.2	213.8
9	50	0	1.5	5	13142.8	214.2
10	50	0	2.5	5	13419.8	214.3
11	100	2	1.5	5	10455.7	213.2
12	80	2	2.5	5	13594.1	214.3
13	150	4	1.5	5	-13709.2	214.4
14	120	4	2.5	5	1498.8	204.8
15	50	6	1.5	5	13393.7	214.3
16	50	6	2.5	5	13798.6	214.4

Table 3.1: Seismic sound source array configuration details

[6] Erbe C., *Underwater Acoustics: Noise and the Effects on Marine Mammals - A Pocket Handbook,* 3rd Edition, JASCO Applied Sciences. Accessed at http:// oalib.hlsresearch.com.

In order to complete the calculation, it is necessary to assign a suitable value to time t. Hatton[7] notes that energy flux occurs from the moment of array discharge through to the end of a series of bubble pulses and this may last approximately 0.5 seconds. Consequently, this value is taken forward for use in the analysis. Acoustic source levels for individual source elements are included in Table 3.1.

To assist in the calculation of the source level of the array, the concept of near-field and far-field is used. Near-field refers to locations within and close to the airgun array while far-field refers to distances beyond this. The distance over which each term is valid is discussed further below.

To calculate the maximum distributed near-field source level, it is assumed that each source element emits sound as a point source. The total acoustic field for the whole array at a given field location is determined by summing the pressure contributions in Pascals from individual source elements while also taking into account the propagation loss over the distance between the airgun and the field location.

Accordingly, Figure 3.2 shows the near-field representation of the acoustic field within and close to the confines of each source array based on the source levels presented in Table 3.1. The blue lines represent acoustic propagation from the individual source elements emitting sound and acting in isolation – noting that in the Bubbles and Geotiger arrays, various elements are absorbing energy so that the remaining elements in the array therefore act more efficiently. For the elements absorbing energy, the source level has been set to zero. The red line represents the summation of the pressures from the individual elements along the centre-line of the array from the point of origin at (0, 0) (see Figure 3.1) out to a distance of 100 m and in the same plane as the source array i.e. at a depth of 5 m below surface. Within the confines of the array the modelled near-field source level is seen to lie in the range 183 - 185 dB re 1 μPa at 1 m for the VSGA array; between 216 and 219 dB re 1 μPa at 1 m for the Bubbles array; and between 226 - 229 dB re 1 μPa at 1 m for the Geotiger array.

In order to determine the distance at which the sound level derived from the addition of individual element outputs transitions from the near-field to the far-field, the difference between the slope of the modelled near-field data and the slope of the sound field that is back projected from the far-field characteristic was calculated. When the difference became negligible, in this instance at a range of approximately 30 m, this indicated the end of the near-field. A trend line using data from 30 m to 100 m was extended back to 1 m distance from the source (indicated by the green line in Figure 3.2) and this led to a nominal source levels of approximately 191.8 dB re 1 μPa at 1 m; 226.9 dB re 1 μPa at 1 m; and 237.9 dB re 1 μPa at 1 m for the VSGA, Bubbles and Geotiger arrays respectively. These values represent the back-propagated source levels based on the distributed nature of the source array elements, which are used as input for acoustic propagation modelling in the far-field.

[7] Hatton L., (2008), "The Acoustic Field Of Marine Seismic Airguns And Their Potential Impact On Marine Animals", *Proceedings of the Institute of Acoustics: Underwater Noise 2008,* Vol 30 Pt 5.

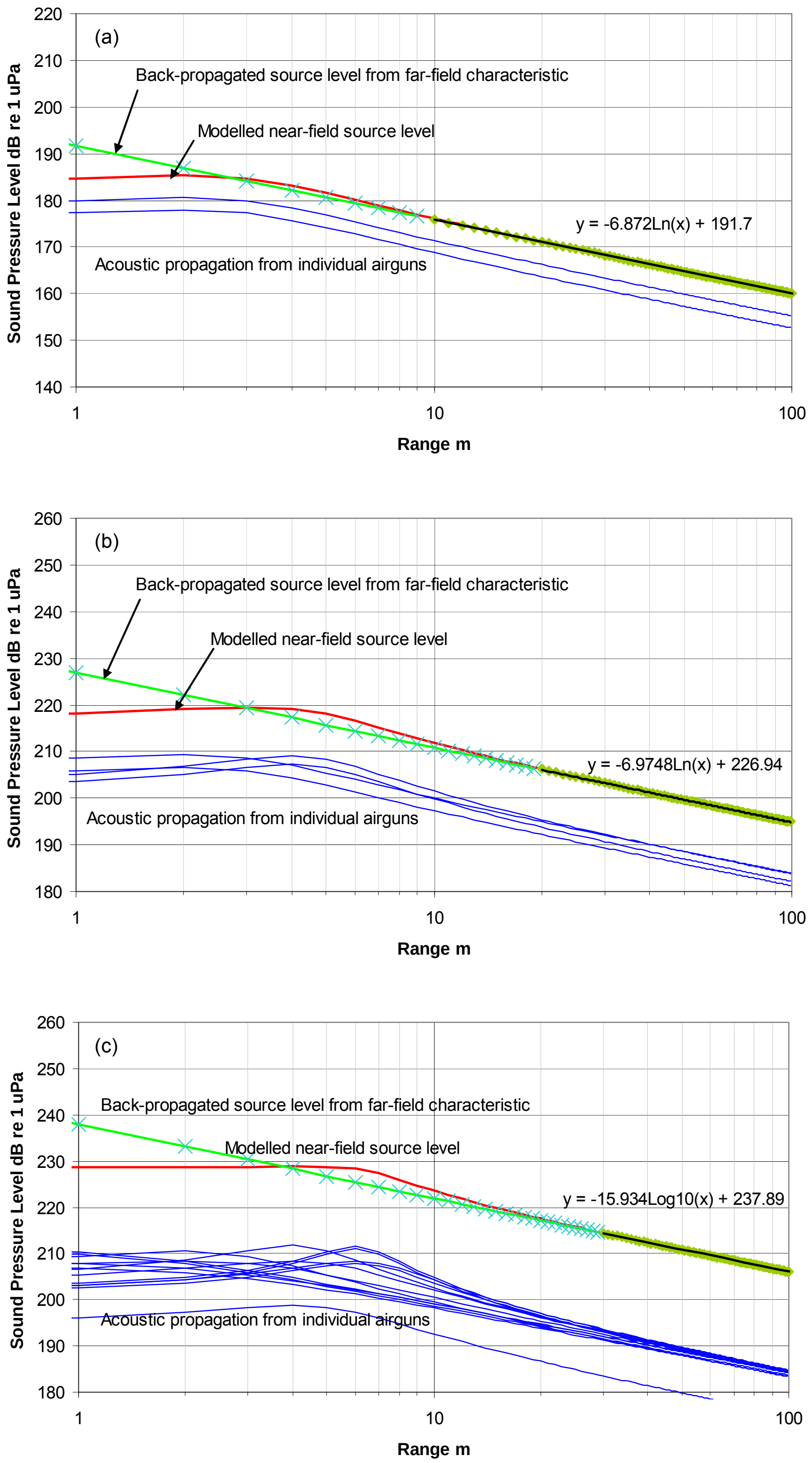

Figure 3.2: Near-field and partial far-field representations of the airgun array sources (a) VSGA; (b) Bubbles; and (c) Geotiger

3.3. Source Spectrum

Seismic sound sources such as airgun arrays are predominantly a low frequency source: the long wavelength sound ensures penetration deep into the seabed sediments. Source modelling software packages such as Nucleus[2] or GUNDALF[3] may be used to determine the frequency bandwidth over which most of the energy is produced in an array. The packages are calibrated against real data where typically, the bandwidth will be around 10 Hz to 200 Hz. By contrast, source spectrum data is required for higher frequencies that extend across the auditory hearing range of the fish and marine mammal species of concern to the Project (see Section 4) such that an assessment of potential effects of sound from the seismic source may be made on these species. However, few seismic source measurement datasets are currently available which include analysis of spectral levels at frequencies above 1kHz[8]. Breitzke *et al*.[9] analysed measured data up to a frequency of 80 kHz: the ensuing analysis suggested that sound levels beyond 1 kHz in frequency was dominated by sound from the vessel operating the seismic source. Tashmukhambetov *et al*.[10] studied a 3D seismic source array consisting of 21 source elements in 3 sub-arrays and having a total volume capacity of 3590 cubic inches (cu in). Measurements of zero-to-peak SPL were made at a distance of 736 m from the hydrophone and from these data, the frequency spectrum was determined up to a frequency of 1000 Hz. For the purposes of calibration, the data was compared with those from both Nucleus[2] and GUNDALF[3]. It was found that at frequencies up to 230 Hz, the modelled data was in close agreement with those derived from the experimental measurements: this was to be expected as data used for calibrating source modelling capabilities focused on the frequency range of interested for geophysical purposes. At higher frequencies, the roll-off of spectral levels as modelled by the software generally followed the measured data, although individual spectral levels from the modelled data were up to 12 dB higher than the measured data.

For the purpose of modelling the SWAP source arrays, the modelled source frequency spectrum was extended up to a frequency of 160 kHz by applying a best-fit line on a logarithmic scale to the data at frequencies from 200 Hz to 1000 Hz then extrapolating the resulting trend line up to the requisite frequency. Following this, the spectral levels were adjusted by adding a spherical spreading term to account for the propagation over the distance from 736 m to 1 m so as to arrive at the same far-field source levels for each of the SWAP 3D arrays. (Note that the spectrum is adjusted to give a source level corresponding to the back propagated values rather than the lower near-field source level as the higher figure is used for sound propagation beyond the near-field of the source array's acoustic field *i.e*. beyond a range of 30 m – see Figure 3.2.)

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[8] Efforts are underway to obtain higher frequency datasets for calibration and impact studies, see eg. http://soundandmarinelife.org/research-categories/sound-source-characterisation-and-propagation/single-gunguncluster-measurements-and-source-modelling.aspx

[9] Breitzke M., Boelbel O., El Naggar S., Jokat W., Werner B., (2008), "Broad-band calibration of marine seismic sources used by *R/V Polarstern* for academic research in polar regions", *Geophys. J. Int*. (2008) **174**, 505–524.

[10] Tashmukhambetov, A.R., G.E. Ioup, J.W. Ioup, N.A. Sidorovskaia, J.J. Newcomb, (2008), "Three-dimensional seismic array characterization study: Experiment and modeling", *J. Acoust. Soc. Am*. **123(**6).

Data from each of the proposed SWAP 3D array frequency spectra in 1/3rd octave bands are given in Figure 3.3.

The figure shows that over the frequency range 10 Hz to 100 Hz, band levels are around 180 - 204 dB re 1 μPa depending on the source array. This is followed by a notch at around 6 kHz where subsequently there is a general roll-off in spectral levels at higher frequencies.

It is likely that the low frequency components (i.e. less than ~200 Hz) of the acoustic signals generated by the airgun arrays will not propagate to any great distance and the energy associated with these will become absorbed into the seabed. This is discussed further in Section 7.

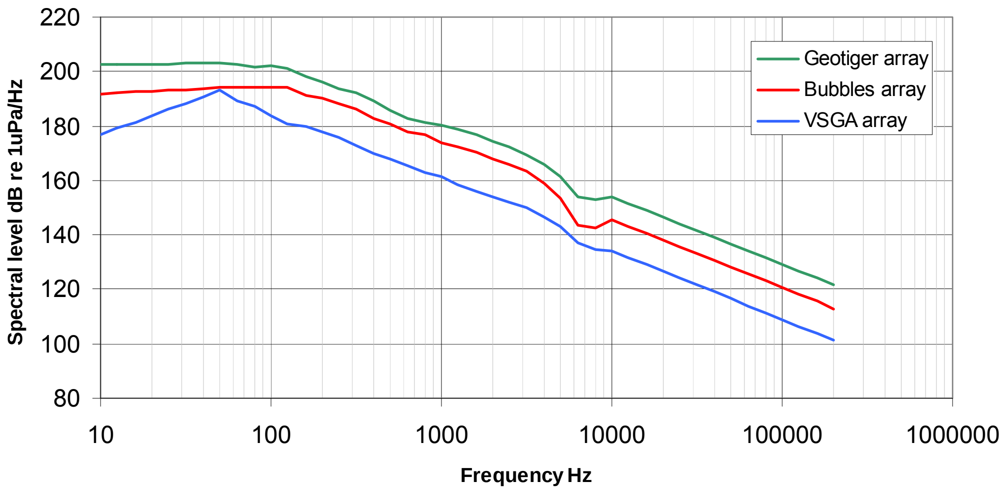

Figure 3.3: Indicative frequency spectra for the SWAP 3D seismic source arrays

3.4. Summary of 3D Source Characteristics

Using the available source data and developing a simple model to account for the contributions of individual source elements and the acoustic energy lost as sound propagates from each, an appropriate value for the acoustic near-field source level of the SWAP source arrays has been determined. In addition, based on data from the international published literature, it is possible to estimate a representative frequency spectrum for the output signal of the source array.

Based on Sections 3.2 and 3.3 above the SWAP 3D source array characteristics have been estimated as follows:

VSGA array:

- Near field or distributed source level - 185.4 dB re 1 μPa;
- Near field derived point source level - 191.8 dB re 1 μPa;

Bubbles array:

- Near field or distributed source level - 219.4 dB re 1 μPa;
- Near field derived point source level - 226.9 dB re 1 μPa;

Geotiger array:

- Near field or distributed source level - 228.8 dB re 1 μPa;
- Near field derived point source level - 237.9 dB re 1 μPa;

Frequency spectrum (refer to Figure 3.3).

4. SENSITIVITY OF MARINE FAUNA IN THE SWAP 3D SEISMIC SURVEY TO UNDERWATER SOUND

4.1. Introduction

Previous studies have identified a number of species of fish and one species of marine mammal that are expected to be present in the Azerbaijan Sector of the Caspian Sea and more specifically within the SWAP 3D Seismic Survey Area. This section provides an overview of the susceptibility of the species to underwater sound.

4.2. Fish

The sensitivity of fish to underwater sound is largely dependent on their internal physiology. This has been discussed extensively in the published literature and has been reviewed most recently by Fay and Popper[11] and Popper and Fay[12]. Some fish species do not have a swimbladder (e.g. dab, plaice) and as a consequence they have poor sensitivity to sound and thus relatively poor hearing. By contrast, a number of fish species have a swimbladder. This gas-filled sac performs several different functions such as acting as a float which gives the fish buoyancy; as a lung; and as a sound-producing organ. In addition, the swim bladder can enhance the hearing capability of the fish species through the amplification of underwater sound although this alone, would not necessarily make such a fish highly sensitive to sound. These fish would be deemed to have a medium level of auditory sensitivity. For some species (e.g. members of the herring family) there is a connection between the inner ear and the swim bladder and it is this feature which results in them being the most sensitive to underwater sound. Subsequently, there is the potential for such species to be more susceptible to acoustic impacts than fish with low or medium hearing sensitivity.

The literature suggests that the terms high-, medium- and low-sensitivity appear somewhat subjective. Auditory data[13] shows that, in general, fish hearing covers the frequency range 10 Hz to 1000 Hz. Hearing threshold data varies considerably from species to species. The data shows that the fish with the least sensitive hearing have audibility thresholds[14] greater than 90-110 dB re 1 μPa while those species that have the most sensitive hearing have audibility thresholds as low as 50-60 dB re 1 μPa. Clearly, for those species that are classed as having neither low- nor high-sensitivity hearing, an intermediate class is more appropriate.

4.3. Marine Mammals

The only marine mammal known to be present in the Caspian Sea (including the SWAP 3D Seismic Survey Area) is the Caspian seal. This specie is listed as Critically Endangered on the IUCN Red List of Threatened Species.

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[11] Fay R.R. & Popper A.N. (eds) (1999) *Comparative Hearing: Fish and Amphibians*. New York: Springer-Verlag.
[12] Popper A. N. & R. .R. Fay (2009). "Rethinking sound detection by fishes". Hearing Research.
[13] Nedwell J R, Edwards B., Turnpenny A W H , Gordon J., (2004) "Fish and Marine Mammal Audiograms: A summary of available information", Subacoustech Report ref: 534R0214.
[14] Strictly, the audibility thresholds refer to hearing levels above background noise. Hearing tests are carried out in a controlled acoustic environment where background noise levels are as low as possible.

Although seals are classed as marine mammals they spend considerable periods of time on land. As a consequence, seals are known to hear very well in-air as well as underwater. When diving or swimming, they may be susceptible to impacts arising from high levels of underwater sound.

A number of species of seal have been auditory tested – principally harbour, ringed, harp and monk seals as well as Californian sea lions and northern fur seals (reviewed in Richardson *et al*.[15]) but not, it is noted, the Caspian seal. Auditory data is thus generally available over the frequency range 100 Hz to 200 kHz. Audibility thresholds are as low as 60-70 dB re 1 μPa over the frequency range 4 kHz to 30 kHz. For the purpose of the analysis undertaken in the current study, it is assumed that the hearing sensitivity of the Caspian seal is broadly in line with the pinniped species for which data exists.

[15] Richardson, W.J., Green Jr, C.R., Malme, C.I. & Thomson, D.H. (1995). *Marine Mammals and Noise*. Academic Press, New York.

5. POTENTIAL IMPACTS AND ACOUSTIC THRESHOLDS

5.1. Introduction

The extent to which a given species might be affected by man-made underwater sound depends on the hearing ability of the species, the activity/behaviour of the individuals during exposure, and the level, frequency and duration of the sound.

This section of the report provides a discussion of the various sound thresholds discussed within available literature, which are associated with fish and seal species anticipated to be present in the SWAP 3D Seismic Survey area and identifies which sound thresholds are adopted for the purpose of comparisons with the underwater acoustic propagation modelling results to determine distances at which sound levels will fall below these thresholds.

5.2. Limitations

All acoustic potential impact criteria considered in this study have been developed in accordance with best scientific practice and have been discussed extensively in the international peer-reviewed literature. It should be noted however that in many cases the criteria used have had little or no validation under open water conditions. For marine mammals, sound exposure studies have been limited to just a few species. However, the results derived from such work have been extrapolated to other species based on best knowledge of marine mammal physiology and comparisons with data from terrestrial mammals.

Observations of behavioural avoidance with concurrent acoustic measurements are sparse, and hence the behavioural avoidance criteria are limited and informed by scientific studies such as those reviewed by Southall *et al*[16]. With regards to fish, only a few of the 30,000 plus species have been auditory tested. Of those however, the sample sizes are such that the results may be considered statistically significant. The qualitative threshold assessment methodology subsequently developed[17] offers an indication of potential impact on an individual basis, and therefore not easily transferable to enable assessment or inference of potential impacts to fish or marine mammal populations.

5.3. Marine Mammals

5.3.1. Mortality

Very high levels of underwater sound can be potentially lethal to marine life. Yelverton *et al.*[18] carried out a number of studies on the impact of explosive blasts on various species

[16] Southall, B.L., Bowles, A.E., Ellison, W.T., Finneran, J.J., Gentry, R.L., Greene Jr., C.R., Kastak, D., Ketten, D.R., Miller, J.H., Nachtigall, P.E., Richardson, W.J., Thomas, J.A., Tyack, P.L., 2007. “Marine mammal noise exposure criteria: initial scientific recommendations”. Aquatic Mammals 33, 411–521.
[17] Popper, A. N., Hawkins, A. D., Fay, R. R., Mann, D., Bartol, S., Carlson, T., Coombs, S., Ellison, W. T., Gentry, R., Halvorsen, M. B., Løkkeborg, S., Rogers, P., Southall, B. L., Zeddies, D., and Tavolga, W. N. (2014). “Sound Exposure Guidelines for Fishes and Sea Turtles: A Technical Report,” ASA S3/SC1.4 TR-2014 prepared by ANSI Accredited Standards Committee S3/SC1 and registered with ANSI. Springer and ASA Press, Cham, Switzerland.
[18] Yelverton, J. T., Richmond, D. R., Hicks, W., Saunders, K., and Fletcher, E. R. (1975). "The Relationship Between Fish Size and Their Response to Underwater Blast." Report DNA 3677T, Director, Defense Nuclear Agency, Washington, DC.

of fish and terrestrial animals and demonstrated that mortality rates were related to body mass of the subject and the magnitude of the impulsive wave. It was noted that mortality or direct physical injury from the sound generated by the blast was associated with very high peak pressure levels – in excess of 240 dB re 1 μPa. The effects associated with sound from explosives are often assumed to also be associated with sound from a seismic source array due to the similar impulsive characteristics of the source output signal. It is observed however that the studies by Yelverton *et al.*[18] concerned predominantly terrestrial animals hence it is unclear whether the conclusions arising could readily be applied to marine animals and sound from seismic sources. In addition, a literature search has indicated that there are no known studies or examples concerning mortality in marine mammals directly related to exposure to sound from seismic sources. As a result, this impact threshold is not used further in the current study.

5.3.2. Auditory Impairment

Permanent and temporary hearing loss may occur when marine animals are exposed to sound levels lower than those which are commonly associated with potential lethality. Permanent hearing loss in mammals results from non-recoverable damage to the sensory hair cells of the inner ear and therefore may be considered a form of physical injury. The resulting permanent increase in threshold sensitivity over the affected frequencies is known as Permanent Threshold Shift (PTS). It is noted that PTS has not been measured in marine mammals following exposure to loud sounds. Thresholds for PTS are based on Temporary Threshold Shift (TTS) thresholds. Southall *et al*.[16] state that:

> *"Procedures for estimating PTS-onset, assumed to occur in conditions causing 40 dB of TTS, were derived by combining (1) measured or estimated TTS-onset levels in marine mammals and (2) the estimated "growth" of TTS in certain terrestrial mammals exposed to increasing noise levels. The general PTS-onset procedures differ according to sound type (pulses and non-pulses), the extent of available information, and required extrapolation"*

Temporary Threshold Shift (TTS) is a temporary and recoverable hearing impairment and not typically considered an injury. While experiencing TTS, the hearing threshold rises and a sound must get louder in order to be heard. For sound exposures at or somewhat above the TTS threshold, hearing sensitivity in both terrestrial and marine mammals recovers after exposure to the sound ends. The recovery period can last from minutes or hours to (in cases of strong TTS) days. A number of studies on TTS have been reviewed in some detail by Southall *et al*.[16] and additional work on sound levels and durations necessary to elicit TTS has been provided by Finneran and Schlundt[19], Lucke *et al*.[20], and Kastelein *et al*.[21].

[19] Finneran J.J., Schlundt C.E., (2013), "Effects of fatiguing tone frequency on temporary threshold shift in bottlenose dolphins (*Tursiops truncatus*)", *J Acoust Soc Am*. **133**(3):1819-26.
[20] Lucke K., Siebert U., Lepper P.A., Blanchet M.A., (2009), "Temporary shift in masked hearing thresholds in a harbor porpoise (Phocoena phocoena) after exposure to seismic airgun stimuli", *J Acoust Soc Am*. **125**(6):4060-70. doi: 10.1121/1.3117443.
[21] Kastelein R.A., Gransier R., Hoek L., (2013), "Comparative temporary threshold shifts in a harbor porpoise and harbor seal, and severe shift in a seal.", *J Acoust Soc Am*. **134**(1):13-6.

Southall *et al.*[16] grouped marine mammals according to the frequency response of their hearing. Southall *et al*. suggest that SEL thresholds for potential injury (and behavioural responses) should be examined separately by applying an M-weighting function for five functional hearing groups and these are summarised in Table 5.1.

Functional grouping	Denoted by	Hearing range bandwidth
Cetaceans - Mysticetes	Mlf	7 Hz -22 kHz
Cetaceans - odontocetes such as common dolphin and beaked whale	Mmf	150 Hz - 160 kHz
Cetaceans - odontocetes such as porpoise	Mhf	200 Hz - 180 kHz
Pinnipeds in water	Mpw	75 Hz - 75 kHz
Pinnipeds in air	Mpa	75 Hz - 30 kHz

Table 5.1: Summary of functional hearing groups and hearing bandwidth[16]

Studies reviewed by Southall *et al.*[16] indicated that hearing damage could occur following a single exposure to a loud sound or to multiple exposures of lower level sound. In the first case, the threshold is given by the peak SPL while in the second case; the threshold is given by the SEL indicating a build-up of energy over a period of time.

Assessment criteria were also based on the type of sound e.g. single and multiple pulse such as those arising from seismic sources; and non-pulse or continuous sound such as that arising from shipping. Consequently, for pinnipeds exposed to single or multiple pulses thresholds based on peak level metrics were derived and these are summarised in Table 5.2.

5.3.3. Behavioural Reactions

It has been observed that animals may exhibit changes in behaviour in response to underwater sound. These changes can range from a startle reaction to the sound, a cessation of their current activities (e.g. feeding, nursing, breeding) or a movement away from the sound source for a period of time. Often behavioural responses are context-dependent and very subtle. Painstaking experimental procedures and much analysis are required to determine whether the observed results are statistically significant. Southall et al. [16] assumed that a behavioural reaction might arise if the sound exposure is sufficient to have a measureable effect on hearing such as TTS-onset. From this, it is concluded that although TTS is not a behavioural effect as such, any impact on hearing ability however temporary, has the potential to compromise essential communication or detection capabilities. This approach is expected to be precautionary because TTS at onset levels is unlikely to last a full diel cycle or to have serious biological consequences during the time TTS persists.

Southall *et al*[16]. reviewed a number of studies on behavioural disturbances in marine mammals including seals exposed to multiple pulses such as those emitted by seismic sound sources as airguns. From the limited data available, it was found that there was “limited potential to induce avoidance behaviour” at received sound levels in the range 150-180 dB re 1 μPa (RMS) while received levels at 190 dB re 1 μPa (RMS) and above were likely to elicit avoidance responses, at least in the species observed which was predominantly ringed seals. The review also noted that threshold levels associated with the onset of TTS may be considered for potential behavioural disturbance following exposure to a single pulse sound. However this was suggested as being a precautionary approach as TTS likely to be of short duration. Behavioural threshold levels in peak-level and SEL metrics for exposure to both multiple pulses and single pulses are summarised in Table 5.2.

Threshold level	Effect	Study
218 dB re 1 μPa Peak OR 186 dB re.1μPa^{2}s SEL M-Weighted	Onset of Permanent Threshold Shift (PTS)	Southall *et al.* (2007) Dual criteria – applicable for multiple pulses
212 dB re 1 μPa Peak OR 171 dB re.1μPa^{2}s SEL M-Weighted	Onset of Temporary Threshold Shift (TTS) Also indicating significant behavioural disturbance	Southall *et al.* (2007) For TTS, dual criteria – applicable for multiple pulses For disturbance, dual criteria – applicable for single pulses
190 dB re 1 μPa RMS	Avoidance behaviour in pinnipeds exposed to impulsive sounds	Southall *et al*. (2007)
150-180 dB re 1 μPa RMS	Limited disturbance expected in pinnipeds exposed to impulsive sounds	Southall *et al*. (2007)

Table 5.2: Summary of acoustic impact threshold criteria for pinnipeds

5.4. Fish

5.4.1. Mortality

Until very recently, acoustic sound threshold criteria for fish were somewhat less well developed compared with those for marine mammals. In order to address this, Popper *et al*.[17] conducted a similar process for fish as Southall *et al*.[16] had done for marine mammals. Reviewing a number of studies and subsequently suggesting various sound thresholds related to potential impacts that were a function of the hearing sensitivity of fish species. The hearing function groupings, labelled as "High sensitivity"; "Medium sensitivity"; and "Low sensitivity"; refer back to studies either of the internal physiology of the fish or else to their auditory sensitivity (see Section 4).

As with the Southall *et al*.[16] work, the potential impact thresholds use a dual criteria in recognition of the fact that an impact may arise either through exposure to a single loud sound or from exposure at a lower level but over a long period of time. Accordingly, potential mortality injury in fish with low hearing sensitivity was found to occur at 213 dB re 1 μPa (Peak SPL) or 219 dB re 1 μPa^2.s (SEL). For fish with medium hearing sensitivity and for fish eggs and larvae, the corresponding thresholds are 207 dB re 1 μPa (peak) and 210 dB re 1 μPa^2.s (SEL) while for fish with high hearing sensitivity, the thresholds are set at 207 dB re 1 μPa (peak) and 207 dB re 1 μPa^2.s (SEL).

It is noted that the thresholds all make use of unweighted SPLs and SELS as the thresholds are categorised based on hearing sensitivity; there is no correction for hearing sensitivity across different species of fish using a methodology similar to the M-weighting criteria presented by Southall *et al.*[16].

5.4.2. Auditory Impairment

Popper *et al*.[17] also proposed thresholds for potential recoverable hearing damage for fish. Again, this was found to vary with the auditory sensitivity of fish. The thresholds for recoverable injury in fish with low hearing sensitivity are 213 dB re 1 μPa (Peak SPL) and 216 dB re 1 μPa^2.s (SEL) while for fish with medium and high hearing sensitivity, the corresponding thresholds are 203 dB re 1 μPa (Peak SPL) and 207 dB re 1 μPa^2.s (SEL). The same study also defined a threshold for temporary hearing damage, indicated by TTS, in fish of all hearing sensitivities, of 186 dB re 1 μPa^2.s (SEL).

5.4.3. Behavioural Reactions

Behavioural reactions have been observed in fish when exposed to man-made underwater sound such as that from pile driving, seismic surveys, and operational sonar and the studies arising have been subject to extensive review[22]. It is acknowledged that the most useful work on behavioural reactions takes place when fish can be observed before, during and after exposure to a given sound. This condition was met when in work undertaken by Wardle *et al*.[23]. Fish were exposed to seismic airgun sound and were seen to exhibit a "C-start" reaction where their bodies curled up then straightened out over a period of about 1 second. Other studies include observations of free-roaming fish that have been shown to move temporarily away from an airgun source[24,25] Similarly, captive fish have been seen to move away from airgun emissions and to show modified behaviour patterns[26].

The logistical difficulties of carrying out statistically meaningful experiments on fish in open-water conditions means that currently, no data is available on threshold criteria relating to behavioural response of fish to sound.

The thresholds for fish exposed to sound from a seismic source array that have been selected for the current study are summarised in Table 5.3.

Exposure limit	Effect	Study
213 dB re 1 μPa Peak OR 219 dB re 1 μPa^2 s SEL	Potential mortal injury in fish with low hearing sensitivity exposed to seismic sound	Popper *et al.* (2014)
207 dB re 1 μPa Peak OR 210 dB re 1 μPa^2 s SEL	Potential mortal injury in fish with medium hearing sensitivity exposed to seismic sound &	Popper *et al.* (2014)

[22] Popper A. N., Hastings M. C., "The effects of human-generated sound on fish", *Integrative Zoology* 2009; 4: 43-52.
[23] Wardle CS, Carter TJ, Urquhart G.G. (2001). "Effects of seismic air guns on marine fish", *Continental Shelf Research* 21, 1005–27.
[24] Løkkeborg, S. (1991). "Effects of a geophysical survey on catching success in longline fishing". ICES (CM) B:40.
[25] Engås A., Løkkeborg S., (2002). "Effects Of Seismic Shooting And Vessel-Generated Noise On Fish Behaviour And Catch Rates", Bioacoustics: The International Journal of Animal Sound and its Recording Volume 12, Issue 2-3.
[26] Fewtrell J.L., McCauley R.D., (2012), "Impact of air gun noise on the behaviour of marine fish and squid", Mar Pollut Bull. **64**(5):984-93.

	Potential mortal injury in fish eggs and larvae exposed to seismic sound	
207 dB re 1 μPa Peak OR 207 dB re 1 μPa^2 s SEL	Potential mortal injury in fish with high hearing sensitivity exposed to seismic sound	Popper *et al.* (2014)
213 dB re 1 μPa Peak OR 216 dB re 1 μPa^2 s SEL	Recoverable injury in fish with low hearing sensitivity exposed to seismic sound	Popper *et al.* (2014)
203 dB re 1 μPa Peak OR 207 dB re 1 μPa^2 s SEL	Recoverable injury in fish with high or medium hearing sensitivity exposed to seismic sound	Popper *et al.* (2014)
186 dB re 1 μPa^2 s SEL	TTS in all fish exposed to seismic sound	Popper *et al.* (2014)

Table 5.3: Summary of acoustic impact threshold criteria for fish

6. UNDERWATER ACOUSTIC PROPAGATION MODELLING

6.1. Introduction

The sections below describe the propagation modelling undertaken in order to estimate sound level variation with distance from the source, specifically the acoustic models used and the geo-acoustic and oceanographic data required as input parameters for the models.

6.2. Description of the Models and limitations

Numerous computer models are available to predict acoustic propagation in the marine environment. Each model has its own strengths and weaknesses in terms of input requirements and calculation methods, but all include some form of description of various environmental parameters, such as the water column sound speed profile (SSP) and sediment acoustic properties.

Reviews of a number of acoustic propagation computer programs are given by Buckingham[27], Jensen *et al.*[28] and Etter[29]. A number of these have been coded up and are included in the Acoustics Toolbox[30]. The computer programs are based on ray-trace, normal mode, parabolic equation and fast field techniques. The models of relevance to the analysis undertaken in this report are BELLHOP – based on the ray-trace method; and RAM – based on the parabolic equation. Both programs carry out a 2D analysis for a given sound speed profile in an ocean waveguide overlying a range-dependent, acoustically absorbent seabed sediment. Both programs provide a solution that is valid over a limited frequency, water depth and range regime: the parabolic equation technique covers low frequencies (~<1 kHz) while the ray-trace is appropriate at high frequencies (~>1 kHz). The sound sources associated with the SWAP 3D Seismic Survey (see Section 3) covers a wide range of frequencies hence it is considered acceptable to use both the BELLHOP and RAM models such that the whole frequency range of interest is covered.

The quality of the output data is highly dependent on obtaining site-specific oceanographic and geo-acoustic data. The sources of data used as inputs to the propagation modelling process are discussed below.

6.3. Transect Bathymetry

Water depth data was taken from the bathymetry database ETOP01[31]. This is a database of water depths having global coverage and a resolution of 1 min of arc (corresponding to

[27] Buckingham M.J., "Ocean-acoustic propagation models". Journal d'Acoustique: 223-287 June 1992.
[28] Finn Jensen, William Kuperman, Michael Porter, and Henrik Schmidt, *Computational Ocean Acoustics*, Springer-Verlag (2000).
[29] Etter Paul C., *Underwater Acoustic Modeling and Simulation* , 3rd edition, Spon Press, New York, 2003, ISBN 0-419-26220-2
[30] An online repository funded by the US Office of Naval Research and containing a number of underwater acoustic propagation loss computer programmes. Found at http://oalib.hlsresearch.com/Modes/AcousticsToolbox/
[31] Amante, C. and B. W. Eakins, (2009), ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources and Analysis. NOAA Technical Memorandum NESDIS NGDC-24, 19 pp, March 2009.

a spatial separation of around 1.8 km in the vicinity of the SWAP 3D Seismic Survey Area).

Bathymetric charts indicate that there is a considerable variation in water depths over each of the Priority Areas and also over the three depth-related sub-areas in which the seismic source arrays are to be used. In order that the subsequent acoustic propagation modelling adequately characterises the underwater environment and is not specific to one given location to the exclusion of all others, it is decided to construct a set of bathymetric profiles that are generic in nature but which nevertheless capture the essence of the Priority Areas. The Priority areas themselves are located on the margins of the Caspian Sea around the southern edge of the Apsheron peninsula. Close to the coast, within a distance of 2-5 km, the water depths increase to a maximum of around 2 - 3 m. Depths around 5 m are attained around 6-7 km from the coast while further out, around 8-10 km, the water depth reaches 10 m. Beyond a distance of around 30 km, water depths quickly reach in excess of 100 m. In order to capture the depth variation, a generic set of 12 equally spaced transects were used where the central modelling point for the shallow water case is at a depth of 2 m, for the medium is at 5 m and for the deep is at a depth of 10 m. The transects themselves vary in length from 6 km to 51 km depending on the proximity of the coastline to the modelling centre location.

6.4. Oceanographic Data

Oceanographic data was obtained through the World Ocean Atlas (WOA 2009[32]). This consists of gridded monthly samples of temperature, salinity and depth and from which, sound speed profiles in the vicinity of the 3D Seismic Survey Area may be reconstructed with the Chen-Millero[33] relationship. Sound speed profiles for the months of June through to October are illustrated in Figure 6.1.

Over the course of a year, temperature changes in the topmost layers of water have a significant effect on the nature of the sound speed profile. Below about 80 m, the seasonal heating has a much smaller effect as water temperatures remain little changed over the course of the year. During the months of June through to August, the top 50 m of the water column get increasingly warmer due to solar insolation with the result that there is a general increase in sound speed at the surface with the effect decreasing with depth. Consequently, the sound speed profile tends to be downward refracting during the summer months and this ensures that the sound from a shallow source is directed towards the seabed. By September, surface cooling and mixing sets in and this effect becomes more pronounced during October as a surface duct extending to a depth of 20 m is created. Within the duct, the sound speed profile is slightly upwardly refracting. The nature of the profile is such that for a shallow sound source, the sound tends to become trapped in a surface channel and subsequently may propagate to considerable distances.

[32] WOA (2009), World Ocean Atlas dataset available for download at www.nodc.noaa.gov/OC5/WOA09/pr_woa09.html
[33] C-T. Chen and F. J. Millero, (1977), “Speed of Sound in Seawater at High Pressures”. J. Acoust Soc Am, 32(10), p 1357

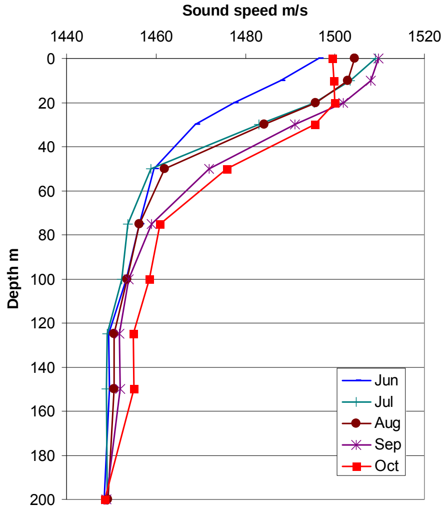

Figure 6.1: Monthly sound speed profiles for the vicinity of the SWAP 3D Seismic Survey Areas

6.5. Seabed Geoacoustics

Seabed mapping surveys in areas adjacent to the 3D Seismic Survey Area [34,35] indicate a range of different sediment types from consolidated material through to soft, silty muds. In inshore regions, the sediments tend to consist of a poorly sorted mixture of silt, clay, sand and shell fragments while further offshore coarse sands and gravel predominate.

From an acoustic perspective, the seabed may be modelled as a layer of soft clay with a thickness of 500 m. Due to its thickness and the acoustic losses inherent in the clay, the nature of the basement rock is of lesser importance. Hamilton[36,37,38] provides guidance on determining seabed sediment parameters and from this, the sound speed and attenuation data was obtained. These are summarised in Table 6.1. It is noted that the classic 3-layer acoustic model as represented in both BELLHOP and RAM assumes a basement that is semi-infinite in thickness.

Layer	Compressional wave velocity Vp m/s	Density kg/m^3	Attenuation dB/m/kHz	Thickness m
Terrigenous mud	1451	1652	0.468	500
Sandstone basement	5548	2745	0.094	-∞

Table 6.1: Seabed sediment properties for the vicinity of the 3D Seismic Survey Area

[34] Shafag Asiman Offshore Block 3d Seismic Exploration Survey Environmental Impact Assessment, Reference No. P140167, Prepared for BP Azerbaijan, 23 August 2011. Accessed:http://www.bp.com/content/dam/bp-country/en_az/pdf/ESIAs/Shafag-Asiman/Shafag-Asiman-3D-seismic-survey-EIA.pdf
[35] Chirag Oil Project, Environmental & Socio-economic Impact Assessment - Volume 1, AIOC Reference Number: BP BFZZZZ, February 2010. Accessed:http://www.bp.com/content/dam/bp-country/en_az/pdf/ESIAs/ACG/COP-ESIA.pdf
[36] E.L. Hamilton (1963), "Sediment Sound Velocity Measurements made In Situ from Bathyscaph TRIESTE", Journal of Geophysical Research 68, pp. 5991-5998.
[37] E.L. Hamilton, (1970), "Sound velocity and related properties of marine sediments, North Pacific", Journal of Geophysical Research 75, pp. 4423-4446.
[38] E.L. Hamilton, (1972), "Compressional-wave attenuation in marine sediments", Geophysics 37, pp. 620-646.

6.6. Background Sound

Background sound levels in shallow water are very variable being dependent on shipping activity and marine industrial activity as well as wind speed and rainfall (Urick, 1983[39]). Typically, at frequencies around 100 Hz, background sound levels are around 70-80 dB re 1 μPa per Hz.

No data on underwater background sound levels in the Caspian Sea have been found. However, comparisons may be made with other shallow water sites in which similar hydrocarbon related activity takes place.

The North Sea contains a number of oil fields that are being both developed and commissioned or else are in full operation. Measurements of background sound in the coastal fringe of the North Sea by Nedwell *et al.*[40], indicate a background sound level range of 100-135 dB re 1 μPa with a modal value of 120 dB re 1 μPa. The report however fails to explain whether the SPL data are given using RMS or peak values. As it is common practice to present background sound levels in RMS units, it is assumed that the data provided in the report follow this convention.

It is proposed that background sound levels in the vicinity of the 3D Seismic Survey Area are considered in the range of 100-120 dB re 1 μPa (RMS). It must be emphasised that the North Sea data is the best estimate available but nevertheless may not be wholly representative of sound levels in the coastal Caspian Sea.

6.7. Source Modelling Parameters

Sound emitted by a seismic source array may be characterised by a pulse of finite duration and covering a wide range of frequencies (see Section 3). For this, a broadband, time-domain propagation model ideally should be used to represent the source and underwater acoustic environment. However, these tend to be difficult to use, and have a considerable time overhead associated with them[28].

An alternative approach is to divide the source frequency bandwidth into 1/3rd octave bands[41] where each band has a given spectral level, centre frequency and bandwidth; and then to use a frequency-domain type program (such as BELLHOP and RAM discussed above) for subsequent propagation modelling. The 1/3rd octave centre frequencies thus selected cover the frequency range of interest for the seismic source array and are listed in Table 6.2 while the 1/3rd octave band levels are given in Figure 3.3.

Parameter	
Frequency Hz	**10, 12.5, 16, 20, 25, 31, 40, 50, 63, 80, 100, 125, 160, 200, 250, 315, 400, 500, 630, 800, 1k, 1.25k, 1.6k, 2k, 2.5k, 3.15k, 4k, 5k, 6.3k, 8k, 10k, 12.5k, 16k, 20k, 25k, 31.5k, 63k, 80k, 100k, 125k, 160k**

Table 6.2: Acoustic modelling frequencies

[39] Urick, Robert J. (1983), Principles of Underwater Sound, 3rd Edition. New York. McGraw-Hill.
[40] Nedwell J R, Parvin S J, Edwards B, Workman R, Brooker A G, Kynoch J E, (2008), "Measurement and interpretation of underwater noise during construction and operation of offshore windfarms in UK waters", COWRIE NOISE-03-2003.
[41] Kinsler, L.E., Frey, A.R., Coppens, A.B. & Sanders, J.V. (1999) *Fundamentals of Acoustics*, 4th edn. Wiley, NJ.

6.8. Sound Propagation Modelling Scenarios

Using the bathymetric and geo-acoustic data given in the preceding sections, propagation loss data was generated along each of the 12 transects using sound speed profile data for the months of June through to October.

The propagation loss data was subtracted from the source level data (equation 2-7) for the seismic source array (given in Figure 3.3) in order to derive SPL data. A discussion of the results generated by this stage is given in Section 7.

Further calculations are then undertaken as described in Section 8 to allow comparison of predicted sound levels with relevant sound level thresholds associated with potential impacts as discussed in Section 5.

7. ACOUSTIC PROPAGATION MODELLING RESULTS

For each of the SWAP 3D seismic source arrays, sound was modelled as a function of range from the source and depth along each of 12 transects (30 degrees incremental bearings from 0° – North) using oceanographic conditions for the months of June through to October.

The modelling results indicate that SPLs generally fall with increasing distance from the seismic source arrays. Both bathymetry and the nature of the sound speed profile (SSP), which varies considerably over the months of June through to October, can have a significant effect on the SPL variation with distance from a given location. The bathymetry may give rise to acoustic shadow zones into which the sound cannot propagate while the SSP may direct the sound either towards the sea surface, where it has the potential to propagate over relatively long distances, or else towards the seabed into which it is absorbed and hence propagates over much shorter distances. Each of these features are discussed in further detail below.

A typical result is given in Figure 7.1 which shows the modelled SPL variation with distance resulting from the VSGA array for the month of August along the transect having a bearing of 0° where the water depth decreases from 3 m to zero over a distance of 4 km.

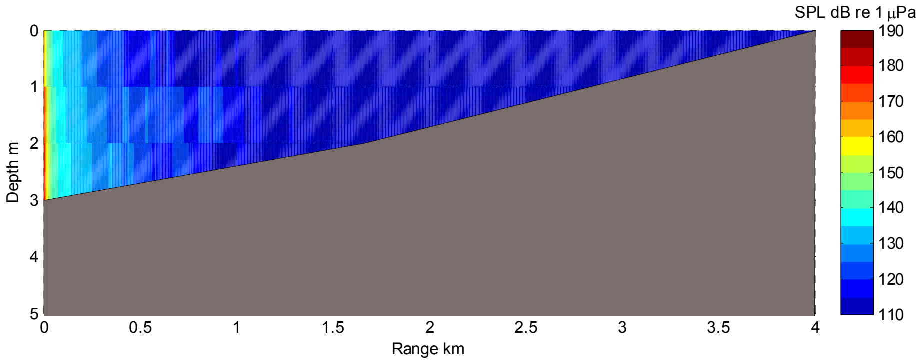

Figure 7.1: Contour plot of seismic sound from the VSGA source array as a function of range and depth along the 0° transect for the month of August
(note the part coloured grey indicates the seabed)

It will be seen that the SPL falls rapidly from 191.7 dB re 1 μPa to 110 dB re 1 μPa over a distance of 1.5 km from the source. The rapid attenuation of sound levels over distance in this example is attributed to three factors: the sound speed profile; the water depth and the wedge-shaped water column channel. The first effect concerns the downwardly refracting nature of the sound speed profile (see Section 5) where the sound is directed away from the sea surface and into the seabed. The dissipative nature of the soft clay sediment means that acoustic energy is readily absorbed into the seabed sediment and relatively low levels of sound are subsequently reflected back into the water column. The second effect is due to the limiting nature of a shallow water channel to support low frequency energy where Urick[39] shows that the cut-off frequency is inversely proportional to water depth. For a water channel of depth 3 m, the cut-off frequency is around 400 Hz.

Below this frequency, energy is increasingly absorbed into the seabed and subsequently contributes very little to sound levels in the water. As the source array is predominantly a low-frequency source (see Section 3) this means that there are relatively low energy levels left to propagate. The last effect is due to the water depth decreasing with increasing range: this is referred to as "up-slope" propagation environment. In such a wedge-shaped water column channel, sound energy is increasingly absorbed into the seabed as water depth decreases, hence SPLs at a given depth and range are lower than would be found in a water column channel with constant or increasing water depth.

Figure 7.2 shows SPL variation with range and depth for the 180° transect for the month of August. Compared with the 0° transect, the water depth increases with range. However, SPLs are still seen to fall rapidly to 110 dB within a distance of 1.5 km from the source. This indicates that the downwardly refracting sound speed profile and the water depth at the source location are the major influences on the attenuation of sound while bathymetry at range plays little or no further part.

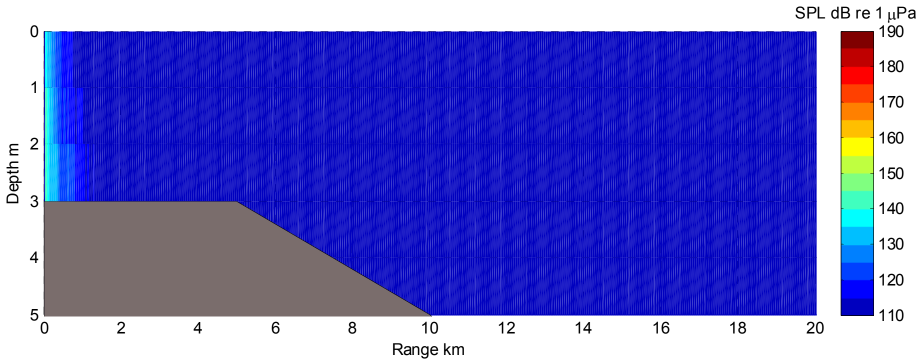

Figure 7.2: Contour plot of seismic sound from the VSGA source array as a function of range and depth along the 180° transect for the month of August

Comparisons may be made between the propagation of sound from the VSGA source array with the two larger source arrays. Figure 7.3 shows SPL for the Bubbles source array as a function of range and depth over the 0° transect using oceanographic conditions for the month of August. It will be seen that SPLs decrease with increasing range from the source and are down to 110 dB re 1 μPa at a distance of 5 km. It is noted that there is also a trend for sound levels at a given range to be slightly higher closer to the seabed than closer to the sea surface - demonstrating the tendency of the sound speed profile to direct the sound downwards. This tendency is more obvious in Figure 7.4 which shows SPLs propagating from the larger Geotiger source array.

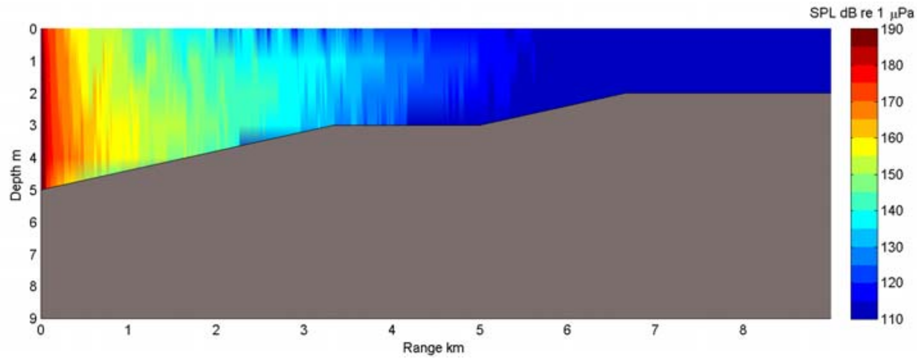

Figure 7.3: Contour plot of seismic sound from the Bubbles source array as a function of range and depth along the 0° transect for the month of August

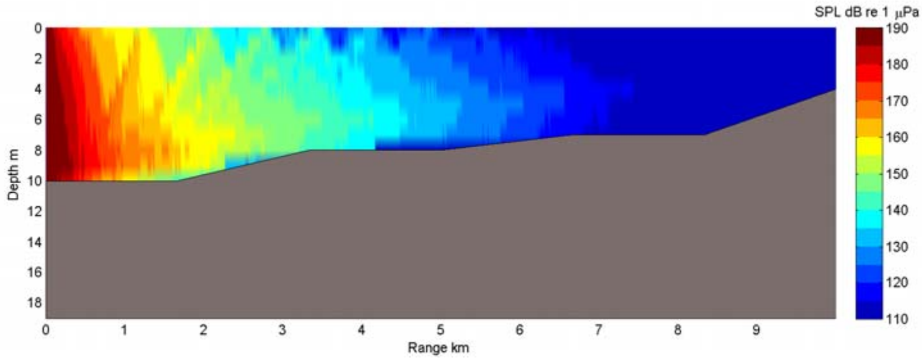

Figure 7.4: Contour plot of seismic sound from the Geotiger source array as a function of range and depth along the 0° transect for the month of August

The influence of the sound speed profile becomes more obvious when looking at the propagation of sound using oceanographic conditions for the month of October. It was noted in Section 5 that a weak sound channel was formed in the sound speed profile close to the sea surface. For such a profile, sound is more likely to be directed upwards towards the sea surface where it subsequently propagates to greater distances. Figures 7.5, 7.6 and 7.7 show SPLs propagating from the VSGA, Bubbles and Geotiger source arrays respectively and in each case, it will be seen that SPLs are indeed higher at a given depth and range compared with those computed using oceanographic conditions from earlier on in the year (See Figures 7.1, 7.3 and 7.4 respectively).

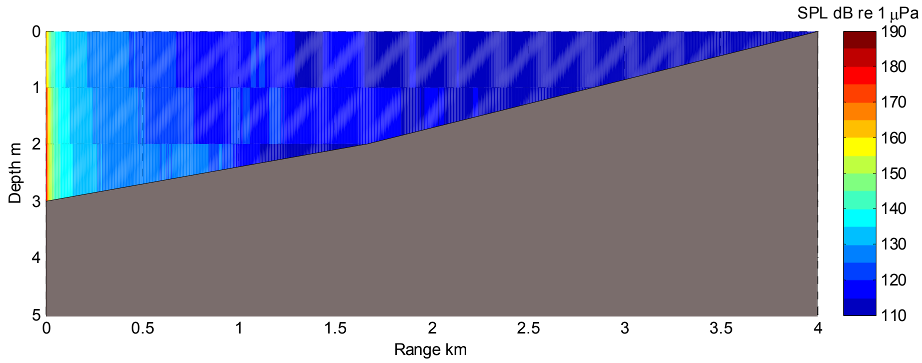

Figure 7.5: Contour plot of seismic sound from the VSGA source array as a function of range and depth along the 0° transect for the month of October

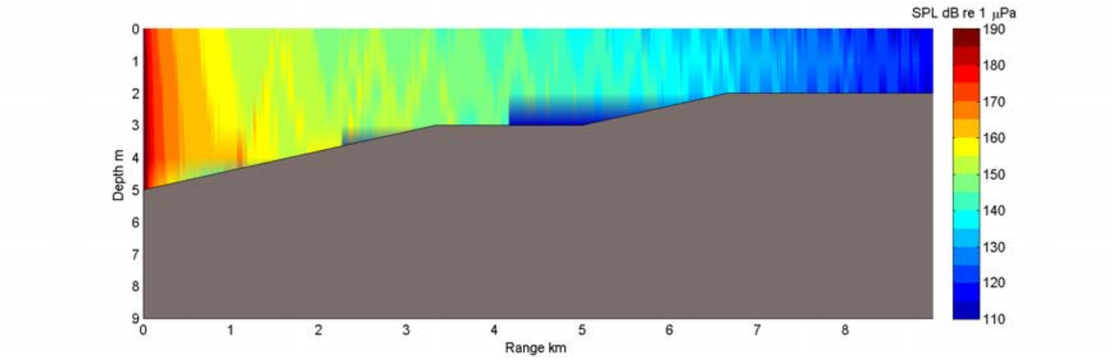

Figure 7.6: Contour plot of seismic sound from the Bubbles source array as a function of range and depth along the 0° transect for the month of October

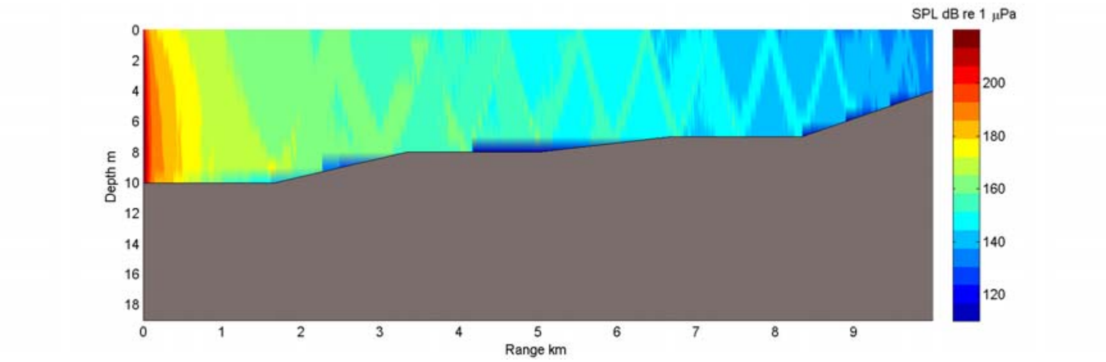

Figure 7.7: Contour plot of seismic sound from the Geotiger source array as a function of range and depth along the 0° transect for the month of October

Figures showing SPLs as a function of range and depth computed along selected transects for the months of August and October oceanographic data are given in Annex A.

8. COMPARISON OF MODELLED SOUND LEVELS WITH RELEVANT THRESHOLD CRITERIA

8.1. Introduction

The previous section discussed the propagation of sound from the seismic source array through the marine environment. This section determines the ranges at which sound levels decrease to below the threshold levels associated with potential impacts introduced in Section 5.

The results discussed in Section 7 show that sound propagation potentially varies slightly along each transect and this is attributed to differences in bathymetry. Accordingly, the range to a given threshold also varies slightly along each transect. As discussed below in further detail, the range at which each threshold criteria is met is given by the furthest distance determined over all of the transects - this may be deemed a conservative measure. Ranges at which the sound level decreases to below the threshold criteria along each transect are given in Annex B.

Potential impacts based on SEL metrics require the sound exposure of a receptor to be calculated over a period of time and this is subsequently compared with the SEL-based thresholds. The calculations are based on unweighted SELs for fish and M-weighted SELs for pinnipeds (see Section 5). These modelling scenarios and the ranges at which predicted sound levels decrease to below each acoustic threshold are discussed below.

8.2. Peak and RMS SPL metrics

Using the peak and RMS SPL metrics, distances within which potential impacts may occur are determined by finding the maximum range at any depth in the water column at which the peak SPL is greater than or equal to a given peak SPL threshold criteria. This procedure is repeated along each transect and the greatest of all the maximum ranges is assumed to be the radial distance from the given source at which a particular potential impact may occur. This is deemed to be a conservative measure - it is quite likely that variation in propagation conditions along each transect (see Section 7) will lead to a range of distances over which the SPL has fallen to a given threshold level.

Peak SPLs may be converted to equivalent RMS SPL following consideration of the nature of the signal. For a sinusoidal signal, the relationship between peak level signal and the RMS equivalent is given by peak level – 3dB. Seismic source signals are not sinusoidal in shape so this conversion is not valid. Furthermore, during propagation the outgoing source signal stretches out in time (see e.g. Urick[39]) and this is attributed to the sound travelling along multiple paths and each arriving at a given location at a slightly different time. As a result, the difference between peak level and RMS varies with distance. Various studies[42,43,44] suggest a range of values between 2 dB and 20 dB. The

[42] Madsen P.T., (2005), "Marine mammals and noise: Problems with root mean square sound pressure levels for transients", J. Acoust. Soc. Am. **117**(6), 3952.

[43] Greene Jnr C.R.,"Physical acoustics measurements". In: W.J. Richardson (ed.) Northstar Marine Mammal Monitoring Program 1996: Marine Mammal and Acoustical Monitoring of a Seismic Program in the Alaskan Beaufort Sea. LGL Rep 2121-2, LGL Ltd, Canada and Greeneridge Sciences Inc. USA for BP (Alaska) Inc. and Nat. Mar. Fish Serv. Alaska. 245 pp.

lower the conversion factor, the greater the overestimation of RMS SPL. For the purpose of the analysis undertaken in the current study, it is suggested that both 10 dB and 15 dB be used for the conversion in order to provide a nominal range of distances to each of the RMS SPL threshold criteria being used to indicate potential behavioural responses to sound from a seismic source.

8.2.1. Fish

The results of the analysis for fish exposed to sound emitted by each of the SWAP 3D seismic sources during surveys in Priority Areas 4 and 2 are shown in Tables 8.1 and 8.2 respectively.

Tables 8.1 and 8.2 show the distances at which the sound level decreases to below the various threshold criteria for both potential mortal injury and recoverable injury for all fish groupings. It will be seen that the sound levels generated by the VSGA source array are insufficient to reach levels associated with either mortal or recoverable injury for fish of all hearing sensitivities. When exposed to sound propagating from either the Bubbles or Geotiger source arrays, the distances are all short-range and are thus unaffected by seasonal changes in the sound speed profile. In addition, they are all within or close to the near-field region of the source array.

For fish with low hearing sensitivity, peak sound levels decrease to below the threshold for potential mortal injury and recoverable injury (both represented by the 213 dB re 1 μPa peak threshold) beyond a distance of 4 m from the Bubbles source array and 27 m for the Geotiger array. For those species having medium and high hearing sensitivity, as well as for fish eggs and larvae, peak sound levels decrease to below the threshold for potential mortal injury (represented by the 207 dB re 1 μPa peak threshold) at distances of 12 m and 40 m from the two source arrays respectively. Similarly, the range at which recoverable injury in fish with high hearing sensitivity (as represented by the 203 dB re 1 μPa threshold) peak sound levels decrease to below the threshold beyond a distance of 12 m and 60 m from the Bubbles array and Geotiger array respectively.

A detailed breakdown of modelling results for fish as a function of transect bearing (see Section 8.1) is given in Annex B.

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

Impact	Threshold	Distance m		
	dB re 1 μPa	VSGA	Bubbles	Geotiger
Potential mortal injury in fish with low hearing sensitivity exposed to impulse sound Recoverable injury in fish with low hearing sensitivity exposed to impulse sound	213 dB peak	<1 m*	4 m*	27 m*
Potential mortal injury in fish with medium hearing sensitivity exposed to impulse sound Potential mortal injury in fish with high hearing sensitivity exposed to impulse sound Potential mortal injury in fish eggs and larvae exposed to impulse sound Recoverable injury in fish with medium hearing sensitivity exposed to impulse sound	207 dB peak	<1 m*	12 m*	42 m
Recoverable injury in fish with high hearing sensitivity exposed to impulse sound	203 dB peak	<1 m*	12 m*	60 m

Table 8.1: Summary of impact ranges for fish species in Priority Area 2 exposed to seismic source array sound using peak level metrics
(* - maximum range derived from near-field source level model)

Impact	Threshold dB re 1 μPa	Distance m		
		VSGA	Bubbles	Geotiger
Potential mortal injury in fish with low hearing sensitivity exposed to impulse sound Recoverable injury in fish with low hearing sensitivity exposed to impulse sound	213 dB peak	<1 m*	4 m*	27 m*
Potential mortal injury in fish with medium hearing sensitivity exposed to impulse sound Potential mortal injury in fish with high hearing sensitivity exposed to impulse sound Potential mortal injury in fish eggs and larvae exposed to impulse sound Recoverable injury in fish with medium hearing sensitivity exposed to impulse sound	207 dB peak	<1 m*	12 m*	42 m
Recoverable injury in fish with high hearing sensitivity exposed to impulse sound	203 dB peak	<1 m*	12 m*	60 m

Table 8.2: Summary of impact ranges for fish species in Priority Area 4 exposed to seismic source array sound using peak level metrics
(* - maximum range derived from near-field source level model)

8.2.2. Pinnipeds

The results of the analysis for pinnipeds exposed to sound emitted by each of the SWAP 3D seismic sources during surveys in Priority Areas 2 and 4 are summarised in Tables 8.3 and 8.4 respectively.

Potential Impact	Threshold dB re 1 μPa	Distance		
		VSGA	Bubbles	Geotiger
Permanent Threshold Shift (PTS) onset	218 dB peak	<1 m*	1 m*	9 m*
Temporary Threshold Shift (TTS) onset	212 dB peak	<1 m*	6 m*	32 m*
Avoidance Behaviour	190 dB RMS[1]	<1 m*	12 m*	51 m
Avoidance Behaviour	190 dB RMS[2]	<1 m*	20 m*	80 m
Limited disturbance	180 dB RMS[1]	<1 m*	30 m*	120 m
Limited disturbance	180 dB RMS[2]	1 m*	51 m	190 m
Limited disturbance	150 dB RMS[1]	14 m*	636 m	1.5 km
Limited disturbance	150 dB RMS[2]	20 m*	931 m	1.9 km
Background level	120 dB RMS[1]	153 m	3.4 km	4.7 km
Background level	120 dB RMS[2]	445 m	4.0 km	5.4 km
Background level	110 dB RMS[1]	664 m	8.1 km	6.0 km
Background level	110 dB RMS[2]	943 m	8.1 km	6.7 km
Background level	100 dB RMS[1]	1.5 km	8.1 km	7.4 km
Background level	100 dB RMS[2]	1.9 km	8.1 km	8.0 km

Table 8.3: Summary of impact ranges for pinnipeds in Priority Area 2 exposed to sound from seismic source arrays based on peak level and RMS metrics (* - maximum range derived from near-field source level model; [1] – based on Peak level – 15 dB; [2] - based on Peak level – 10 dB)

Potential Impact	Threshold dB re 1 μPa	Distance		
		VSGA	Bubbles	Geotiger
Permanent Threshold Shift (PTS) onset	218 dB peak	<1 m*	1 m*	9 m*
Temporary Threshold Shift (TTS) onset	212 dB peak	<1 m*	6 m*	32 m*
Avoidance Behaviour	190 dB RMS[1]	<1 m*	12 m*	51 m
Avoidance Behaviour	190 dB RMS[2]	<1 m*	20 m*	80 m
Limited disturbance	180 dB RMS[1]	<1 m*	30 m*	112 m
Limited disturbance	180 dB RMS[2]	1 m*	51 m	153 m
Limited disturbance	150 dB RMS[1]	14 m*	1.13 km	3.3 km
Limited disturbance	150 dB RMS[2]	20 m*	2.22 km	6.6 km
Background level	120 dB RMS[1]	153 m	38.9 km	51 km†
Background level	120 dB RMS[2]	455 m	51 km†	51 km†
Background level	110 dB RMS[1]	976 m	51 km†	51 km†
Background level	110 dB RMS[2]	2.2 km	51 km†	51 km†
Background level	100 dB RMS[1]	3.9 km	51 km†	51 km†
Background level	100 dB RMS[2]	7.7 km	51 km†	51 km†

Table 8.4: Summary of impact ranges for pinnipeds in Priority Area 4 exposed to sound from seismic source arrays based on peak level and RMS metrics
(* - maximum range derived from near-field source level model; [1] – based on Peak level – 15 dB; [2] - based on Peak level – 10 dB; † - maximum extent of propagation modelling)

The results show that the sound levels generated by the VSGA source array quickly fall below threshold values associated with even limited behavioural disturbances. It is noted that the distances involved, between 14 m and 20 m, lie close to the near-field of the array itself. The sound emitted by the source array may remain audible over ranges varying between 153 m and 7.7 km depending on prevailing background sound levels.

Peak SPL generated by the Bubbles source array decreases to below threshold levels associated with PTS and TTS (represented by the 218 dB re 1 μPa peak and 212 dB re 1 μPa peak thresholds respectively) within 10 m from the array and, it is noted, within the near-field of the array itself.

RMS SPLs decrease below threshold levels associated with avoidance behaviour reactions (190 dB re 1 μPa) beyond 20 m from the array. RMS SPLs decrease to below the upper and lower threshold criteria associated with limited disturbance between:

- 30- 51 m (dependent on the peak-to-RMS correction factor) and 636 m and 931 m in Priority Area 2, (June to August), and
- 30- 51 m and 1.1-2.2 km in Priority Area 4 (September and October).

Neither peak nor RMS SPL within these short distances vary significantly between the months of the year over which the seismic surveys are planned in each Priority Area: the distances are relatively insensitive to the influence of either the sound speed profile or geoacoustic properties of the acoustic propagation model. However the longer distances where RMS SPLs decrease below the lower threshold criteria associated with limited disturbance are affected by the presence of the upwardly refracting sound speed profile later on in the year (see Section 5).

RMS SPLs decrease to below background levels at distances between 3.4 – 4.1 km (dependent on the peak to RMS correction factor) and 8 km in Priority Area 4 and up to 50 km from the source in Priority Area 2 depending on prevailing background sound levels. As pointed out, sound propagation was modelled out to a maximum distance of 51 km. However, it is possible that sound levels remain audible beyond this limit in quiet environments.

For the Geotiger source array, peak SPLs decrease to below threshold levels associated with PTS and TTS beyond relatively short distances – 9 m and 32 m from the source array respectively. RMS SPLs decrease below threshold criteria associated with avoidance behaviour beyond a distance of 51-80 m (dependent on the peak to RMS correction factor). RMS SPLs decrease below the upper and lower threshold criteria associated with limited behavioural disturbance between:

- 120-190 m (dependent on the peak to RMS correction factor) and 1.5-1.9 km in Priority Area 2, and
- 112-153 m and 3.3-6.6 km in Priority Area 4.

Sound levels may remain audible at distances up to 51 km or greater.

A detailed breakdown of modelling results for pinnipeds as a function of transect bearing (see Section 8.1) is given in Annex B.

8.3. Cumulative Exposure – SEL Metrics

8.3.1. Introduction

Sound exposure level is estimated using a moving receptor and source model[45] where the receptor moves away from the source and through the sound field, starting at various distances from the sound source over a period of time. For each sound source – receptor separation starting distance, the corresponding SPL is determined using data for each source from the 180° modelling transect[46] (see Section 6). This is deemed precautionary given that SPLs are likely to show some variation along each transect due to differences in bathymetry. The SEL is calculated using eqn 2-4 in Section 2 and the cumulative SEL is determined by summing the SEL over a given time. The maximum SEL attained is explored for a number of modelling scenarios involving one or more source arrays and this is compared with threshold levels as associated with PTS and TTS given in Tables 5.1 and 5.2. For fish, the SEL is unweighted while for pinnipeds, the M-weighting function is applied to the SEL (see Section 5.3.2).

A number of potential multiple vessel scenarios were identified using information provided by the client and these are summarised in Table 8.5 together with the vessel cross-line separations for each multiple vessel scenario.

Combined Scenario	Survey vessels and separations	Vessel/receptor movement
MS 1	Single source vessel - 200 m	Vessel @270°, receptor @180°
MS 2	1000 **m** Geotiger separation with Geotiger 2 offset	Alternate vessels @270°/90°, receptor @180°
MS 3	2000 m Geotiger separation with Geotiger 2 offset	Alternate vessels @270°/90°, receptor @180°
MS 4	3000 m Geotiger separation with Geotiger 2 offset	Alternate vessels @270°/90°, receptor @180°
MS 5	4000 m Geotiger separation with Geotiger 2 offset	Alternate vessels @270°/90°, receptor @180°
MS 6	5000 m Geotiger separation with Geotiger 2 offset	Alternate vessels @270°/90°, receptor @180°
MS 7	8000 m Geotiger separation with Geotiger 2 offset	Alternate vessels @270°/90°, receptor @180°
MS 8	10000 m Geotiger separation with Geotiger 2 offset	Alternate vessels @270°/90°, receptor @180°
MS 9	12000 m Geotiger separation with Geotiger 2 offset	Alternate vessels @270°/90°, receptor @180°

Table 8.5: Modelling scenarios involving multiple sound sources

45 Theobald P., Lepper P., Robinson S., Hazelwood D., (2009), "Cumulative Noise Exposure Assessment For Marine Mammals Using Sound Exposure Level As A Metric", UAM Conference Proceedings 2009.

46 The 180° transect starts at a shallow depth and increases with increasing range. There is a tendency therefore for longest range propagation to occur on this transect compared with all others.

8.3.2. Moving Receptor/Source Model

The cumulative sound exposure for an animal receptor is dependent not only on its hearing sensitivity relative to the sound but also on its proximity to a sound source and its duration of exposure to a sound. Any result arising from a given receptor - sound source scenario therefore is unique to that specific model scenario only. Nevertheless the results from modelling several scenarios provide some boundary conditions for possible real-world source-receiver movement scenarios to inform an assessment using a cumulative SEL threshold criterion.

For the receptor – sound source scenarios considered, it is assumed that the seismic survey source array is transiting at a speed of 2.3 m/s (corresponding to a typical survey vessel tow speed of 4.5 knots[47]) and at bearings of either 90° or 270° from a nominal point of origin. It is further assumed that an animal swims from a given start location relative to the seismic source array on a constant bearing of 180° and at a constant speed of 0.2 m/s for the fish[48] and typically 2.6 m/s for the seal[49]. The positions of the animal and source vessels are computed at successive regularly spaced distance intervals every 10 seconds. This corresponds to a typical Source Point Interval (SPI). For clarity, it is emphasised that the SEL modelling coordinate system is used to represent the real-world setting i.e. the 90/270° vessel transects in the SEL scenario model represent the 170/350° sail-line direction of the survey while a receptor moving in the 180° direction in the SEL model is representative of a bearing of 260° in the survey coordinate system.

8.3.3. Modelling Scenario MS1

The single source scenario commences with each source array moving at a speed of 2.3 m/s on a bearing of 270°. A receptor moves on a bearing of 180° at a speed of 2.6 m/s (representing a pinniped) or 0.2 m/s (representing a fish). Currently, standard industrial practice is to delay the start of a source if a marine mammal is seen within a radius of 500 m of the source array[50], accordingly an offset of 500 m is built into the modelling scenario with the receptor starting position 500 m offset on the modelling X-axis. The receptor/source vessel layout is shown in Figure 8.1.

Both the variation of instantaneous SPL over time and the build-up of cumulative SEL over a period of time were calculated. The SPL data was generated by using the acoustic modelling processes discussed in Section 6 and oceanographic data for the months of June through to August representing survey activity in PA2 and for the months of September and October representing survey activity in PA4. A typical result is shown in Figure 8.2 for a pinniped moving through the survey area during the month of June. It is noted that the variation of SPL and SEL with time during the other months of interest and

[47] "An overview of marine seismic operations", (2011), OGP IAGC Report No. 448. Accessed http://www.ogp.org.uk/pubs/448.pdf
[48] Based on a sustained swim speed for a sturgeon - http://www.fsl.orst.edu/geowater/FX3/help/FX3_Help.html#9_Fish_Performance/Fish_Length_and_Swim_Speeds.htm
[49] Gallon, S. L., Sparling, C. E., Georges, J-Y., Fedak, M. A., Biuw, M., & Thompson, D. (2007). How fast does a seal swim? Variations in swimming behaviour under differing foraging conditions. The Journal of Experimental Biology, **210**, 3285-3294.
[50] JNCC (2010), JNCC guidelines for minimising the risk of injury and disturbance to marine mammals from seismic surveys. Accessed http://jncc.defra.gov.uk, November 2015.

involving either fish or pinniped is very similar to that shown in Figure 8.2 - just the finer details differ. For brevity, these results are not shown. From such results, the maximum SEL experienced by a receptor was determined during each month and for each offset position varying from 500 m to 8000 m. The results are given in Tables 8.5 to 8.7 for fish and Tables 8.8 to 8.10 for pinnipeds.

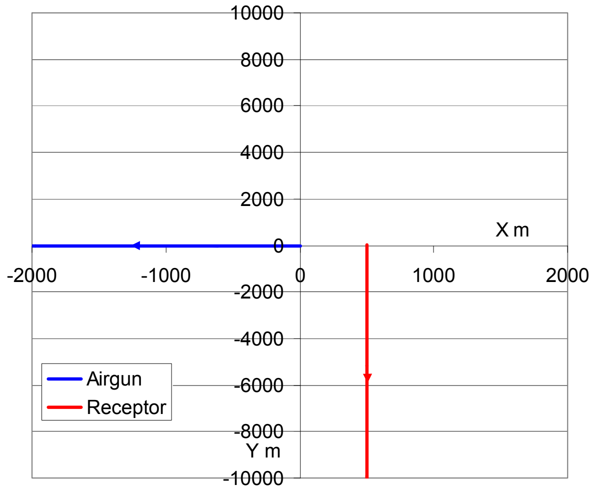

Figure 8.1: Relative locations and paths of receptor and source array during Modelling Scenario 1

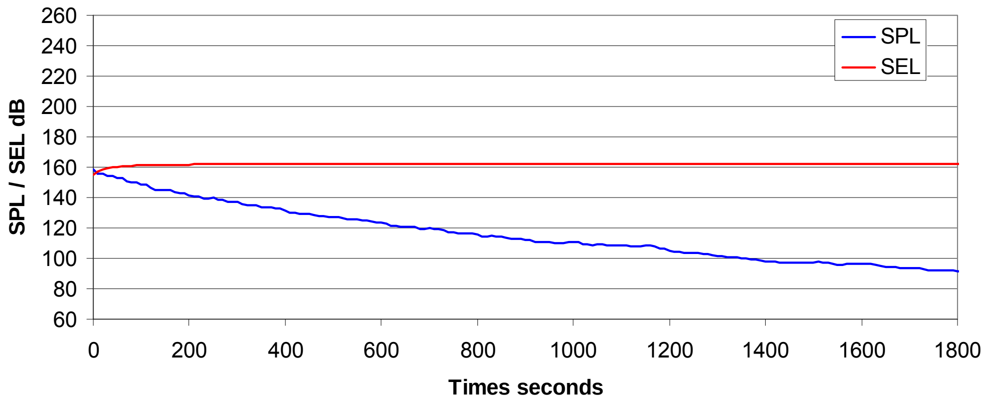

Figure 8.2: Instantaneous SPL and cumulative SEL on a pinniped exposed to sound from the VSGA source array

8.3.3.1. Pinnipeds

Comparisons may be made between the SEL threshold data for pinnipeds given in Table 5.2 with the maximum SELs generated for each month and animal offset.

It will be seen that when a pinniped is exposed to acoustic emissions from the VSGA source, the maximum cumulative SELs generated are below threshold levels relating to the onset of PTS following exposure to multiple pulses (186 dB re.1μPa^{2}s SEL M-

Weighted); or the onset of TTS following exposure to multiple pulses (171 dB re.1μPa^{2}s SEL M-Weighted). In addition, maximum cumulative SELs are below threshold levels related to significant behavioural disturbance for a single pulse signal following exposure to multiple pulses. The results are summarised in Table 8.5.

SPLs generated by the Bubbles source are somewhat higher than those generated by the VSGA source hence maximum cumulative SELs generated over the duration of the model scenario are also higher (Table 8.6). At 500 m initial offset, the SELs are above threshold levels related to TTS during the month of August in PA2 and during the months of September and October in PA4. Maximum SELs are above threshold levels related to TTS during October when the initial animal offset is up to 4 km. This is attributed to the upwardly refracting nature of the sound speed profile which causes the acoustic energy emitted by the source to propagate to longer distances compared with earlier on in the year.

Of the three source arrays considered, the Geotiger array generates the highest maximum SELs. At 500 m initial offset, SELs are above threshold levels associated with TTS during all months and above threshold levels related to PTS during October only.

x-offset	SEL dB re 1 μPa^2.sec				
	Jun	Jul	Aug	Sep	Oct
500 m	117.7	124.1	132.1	132.0	138.9
1000 m	98.9	108.7	125.5	125.9	137.0
2000 m	78.6	85.6	116.5	117.7	135.0
4000 m	50.6	50.8	100.6	102.6	132.6
8000 m	18.3	18.6	69.2	73.4	129.7

Table 8.5: Summary of maximum SELs for a receptor exposed to a single VSGA source as a function of offset distance

x-offset	SEL dB re 1 μPa^2.sec				
	Jun	Jul	Aug	Sep	Oct
500 m	159.3	164.3	172.7	173.0	176.9
1000 m	139.5	149.1	166.5	167.1	175.9
2000 m	116.0	124.6	156.4	157.5	173.7
4000 m	92.0	92.2	140.1	142.2	171.2
8000 m	63.2	63.6	110.1	114.5	168.4

Table 8.6: Summary of maximum SELs for a receptor exposed to a single Bubbles source as a function of offset distance

x-offset	SEL dB re 1 μPa^2.sec				
	Jun	Jul	Aug	Sep	Oct
500 m	175.0	178.1	183.5	183.7	186.2
1000 m	156.6	162.4	176.1	176.8	184.8
2000 m	136.4	139.0	165.4	166.1	182.6
4000 m	112.6	113.0	146.3	148.5	180.7

8000 m	84.1	84.4	107.6	113.7	177.6

Table 8.7: Summary of maximum SELs for a receptor exposed to a single Geotiger source as a function of offset distance

8.3.3.2. Fish

For fish of all hearing sensitivities, the SEL thresholds corresponding to potential mortal injury following exposure to seismic sound lie in the range 207-219 dB re 1 μPa^2.sec while those for recoverable injury are slightly lower at 207-216 dB re 1 μPa^2.sec. The onset of TTS lies at a threshold of 186 dB re 1 μPa^2.sec. Maximum SELs both the VSGA and Bubbles sources are below the threshold levels relating to potential mortal injury, recoverable injury or TTS. For the Geotiger source, maximum SELs are below the threshold levels relating to both potential mortal injury and recoverable injury. Whereas maximum SELs are above the threshold level related to TTS in PA2 during June through to August. In PA4, maximum SELs remain below the threshold level for TTS when the initial receptor offset relative to the source is greater than 500 m during September and greater than 1000 m in October.

x-offset	SEL dB re 1 μPa^2.sec				
	Jun	Jul	Aug	Sep	Oct
500 m	123.4	125.1	132.5	132.4	139.1
1000 m	111.7	111.7	125.8	126.1	137.0
2000 m	96.6	96.8	116.7	117.8	135.1
4000 m	76.4	76.6	100.7	102.6	132.6
8000 m	50.3	50.5	69.3	73.4	129.8

Table 8.8: Summary of maximum SELs for a receptor exposed to a single VSGA source as a function of offset distance

x-offset	SEL dB re 1 μPa^2.sec				
	Jun	Jul	Aug	Sep	Oct
500 m	161.9	165.6	173.2	173.5	177.1
1000 m	150.5	151.4	166.8	167.4	176.0
2000 m	137.1	137.3	156.6	157.7	173.7
4000 m	120.0	120.3	140.3	142.3	171.3
8000 m	95.9	96.3	110.3	114.6	168.4

Table 8.9: Summary of maximum SELs for a receptor exposed to a single Bubbles source as a function of offset distance

x-offset	SEL dB re 1 μPa^2.sec				
	Jun	Jul	Aug	Sep	Oct
500 m	181.7	182.2	185.7	185.8	187.4
1000 m	171.0	171.1	177.6	178.2	185.2
2000 m	157.8	158.0	166.3	166.9	182.6

4000 m	140.7	141.0	147.1	149.0	180.7
8000 m	116.7	117.1	117.0	116.9	177.6

Table 8.10: Summary of maximum SELs for a receptor exposed to a single Geotiger source as a function of offset distance

8.3.4. Discussion

The single source scenarios discussed above showed that maximum SELs for the VSGA source are significantly below threshold level related to potential mortal injury; recoverable injury and TTS in fish; and the onset of both PTS and TTS for pinnipeds. It is concluded that when the VSGA source is used together with either the Bubbles or Geotiger sources, SELs will not be increased to levels above those generated by either the Bubbles or Geotiger sources alone.

8.3.5. Modelling Scenarios MS2 – MS9

The next sequence of models run involve scenarios consisting of a receptor moving through an acoustic field generated by multiple array sources. The relative separations between each source are varied and the resultant variation in overall cumulative SEL and instantaneous SPL is explored.

For these scenarios, the Bubbles source vessel transits at a speed of 2.3 m/s on a bearing of 270° while both the Geotiger source vessels head in the opposite direction on a bearing of 90°. The Bubbles and each Geotiger source are separated by an initial cross line distance (on the modelling Y-axis) of 500 m while the two Geotiger sources are separated by an initial 1000 m. In addition, one of the Geotiger source arrays is also offset in the x-direction by 2000 m. The Geotiger separation in the Y-direction is systematically incremented and the overall SEL and SPL is calculated as vessels and receptor move at each time step within the model.

The relative positions and paths of the sources and receptor for a Geotiger separation of 1000 m are shown in Figure 8.3. The variation of SPL from the individual sources and the overall SPL and SEL for this separation is shown in Figure 8.4. It will be seen that at the commencement of the scenario, the main contribution to the overall SPL is due to the Geotiger sources (coloured amber in Figures 8.3 and 8.4): the contributions of the Bubbles and the Geotiger (green) sources is much smaller by comparison. Over the course of the scenario, the distance between the receptor and the Bubbles and Geotiger (green) sources increases and these contribute very little to the overall acoustic field. For this model run, the maximum SPL received by the receptor is 166.9.1 dB re 1 μPa while the maximum SEL of 173.1 dB re 1 μPa^2.sec is reached around 150 seconds after the start of the scenario.

The scenario is repeated but this time with a Geotiger cross-line (Y-axis) separation of 3000 m. Figure 8.5 shows the relative positions and paths of the sources and receptor for this configuration while Figure 8.6 shows the variation in SPL and SEL over the duration of the scenario. It will be seen that at the start of the scenario, the dominant source is Bubbles. However, after a duration of around 200 seconds, the separation between the receptor and the Bubbles source has increased while that between the receptor and the Geotiger (amber) source has decreased and this subsequently becomes the major contributor to the overall SPL received by the receptor. The maximum SPL for this configuration is 159.4 dB re 1 μPa and the maximum SEL of 173.1 dB re 1 μPa^2.sec is reached around 100 seconds after the start of the scenario.

For a Geotiger cross-line (Y-axis) separation of 6000 m, the relative positions of the sources and receptor are shown in Figure 8.7. For this configuration, it may be assumed that, as the Geotiger (green) source is by now displaced a considerable distance away from the receptor and that the separation increases over the course of the scenario, the contribution to the total acoustic field at the receptor location is reduced compared to when the Geotiger vessels are closer together and continues to reduce over time and with increasing distance from the receptor. This is supported by the results in Figure 8.8 showing the variation of SPL and SEL over the duration of the scenario. This shows that, initially, the Bubbles source provides the main contribution to SPL and hence SEL but as the receptor moves closer to the Geotiger (amber) source, after a time of approximately 300 seconds, the Geotiger source becomes dominant. The maximum SPL for this configuration is 156.2 dB re 1 μPa and the maximum SEL of 159.5 dB re 1 μPa^2.sec is reached around 100 seconds after the start of the scenario.

When the two Geotiger source arrays start with an initial separation of 12000 m, the relative positions of sources and receptor are as shown in Figure 8.9. From the start of the scenario, the receptor moves towards the Geotiger (amber) source. The dominant source therefore switches from being the Bubbles source to the Geotiger source after a duration of around 700 seconds. The maximum SPL for this configuration is 156.2 dB re 1 μPa and the maximum SEL of 159.3 dB re 1 μPa^2.sec is reached around 100 seconds after the start of the scenario.

The scenario was repeated for each month and the results summarising the maximum SPL and SEL as a function of Geotiger separation are given in Tables 8.10 and 8.11 for fish and Tables 8.12 and 8.13 for pinnipeds respectively.

The results indicate that for the given scenarios involving fish as the receptor (with a slower swim speed compared to pinnipeds), the maximum overall SPLs are below threshold levels related to both potential mortal injury (in the range 207-213 dB re 1 μPa depending on fish hearing sensitivity), and recoverable injury (in the range 203-207 dB re 1 μPa).

For the SEL metric, maximum SELs are below the threshold levels related to injury. Whereas maximum SELs ae above the threshold level related to TTS (186 dB re 1 μPa^2.sec) for the closest Geotiger cross-line separation distances when operating in PA4 during the month of August and in PA2 during the month of September. By October, maximum SELs are above the TTS threshold level for all of the Geotiger separations scenarios considered.

Pinnipeds are somewhat more sensitive to the sound emitted by the seismic arrays. Even so, for the given configurations discussed above, overall peak SPLs are below the threshold levels related to both PTS and TTS criteria (218 dB re 1 μPa peak and 212 dB re 1 μPa peak SPL respectively). Similarly, SPLs are below thresholds related to avoidance behaviour (190 dB re 1 μPa rms). SPLs that may cause limited behavioural disturbance reactions (in the range 150-180 dB re 1 μPa rms) occur for the smallest Geotiger cross-line separations during the months of June and July in PA2. As the survey season progresses, SPLs are within this range for scenarios with greater cross-line separations. By October in PA4, the threshold is exceeded for all separations considered.

Maximum SELs are above the threshold level related to PTS (186 dB re 1 μPa^2.sec) only during October in PA4 and TTS (171 dB re 1 μPa^2.sec) during all months for different cross-line separation distances between Geotiger vessels - initially only for the smallest Geotiger separations during June and July in PA2 but increasing to all separations during August in PA2 and during both September and October in PA4.

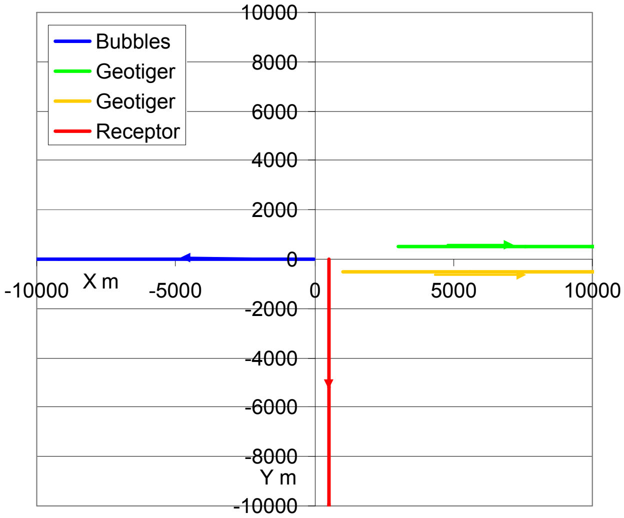

Figure 8.3: Relative locations and paths of receptor and source arrays for an initial Geotiger separation of 1000 m

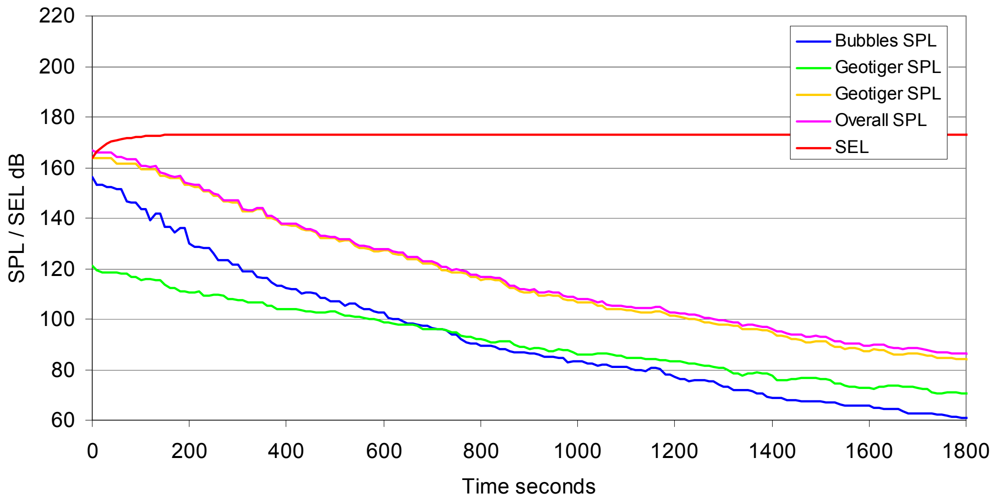

Figure 8.4: Instantaneous SPL and cumulative SEL on an pinniped exposed to sound from the source arrays

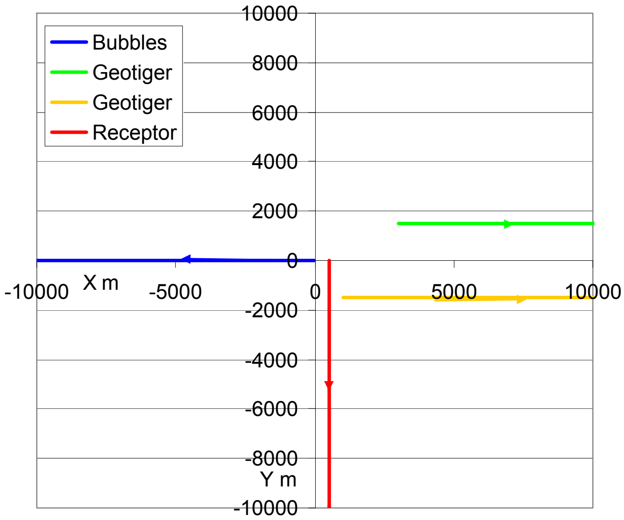

Figure 8.5: Relative locations and paths of receptor and source arrays for an initial Geotiger separation of 3000 m

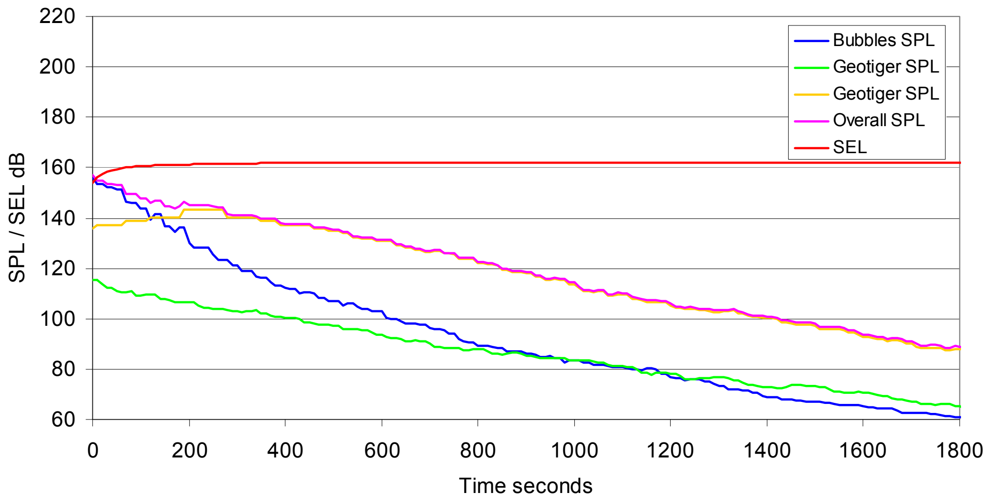

Figure 8.6: Instantaneous SPL and cumulative SEL on a pinniped exposed to sound from the source arrays

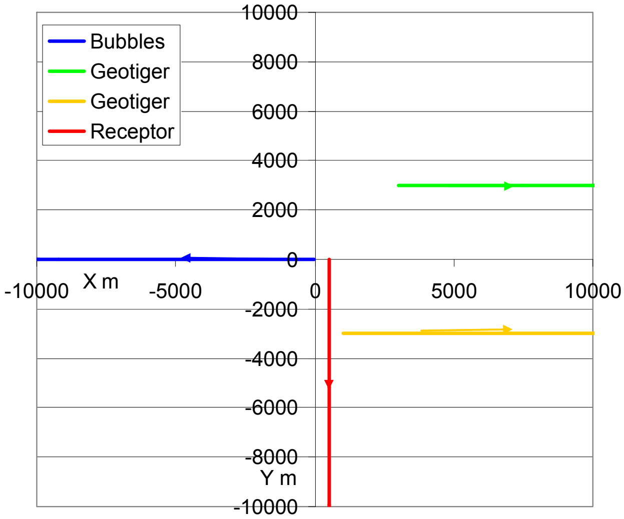

Figure 8.7: Relative locations and paths of receptor and source arrays for an initial Geotiger separation of 6000 m

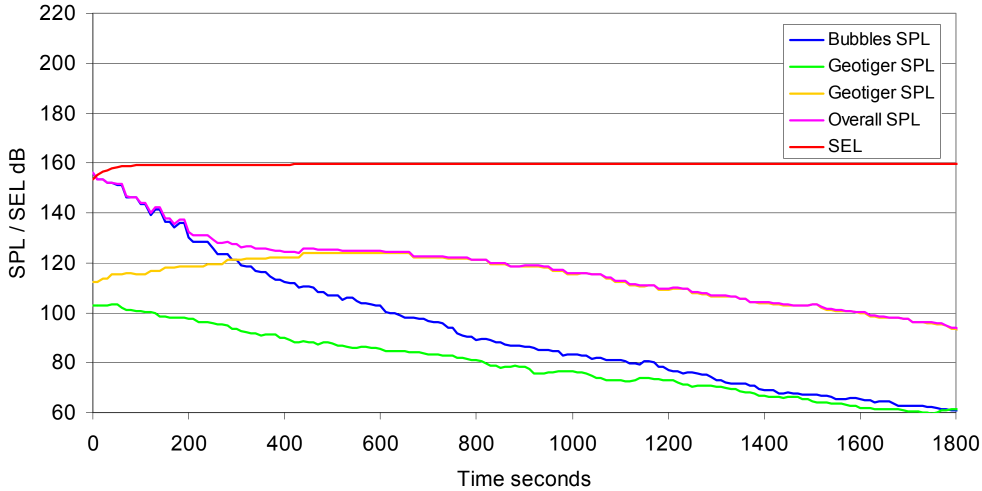

Figure 8.8: Instantaneous SPL and cumulative SEL on a pinniped exposed to sound from the source arrays

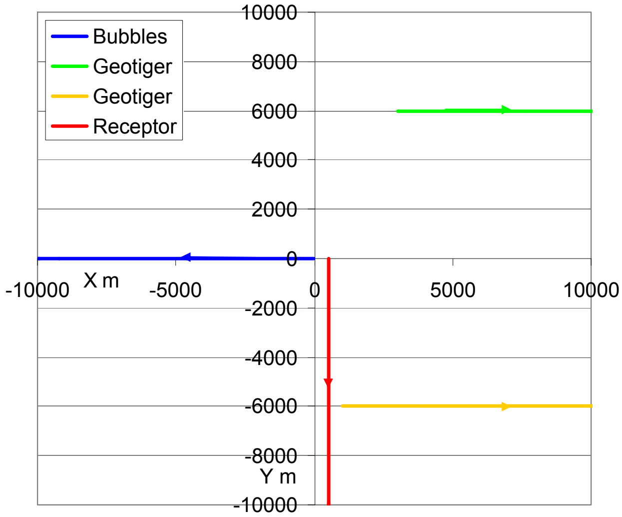

Figure 8.9: Relative locations and paths of receptor and source arrays for an initial Geotiger separation of 12000 m

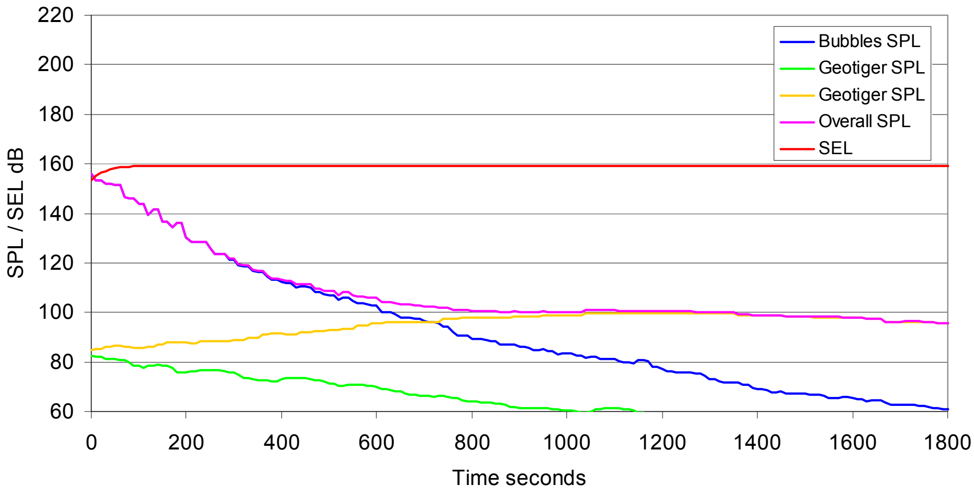

Figure 8.10: Instantaneous SPL and cumulative SEL on a pinniped exposed to sound from the source arrays

Priority Area		Geotiger separation								
	Month	1 km	2 km	3 km	4 km	5 km	6 km	8 km	10 km	12 km
PA4	Jun	172.6	166.7	163.4	161.2	159.9	159.3	158.8	158.5	158.4
PA4	Jul	173.9	167.6	164.6	162.9	161.8	161.4	161.0	160.8	160.7
PA4	Aug	177.9	174.3	171.0	169.2	168.1	167.5	166.7	166.4	166.3
PA2	Sept	179.9	174.1	171.5	169.7	168.4	167.6	166.7	166.5	166.3
PA2	Oct	178.2	177.1	177.1	176.0	173.5	173.1	172.5	172.1	171.3

Table 8.11: Summary of maximum SPLs experienced by fish as a function of Geotiger separation

Priority Area		Geotiger separation								
	Month	1 km	2 km	3 km	4 km	5 km	6 km	8 km	10 km	12 km
PA4	Jun	179.9	174.9	171.4	168.3	166.2	165.0	163.7	163.1	162.8
PA4	Jul	181.8	177.7	174.5	171.8	169.6	168.2	166.6	166.1	165.9
PA4	Aug	187.2	184.8	182.3	179.5	178.0	176.7	174.5	173.7	173.4
PA2	Sept	188.0	184.8	183.7	180.6	178.5	177.2	175.2	174.2	173.8
PA2	Oct	192.4	192.1	192.1	191.8	190.6	190.3	190.5	189.6	189.2

Table 8.12: Summary of maximum SELs experienced by fish as a function of Geotiger separation

Priority Area		Geotiger separation								
	Month	1 km	2 km	3 km	4 km	5 km	6 km	8 km	10 km	12 km
PA4	Jun	166.9	159.4	157.0	156.5	156.3	156.2	156.2	156.2	156.2
PA4	Jul	170.5	163.6	160.6	159.7	159.5	159.4	159.4	159.4	159.3
PA4	Aug	176.1	173.2	170.1	168.5	167.5	166.9	166.2	165.8	165.7
PA2	Sept	178.5	173.0	170.8	169.0	167.8	167.0	166.2	165.9	165.8
PA2	Oct	176.5	176.4	176.6	175.7	173.4	173.0	172.4	171.9	171.0

Table 8.13: Summary of maximum SPLs experienced by pinnipeds as a function of Geotiger separation

Priority Area		Geotiger separation								
	Month	1 km	2 km	3 km	4 km	5 km	6 km	8 km	10 km	12 km
PA4	Jun	173.1	165.9	161.9	160.3	159.7	159.5	159.3	159.3	159.3
PA4	Jul	177.6	171.5	167.4	165.4	164.7	164.5	164.4	164.4	164.4
PA4	Aug	185.5	183.5	181.2	178.6	177.3	176.1	174.0	173.2	172.9
PA2	Sept	186.5	183.6	182.9	179.9	177.8	176.7	174.7	173.7	173.3
PA2	Oct	191.8	191.7	191.8	191.6	190.5	190.2	190.4	189.5	189.2

Table 8.14: Summary of maximum SELs experienced by pinnipeds as a function of Geotiger separation

9. SUMMARY AND CONCLUSIONS

Man-made underwater sound will be generated during the proposed SWAP 3D seismic survey planned for the Priority Areas in the Caspian Sea. The sound thus produced has the potential to impact on biological receptors in the marine environment.

The size of the seismic sound source arrays, which are proposed for deployment in each Priority Area varies dependent on the depth of water over the survey zone. The VSGA, Bubbles and Geotiger source arrays will be used in water depths of 0-2 m, 2-5 m and greater than 5 m respectively. A simple model was developed in order to estimate the near-field acoustic source level for each of the source arrays. The source levels are estimated at 185.4 dB re 1 μPa, 219.4 dB re 1 μPa and 228.8 dB re 1 μPa compared with levels approximately 10-15 dB higher than would have been derived from far-field modelling assumptions. The improved accuracy of the source modelling helps to ensure that source sound levels are not over-estimated within the near-field of the seismic airgun array.

A number of marine species have been identified as being present in the SWAP survey are considered to be sensitive to underwater sound. These are the Caspian seal and species of fish including members of the sturgeon, lamprey and shad families. The published literature was accessed to determine appropriate threshold values related to potential acoustic impacts on marine life. The potential impacts considered were mortality; auditory impairment (Permanent and Temporary Threshold Shift) and behavioural reactions, which were assessed based on peak SPL, cumulative SEL and RMS SPL metrics derived from studies by Southall *et al*.[16] and Popper *et al*.[17]..

Underwater acoustic propagation modelling was undertaken using site- and time- specific environmental data relating to Priority Areas 2 and 4 in the SWAP 3D Contract Area and the results were applied where appropriate to the source data for each of the seismic source arrays.

Ranges relative to the source array within which potential impacts may occur based on peak SPL metrics are given in Tables 9.1 for fish and Tables 9.2 and 9.3 for pinnipeds. The analysis showed that for fish, sound levels generated by the seismic source arrays are relatively low and fall to below threshold levels associated with mortal injury or recoverable injury over short distances within or very close to the acoustic near-field of the array. Between <1 m to 40 m depending on the source array used and the hearing sensitivity of the species considered. Similar distance ranges were estimated relative peak SPL threshold levels associated with recoverable injury in fish.

When using the same peak SPL metric, the analysis showed that sound pressure levels fall below threshold for PTS and TTS in pinnipeds at maximum distances of 9 m and 32 m respectively from the largest source array. It is noted that these ranges are within or close to the acoustic near-field of the seismic source array. Based on RMS metrics, sound levels fall to below thresholds related to the occurrence of potential avoidance behavioural responses at distances up to 80 m from the array and below threshold levels related to potential limited behavioural reactions at ranges between <1 m to 6.6 km depending on the source array used and the time of year considered.

Impact	Threshold dB re 1 μPa	Distance m		
		VSGA	Bubbles	Geotiger
Potential mortal injury in fish with low hearing sensitivity exposed to impulse sound Recoverable injury in fish with low hearing sensitivity exposed to impulse sound	213 dB peak	<1 m*	4 m*	27 m*
Potential mortal injury in fish with medium hearing sensitivity exposed to impulse sound Potential mortal injury in fish with high hearing sensitivity exposed to impulse sound Potential mortal injury in fish eggs and larvae exposed to impulse sound Recoverable injury in fish with medium hearing sensitivity exposed to impulse sound	207 dB peak	<1 m*	12 m*	42 m
Recoverable injury in fish with high hearing sensitivity exposed to impulse sound	203 dB peak	<1 m*	12 m*	60 m

Table 9.1: Summary of impact ranges for fish species exposed to seismic source array sound using peak level metrics
(* - maximum range derived from near-field source level model)

Potential Impact	Threshold dB re 1 μPa	Distance m		
		VSGA	Bubbles	Geotiger
Permanent Threshold Shift (PTS) onset	218 dB peak	<1 m*	1 m*	9 m*
Temporary Threshold Shift (TTS) onset	212 dB peak	<1 m*	6 m*	32 m*
Avoidance Behaviour	190 dB RMS[1]	<1 m*	12 m*	51 m
Avoidance Behaviour	190 dB RMS[2]	<1 m*	20 m*	80 m
Limited disturbance	180 dB RMS[1]	<1 m*	30 m*	120 m
Limited disturbance	180 dB RMS[2]	1 m*	51 m	190 m
Limited disturbance	150 dB RMS[1]	14 m*	636 m	1.5 km
Limited disturbance	150 dB RMS[2]	20 m*	931 m	1.9 km
Background level	120 dB RMS[1]	153 m	3.4 km	4.7 km
Background level	120 dB RMS[2]	445 m	4.0 km	5.4 km
Background level	110 dB RMS[1]	664 m	8.1 km	6.0 km
Background level	110 dB RMS[2]	943 m	8.1 km	6.7 km
Background level	100 dB RMS[1]	1.5 km	8.1 km	7.4 km
Background level	100 dB RMS[2]	1.9 km	8.1 km	8.0 km

Table 9.2: Summary of impact ranges for pinnipeds in Priority Area 2 exposed to seismic source sound based on peak level and RMS metrics (* - maximum range derived from near-field source level model; [1] – based on Peak level – 15 dB; [2] - based on Peak level – 10 dB)

Potential Impact	Threshold dB re 1 μPa	Distance m		
		VSGA	Bubbles	Geotiger
Permanent Threshold Shift (PTS) onset	218 dB peak	<1 m*	1 m*	9 m*
Temporary Threshold Shift (TTS) onset	212 dB peak	<1 m*	6 m*	32 m*
Avoidance Behaviour	190 dB RMS[1]	<1 m*	12 m*	51 m
Avoidance Behaviour	190 dB RMS[2]	<1 m*	20 m*	80 m
Limited disturbance	180 dB RMS[1]	<1 m*	30 m*	112 m
Limited disturbance	180 dB RMS[2]	1 m*	51 m	153 m
Limited disturbance	150 dB RMS[1]	14 m*	1.13 km	3.3 km
Limited disturbance	150 dB RMS[2]	20 m*	2.22 km	6.6 km
Background level	120 dB RMS[1]	153 m	38.9 km	51 km†
Background level	120 dB RMS[2]	455 m	51 km†	51 km†
Background level	110 dB RMS[1]	976 m	51 km†	51 km†
Background level	110 dB RMS[2]	2.2 km	51 km†	51 km†
Background level	100 dB RMS[1]	3.9 km	51 km†	51 km†
Background level	100 dB RMS[2]	7.7 km	51 km†	51 km†

Table 9.3: Summary of impact ranges for pinnipeds in Priority Area 4 exposed to seismic source sound based on peak level and RMS metrics (* - maximum range derived from near-field source level model; [1] – based on Peak level – 15 dB; [2] - based on Peak level – 10 dB; † - maximum extent of propagation modelling)

In order to determine the sensitivity of pinnipeds and fish to the source array sound using energy-level metrics, a moving source/receptor model was constructed for various multiple vessel scenarios. The cumulative exposure for receptoris dependent not only on its hearing sensitivity to the sound but also on its proximity and duration of exposure to a sound source. Any result arising from a given –source/receptor scenario therefore is unique to that specific model scenario only. Nevertheless the results from modelling several scenarios provide some boundary conditions for real-world source-receiver movement scenarios to inform an assessment using a cumulative SEL threshold criterion.

A number of source/receptor movement scenarios were modelled and these are summarised in Table 9.4. The scenarios are underpinned by a number of key assumptions:

1. The starting point of the receptor is assumed to be between the Bubbles and the Geotigers source vessels;

2. The starting location for the receptor and Bubbles is fixed and always 500 m based on a mitigation buffer zone;

3. The receptor is always moving away from the vessels at 90°; this is a simplification for modelling purposes;

4. The Geotiger and Bubbles source vessels are moving away from each other;.

Combined Scenario	Survey vessels and separations	Vessel/receptor movement
MS 1	Single source vessel	Vessel @270°, receptor @180°
MS 2	Increasing Geotiger separation with Geotiger 2 offset	Alternate vessels @270°/90°, receptor @180°

Table 9.4: Modelling scenarios involving multiple sound sources

The results showed that the maximum SELs received by a receptor for a single VSGA source array is used are below the threshold levels for all potential impacts considered either potential mortal injury; recoverable injury or TTS in fish; or PTS, TTS or significant behavioural disturbance in pinnipeds.

A further scenario consisting of a receptor moving through an acoustic field generated by multiple source arrays was modelled. For this scenario, the Bubbles source vessel transits at a speed of 2.3 m/s on a bearing of 270° while both the Geotiger source vessels transit at the same speed in the opposite direction on a bearing of 90°. The Bubbles and each Geotiger source are separated by an initial cross line distance (on the modelling Y-axis) of 500 m while the two Geotiger sources are separated by an initial 1000 m. In addition, one of the Geotiger array sources is offset in the x-direction by 2000 m. The Geotiger separation in the Y-direction is systematically incremented and the overall SEL and SPL is noted at each stage. It is noted that as the receptor starts at a fixed location relative to the Bubbles source vessel and transits through the acoustic field, the distance between the receptor and the Bubbles and each of the Geotiger sources changes and hence the main contributing sound source to the acoustic field also changes. At the commencement of the scenario, the dominant source is Bubbles. After a period varying between 150 seconds and 700 seconds (2.5 - ~11 minutes) the southernmost Geotiger becomes the dominant source.

The results indicate that for the given scenario involving fish as the receptor, the maximum overall SPLs are below threshold levels related to potential mortal injury (in the range 207-213 dB re 1 μPa depending on fish hearing sensitivity), and recoverable injury (in the range 203-207 dB re 1 μPa). When SEL is used as the metric, maximum SELs are above threshold levels related to potential, TTS (186 dB re 1 μPa^2.sec) only for the closest Geotiger separations when operating in PA2 during the month of August and in PA4 during the month of September. By October, SELs are above the TTS threshold for all Geotiger separations considered.

When pinnipeds are considered, overall SPLs are lower than the threshold levels for potential PTS and TTS (218 dB re 1 μPa peak and 212 dB re 1 μPa peak respectively). Similarly, RMS SPLs are lower than the threshold levels corresponding to potential avoidance behaviour (190 dB re 1 μPa rms). RMS SPLs that may result in limited behavioural disturbance reactions (in the range 150-180 dB re 1 μPa rms) occur for the smallest Geotiger cross-line separations during the months of June and July in PA2. RMS SPLs are above threshold levels related to limited behavioural disturbance at increasingly greater cross-line separations between Geotiger vessels. By October in PA4, RMS SPLs are above threshold levels for all separations considered.

Maximum cumulative SEL is below the threshold level for potential PTS (186 dB re 1 μPa^2.sec) for all months except during October in PA4. While maximum cumulative SEL is above the TTS threshold level (171 dB re 1 μPa^2.sec) in all months - initially only for the smallest Geotiger separations during June and July in PA2 but increasing to all separations during August in PA2 and during both September and October in PA4.

In general, for the longer range impacts it is noted that there is some seasonal variation with the longer ranges occurring during the month of August in Priority Area 2 and notably during October in Priority Area 4.

Annex A

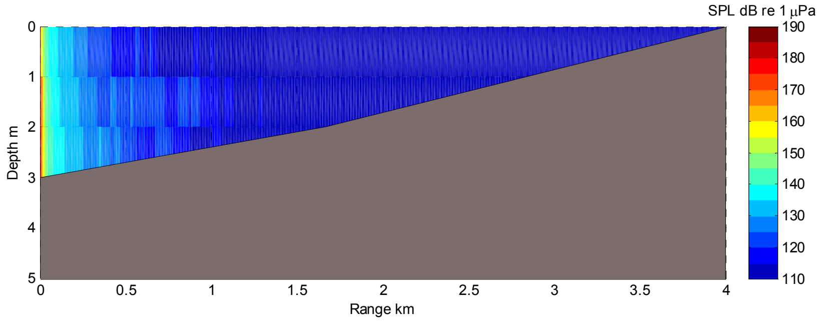

Figure A.1: Contour plot of SPL as a function of range and depth along the 0° transect in shallow water during the month of August

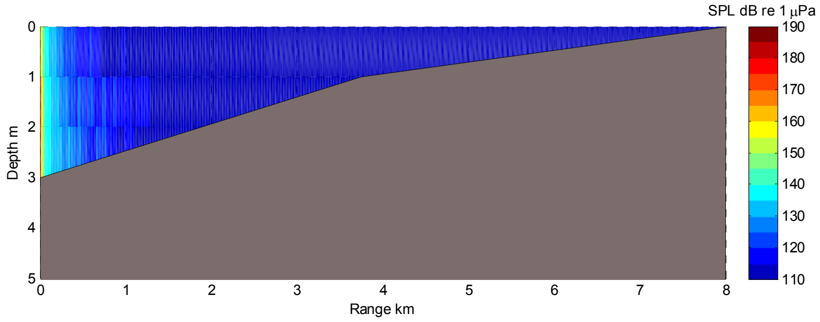

Figure A.2: Contour plot of SPL as a function of range and depth along the 90° transect in shallow water during the month of August

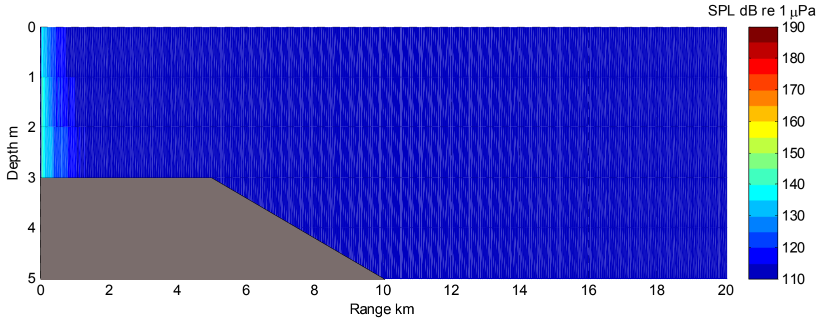

Figure A.3: Contour plot of SPL as a function of range and depth along the 180° transect in shallow water during the month of August

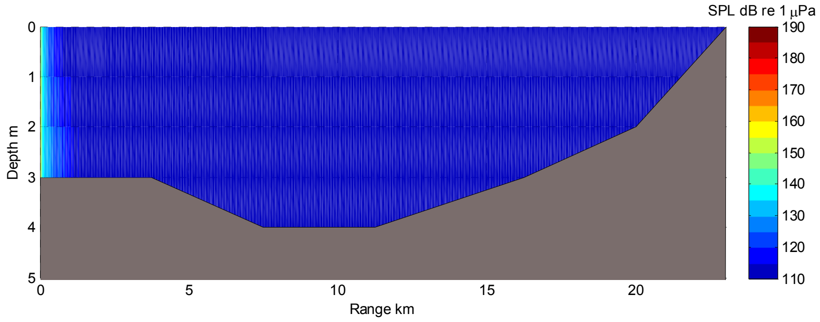

Figure A.4: Contour plot of SPL as a function of range and depth along the 270° transect in shallow water during the month of August

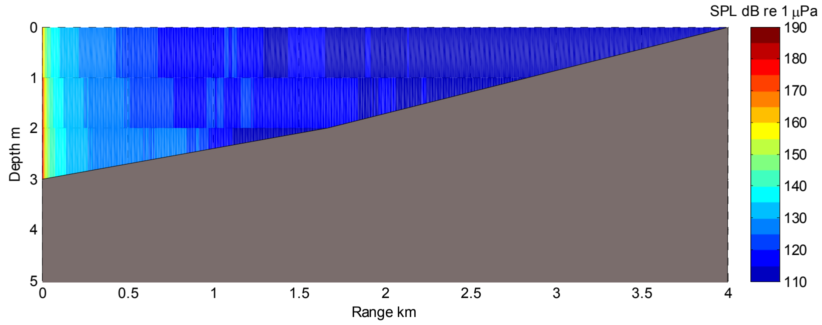

Figure A.5: Contour plot of SPL as a function of range and depth along the 0° transect in shallow water during the month of October

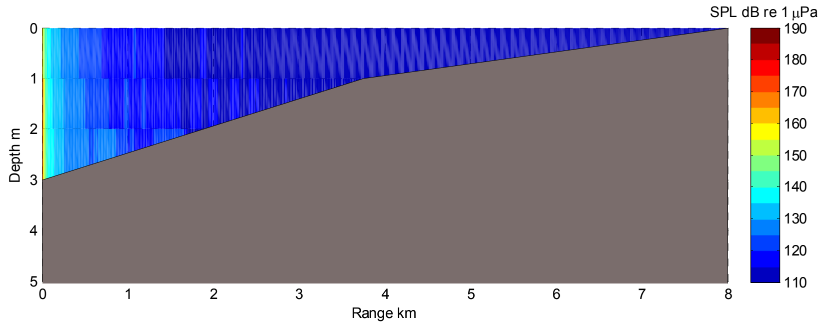

Figure A.6: Contour plot of SPL as a function of range and depth along the 90° transect in shallow water during the month of October

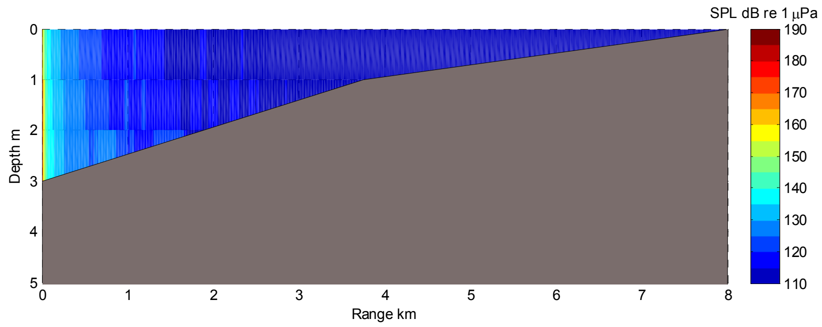

Figure A.7: Contour plot of SPL as a function of range and depth along the 180° transect in shallow water during the month of October

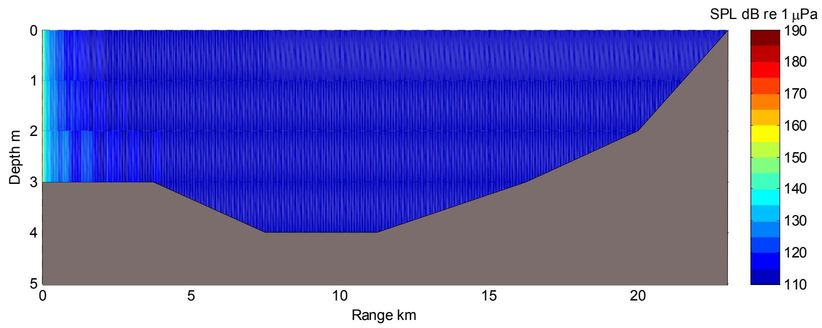

Figure A.8: Contour plot of SPL as a function of range and depth along the 270° transect in shallow water during the month of October

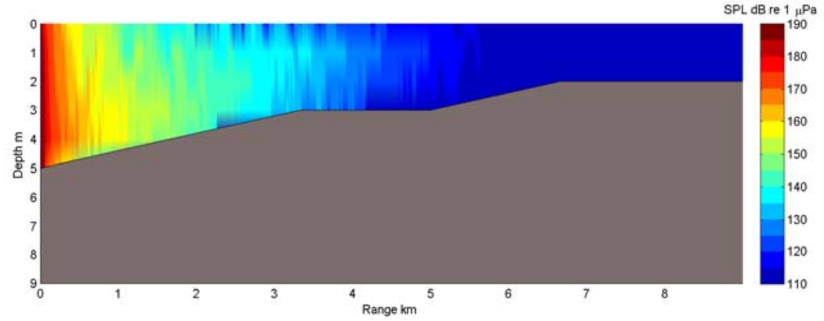

Figure A.9: Contour plot of SPL as a function of range and depth along the 0° transect in medium depth water during the month of August

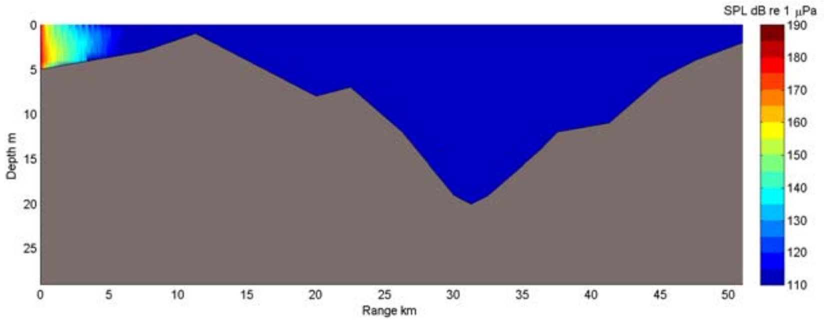

Figure A.10: Contour plot of SPL as a function of range and depth along the 90° transect in medium depth water during the month of August

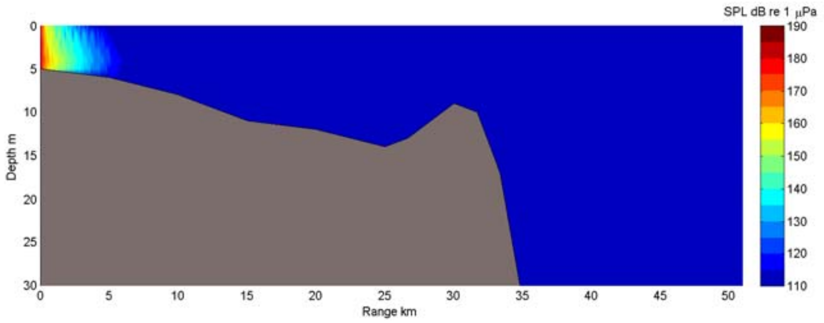

Figure A.11: Contour plot of SPL as a function of range and depth along the 180° transect in medium depth water during the month of August

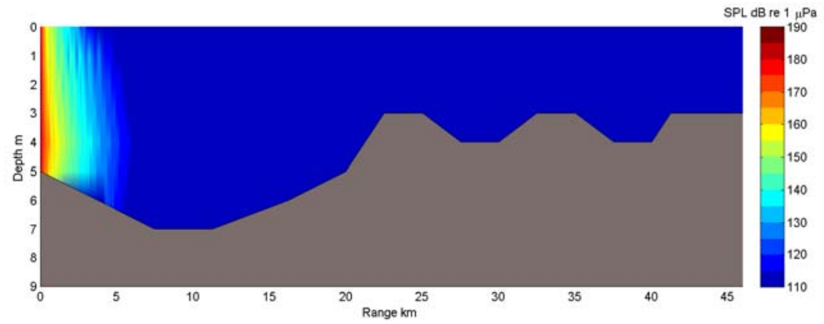

Figure A.12: Contour plot of SPL as a function of range and depth along the 270° transect in medium depth water during the month of August

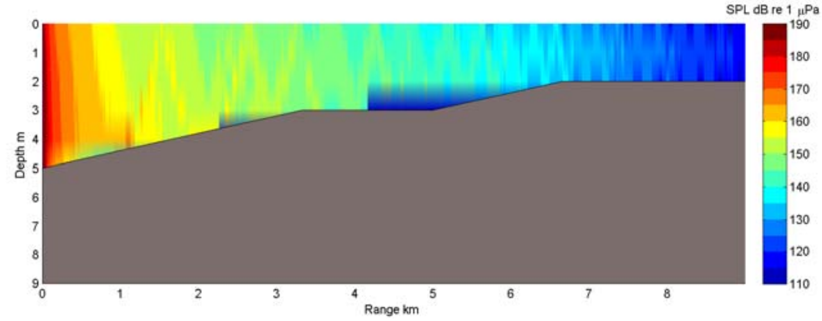

Figure A.13: Contour plot of SPL as a function of range and depth along the 0° transect in medium depth water during the month of October

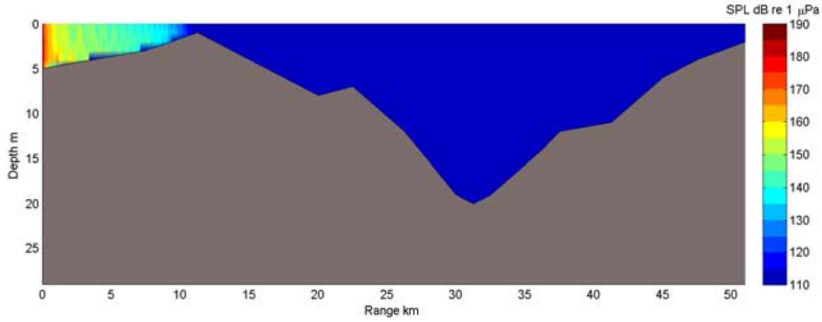

Figure A.14: Contour plot of SPL as a function of range and depth along the 90° transect in medium depth water during the month of October

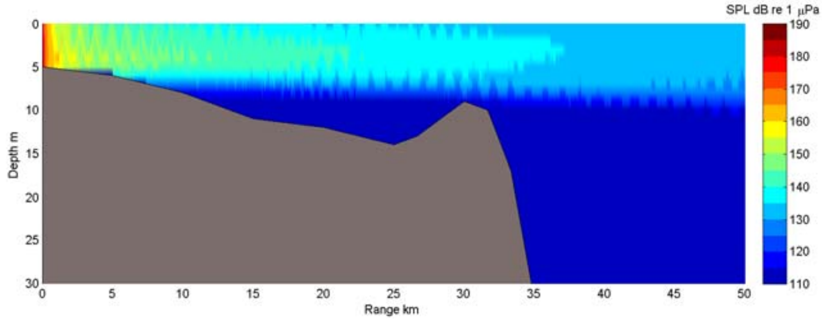

Figure A.15: Contour plot of SPL as a function of range and depth along the 180° transect in medium depth water during the month of October

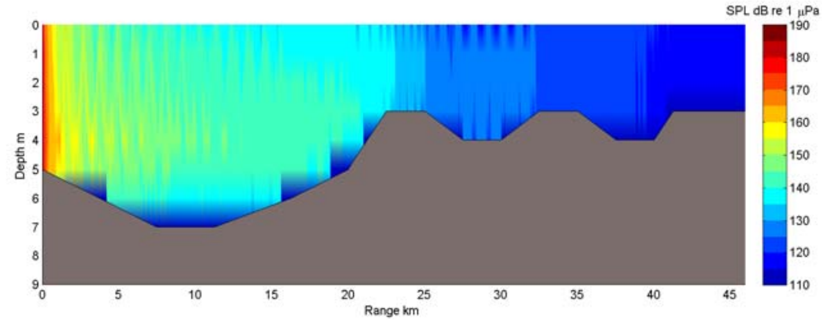

Figure A.16: Contour plot of SPL as a function of range and depth along the 270° transect in medium depth water during the month of October

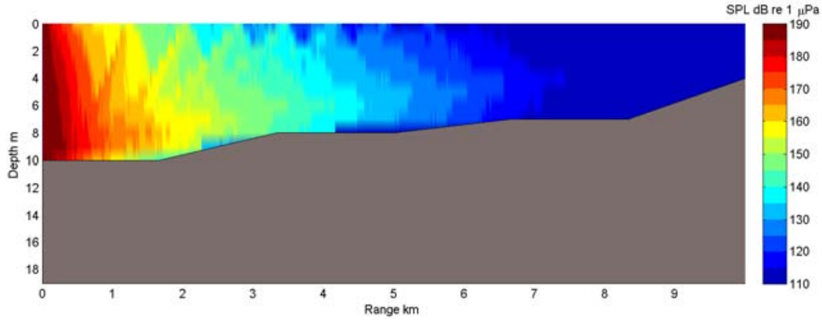

Figure A.17: Contour plot of SPL as a function of range and depth along the 0° transect in deep water during the month of August

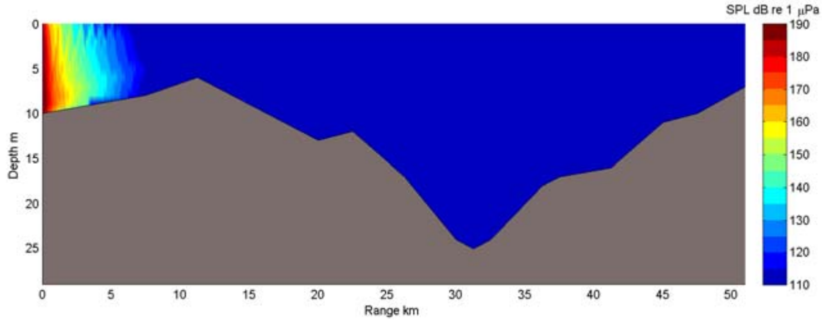

Figure A.18: Contour plot of SPL as a function of range and depth along the 90° transect in deep water during the month of August

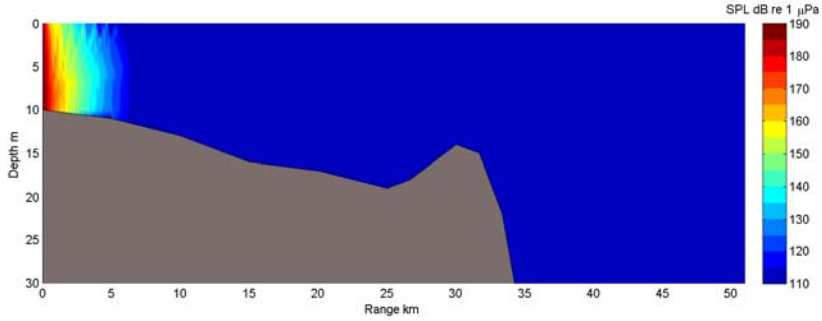

Figure A.19: Contour plot of SPL as a function of range and depth along the 180° transect in deep water during the month of August

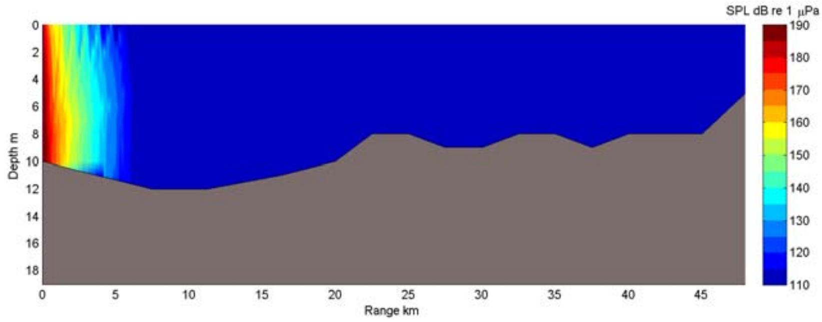

Figure A.20: Contour plot of SPL as a function of range and depth along the 270° transect in deep water during the month of August

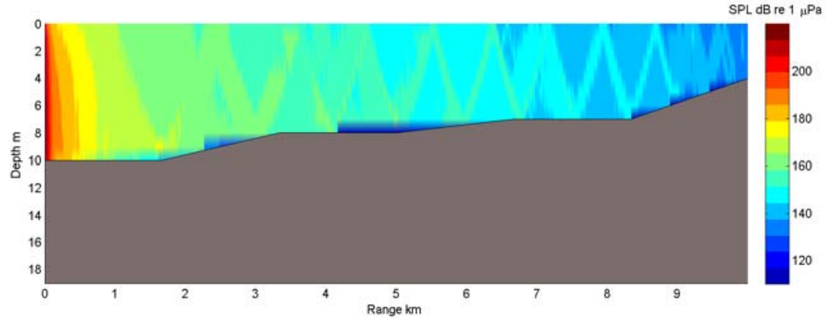

Figure A.21: Contour plot of SPL as a function of range and depth along the 0° transect in deep water during the month of October

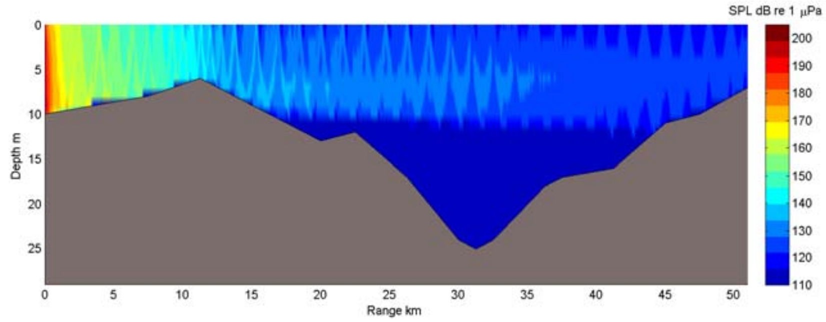

Figure A.22: Contour plot of SPL as a function of range and depth along the 90° transect in deep water during the month of October

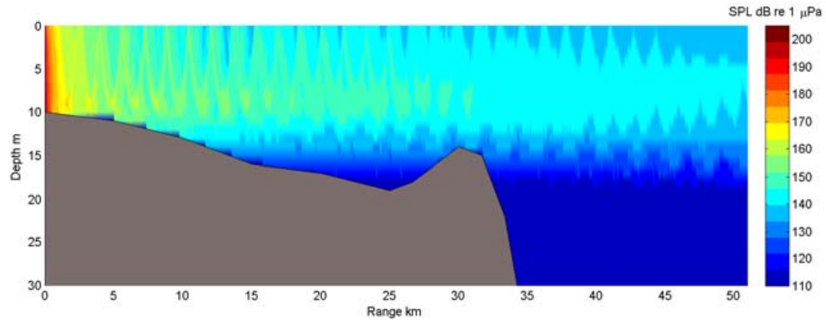

Figure A.23: Contour plot of SPL as a function of range and depth along the 180° transect in deep water during the month of October

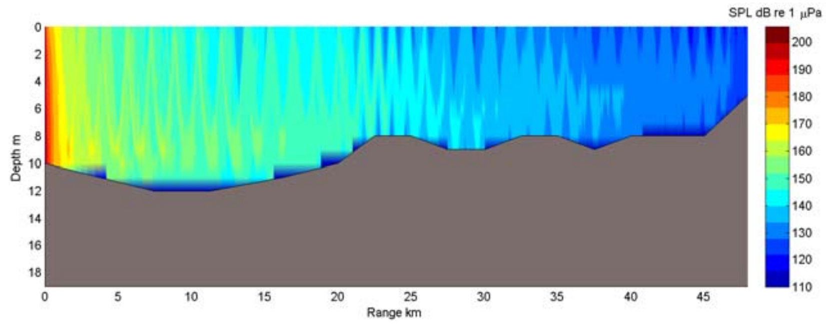

Figure A.24: Contour plot of SPL as a function of range and depth along the 270° transect in deep water during the month of October

Annex B

Impact	Threshold dB re 1 μPa	Transect bearing (degrees)												Max range m
		0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°	
Potential mortal injury in fish with low hearing sensitivity exposed to impulse noise Recoverable injury in fish with low hearing sensitivity exposed to impulse noise	213 dB peak	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m
Potential mortal injury in fish with medium hearing sensitivity exposed to impulse noise Potential mortal injury in fish with high hearing sensitivity exposed to impulse noise Potential mortal injury in fish eggs and larvae exposed to impulse noise Recoverable injury in fish with medium hearing sensitivity exposed to impulse noise	207 dB peak	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m
Recoverable injury in fish with high or medium hearing sensitivity exposed to seismic sound	203 dB peak	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m

Table B.1: Ranges in metres at which SPL has fallen to threshold level along individual transects for fish exposed to VSGA sound during the month of June (* - maximum range derived from near-field source level model)

Impact	**Threshold dB re 1 μPa**	**Transect bearing (degrees)**												**Max range m**
		0°	**30°**	**60°**	**90°**	**120°**	**150°**	**180°**	**210°**	**240°**	**270°**	**300°**	**330°**	
Potential mortal injury in fish with low hearing sensitivity exposed to impulse noise Recoverable injury in fish with low hearing sensitivity exposed to impulse noise	213 dB peak	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m
Potential mortal injury in fish with medium hearing sensitivity exposed to impulse noise Potential mortal injury in fish with high hearing sensitivity exposed to impulse noise Potential mortal injury in fish eggs and larvae exposed to impulse noise Recoverable injury in fish with medium hearing sensitivity exposed to impulse noise	207 dB peak	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m
Recoverable injury in fish with high or medium hearing sensitivity exposed to seismic sound	203 dB peak	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m

Table B.2: Ranges in metres at which SPL has fallen to threshold level along individual transects for fish exposed to VSGA sound during the month of July (* - maximum range derived from near-field source level model)

Impact	**Threshold dB re 1 μPa**	**Transect bearing (degrees)**												**Max range m**
		0°	**30°**	**60°**	**90°**	**120°**	**150°**	**180°**	**210°**	**240°**	**270°**	**300°**	**330°**	
Potential mortal injury in fish with low hearing sensitivity exposed to impulse noise Recoverable injury in fish with low hearing sensitivity exposed to impulse noise	213 dB peak	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m
Potential mortal injury in fish with medium hearing sensitivity exposed to impulse noise Potential mortal injury in fish with high hearing sensitivity exposed to impulse noise Potential mortal injury in fish eggs and larvae exposed to impulse noise Recoverable injury in fish with medium hearing sensitivity exposed to impulse noise	207 dB peak	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m
Recoverable injury in fish with high or medium hearing sensitivity exposed to seismic sound	203 dB peak	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m

Table B.3: Ranges in metres at which SPL has fallen to threshold level along individual transects for fish exposed to VSGA sound during the month of August (* - maximum range derived from near-field source level model)

Impact	**Threshold dB re 1 μPa**	**Transect bearing (degrees)**												**Max range m**
		0°	**30°**	**60°**	**90°**	**120°**	**150°**	**180°**	**210°**	**240°**	**270°**	**300°**	**330°**	
Potential mortal injury in fish with low hearing sensitivity exposed to impulse noise Recoverable injury in fish with low hearing sensitivity exposed to impulse noise	213 dB peak	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m
Potential mortal injury in fish with medium hearing sensitivity exposed to impulse noise Potential mortal injury in fish with high hearing sensitivity exposed to impulse noise Potential mortal injury in fish eggs and larvae exposed to impulse noise Recoverable injury in fish with medium hearing sensitivity exposed to impulse noise	207 dB peak	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m
Recoverable injury in fish with high or medium hearing sensitivity exposed to seismic sound	203 dB peak	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m

Table B.4: Ranges in metres at which SPL has fallen to threshold level along individual transects for fish exposed to VSGA sound during the month of August (* - maximum range derived from near-field source level model)

Impact	Threshold dB re 1 μPa	Transect bearing (degrees)												Max range m
		0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°	
Potential mortal injury in fish with low hearing sensitivity exposed to impulse noise Recoverable injury in fish with low hearing sensitivity exposed to impulse noise	213 dB peak	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m
Potential mortal injury in fish with medium hearing sensitivity exposed to impulse noise Potential mortal injury in fish with high hearing sensitivity exposed to impulse noise Potential mortal injury in fish eggs and larvae exposed to impulse noise Recoverable injury in fish with medium hearing sensitivity exposed to impulse noise	207 dB peak	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m
Recoverable injury in fish with high or medium hearing sensitivity exposed to seismic sound	203 dB peak	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m

Table B.5: Ranges in metres at which SPL has fallen to threshold level along individual transects for fish exposed to VSGA sound during the month of September (* - maximum range derived from near-field source level model)

Impact	Threshold dB re 1 μPa	Transect bearing (degrees)												Max range m
		0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°	
Potential mortal injury in fish with low hearing sensitivity exposed to impulse noise Recoverable injury in fish with low hearing sensitivity exposed to impulse noise	213 dB peak	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m
Potential mortal injury in fish with medium hearing sensitivity exposed to impulse noise Potential mortal injury in fish with high hearing sensitivity exposed to impulse noise Potential mortal injury in fish eggs and larvae exposed to impulse noise Recoverable injury in fish with medium hearing sensitivity exposed to impulse noise	207 dB peak	9	10	0	0	0	0	0	0	0	0	0	0	9*
Recoverable injury in fish with high or medium hearing sensitivity exposed to seismic sound	203 dB peak	9	10	0	0	0	0	0	0	0	0	0	12	9*

Table B.6: Ranges in metres at which SPL has fallen to threshold level along individual transects for fish exposed to Bubbles sound during the month of June (* - maximum range derived from near-field source level model)

Impact	Threshold dB re 1 μPa	Transect bearing (degrees)												Max range m
		0°	**30°**	**60°**	**90°**	**120°**	**150°**	**180°**	**210°**	**240°**	**270°**	**300°**	**330°**	
Potential mortal injury in fish with low hearing sensitivity exposed to impulse noise Recoverable injury in fish with low hearing sensitivity exposed to impulse noise	213 dB peak	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m
Potential mortal injury in fish with medium hearing sensitivity exposed to impulse noise Potential mortal injury in fish with high hearing sensitivity exposed to impulse noise Potential mortal injury in fish eggs and larvae exposed to impulse noise Recoverable injury in fish with medium hearing sensitivity exposed to impulse noise	207 dB peak	9	10	0	0	0	0	0	0	0	0	0	0	9*
Recoverable injury in fish with high or medium hearing sensitivity exposed to seismic sound	203 dB peak	9	10	0	0	0	0	0	0	0	0	0	12	9*

Table B.7: Ranges in metres at which SPL has fallen to threshold level along individual transects for fish exposed to Bubbles sound during the month of July (* - maximum range derived from near-field source level model)

Impact	Threshold dB re 1 μPa	Transect bearing (degrees)												Max range m
		0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°	
Potential mortal injury in fish with low hearing sensitivity exposed to impulse noise Recoverable injury in fish with low hearing sensitivity exposed to impulse noise	213 dB peak	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m
Potential mortal injury in fish with medium hearing sensitivity exposed to impulse noise Potential mortal injury in fish with high hearing sensitivity exposed to impulse noise Potential mortal injury in fish eggs and larvae exposed to impulse noise Recoverable injury in fish with medium hearing sensitivity exposed to impulse noise	207 dB peak	9	10	0	0	0	0	0	0	0	0	0	0	9*
Recoverable injury in fish with high or medium hearing sensitivity exposed to seismic sound	203 dB peak	9	10	0	0	0	0	0	0	0	0	0	12	9*

Table B.8: Ranges in metres at which SPL has fallen to threshold level along individual transects for fish exposed to Bubbles sound during the month of August (* - maximum range derived from near-field source level model)

Impact	Threshold dB re 1 μPa	Transect bearing (degrees)												Max range m
		0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°	
Potential mortal injury in fish with low hearing sensitivity exposed to impulse noise Recoverable injury in fish with low hearing sensitivity exposed to impulse noise	213 dB peak	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m
Potential mortal injury in fish with medium hearing sensitivity exposed to impulse noise Potential mortal injury in fish with high hearing sensitivity exposed to impulse noise Potential mortal injury in fish eggs and larvae exposed to impulse noise Recoverable injury in fish with medium hearing sensitivity exposed to impulse noise	207 dB peak	9	10	0	0	0	0	0	0	0	0	0	0	9*
Recoverable injury in fish with high or medium hearing sensitivity exposed to seismic sound	203 dB peak	9	10	0	0	0	0	0	0	0	0	0	12	9*

Table B.9: Ranges in metres at which SPL has fallen to threshold level along individual transects for fish exposed to Bubbles sound during the month of September (* - maximum range derived from near-field source level model)

Impact	**Threshold dB re 1 μPa**	**Transect bearing (degrees)**												**Max range m**
		0°	**30°**	**60°**	**90°**	**120°**	**150°**	**180°**	**210°**	**240°**	**270°**	**300°**	**330°**	
Potential mortal injury in fish with low hearing sensitivity exposed to impulse noise Recoverable injury in fish with low hearing sensitivity exposed to impulse noise	213 dB peak	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m
Potential mortal injury in fish with medium hearing sensitivity exposed to impulse noise Potential mortal injury in fish with high hearing sensitivity exposed to impulse noise Potential mortal injury in fish eggs and larvae exposed to impulse noise Recoverable injury in fish with medium hearing sensitivity exposed to impulse noise	207 dB peak	9	10	0	0	0	0	0	0	0	0	0	0	9*
Recoverable injury in fish with high or medium hearing sensitivity exposed to seismic sound	203 dB peak	9	10	0	0	0	0	0	0	0	0	0	12	9*

Table B.10: Ranges in metres at which SPL has fallen to threshold level along individual transects for fish exposed to Bubbles sound during the month of October (* - maximum range derived from near-field source level model)

Impact	Threshold dB re 1 μPa	Transect bearing (degrees)												Max range m
		0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°	
Potential mortal injury in fish with low hearing sensitivity exposed to impulse noise Recoverable injury in fish with low hearing sensitivity exposed to impulse noise	213 dB peak	20	20	0	0	0	0	0	0	0	0	20	14	27 m*
Potential mortal injury in fish with medium hearing sensitivity exposed to impulse noise Potential mortal injury in fish with high hearing sensitivity exposed to impulse noise Potential mortal injury in fish eggs and larvae exposed to impulse noise Recoverable injury in fish with medium hearing sensitivity exposed to impulse noise	207 dB peak	40	40	0	0	0	0	0	0	0	0	40	42	42 m
Recoverable injury in fish with high or medium hearing sensitivity exposed to seismic sound	203 dB peak	60	60	50	51	51	51	51	51	51	48	60	56	60 m

Table B.11: Ranges in metres at which SPL has fallen to threshold level along individual transects for fish exposed to Geotiger sound during the month of June (* - maximum range derived from near-field source level model)

Impact	Threshold dB re 1 μPa	Transect bearing (degrees)												Max range m
		0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°	
Potential mortal injury in fish with low hearing sensitivity exposed to impulse noise Recoverable injury in fish with low hearing sensitivity exposed to impulse noise	213 dB peak	20	20	0	0	0	0	0	0	0	0	20	14	27
Potential mortal injury in fish with medium hearing sensitivity exposed to impulse noise Potential mortal injury in fish with high hearing sensitivity exposed to impulse noise Potential mortal injury in fish eggs and larvae exposed to impulse noise Recoverable injury in fish with medium hearing sensitivity exposed to impulse noise	207 dB peak	40	40	0	0	0	0	0	0	0	0	40	42	42
Recoverable injury in fish with high or medium hearing sensitivity exposed to seismic sound	203 dB peak	60	60	50	51	51	51	51	51	51	48	60	56	60

Table B.12: Ranges in metres at which SPL has fallen to threshold level along individual transects for fish exposed to Geotiger sound during the month of July (* - maximum range derived from near-field source level model)

Impact	**Threshold dB re 1 μPa**	**Transect bearing (degrees)**												**Max range m**
		0°	**30°**	**60°**	**90°**	**120°**	**150°**	**180°**	**210°**	**240°**	**270°**	**300°**	**330°**	
Potential mortal injury in fish with low hearing sensitivity exposed to impulse noise Recoverable injury in fish with low hearing sensitivity exposed to impulse noise	213 dB peak	20	20	0	0	0	0	0	0	0	0	20	14	27 m*
Potential mortal injury in fish with medium hearing sensitivity exposed to impulse noise Potential mortal injury in fish with high hearing sensitivity exposed to impulse noise Potential mortal injury in fish eggs and larvae exposed to impulse noise Recoverable injury in fish with medium hearing sensitivity exposed to impulse noise	207 dB peak	40	40	0	0	0	0	0	0	0	0	40	42	42
Recoverable injury in fish with high or medium hearing sensitivity exposed to seismic sound	203 dB peak	60	60	50	51	51	51	51	51	51	48	60	56	60

Table B.13: Ranges in metres at which SPL has fallen to threshold level along individual transects for fish exposed to Geotiger sound during the month of August (* - maximum range derived from near-field source level model)

Impact	**Threshold dB re 1 μPa**	**Transect bearing (degrees)**												**Max range m**
		0°	**30°**	**60°**	**90°**	**120°**	**150°**	**180°**	**210°**	**240°**	**270°**	**300°**	**330°**	
Potential mortal injury in fish with low hearing sensitivity exposed to impulse noise Recoverable injury in fish with low hearing sensitivity exposed to impulse noise	213 dB peak	20	20	0	0	0	0	0	0	0	0	20	14	27*
Potential mortal injury in fish with medium hearing sensitivity exposed to impulse noise Potential mortal injury in fish with high hearing sensitivity exposed to impulse noise Potential mortal injury in fish eggs and larvae exposed to impulse noise Recoverable injury in fish with medium hearing sensitivity exposed to impulse noise	207 dB peak	40	40	0	0	0	0	0	0	0	0	40	28	40
Recoverable injury in fish with high or medium hearing sensitivity exposed to seismic sound	203 dB peak	60	60	50	51	51	51	51	51	51	48	60	56	60

Table B.14: Ranges in metres at which SPL has fallen to threshold level along individual transects for fish exposed to Geotiger sound during the month of September (* - maximum range derived from near-field source level model)

Impact	**Threshold dB re 1 μPa**	**Transect bearing (degrees)**												**Max range m**
		0°	**30°**	**60°**	**90°**	**120°**	**150°**	**180°**	**210°**	**240°**	**270°**	**300°**	**330°**	
Potential mortal injury in fish with low hearing sensitivity exposed to impulse noise Recoverable injury in fish with low hearing sensitivity exposed to impulse noise	213 dB peak	20	20	0	0	0	0	0	0	0	0	20	14	27*
Potential mortal injury in fish with medium hearing sensitivity exposed to impulse noise Potential mortal injury in fish with high hearing sensitivity exposed to impulse noise Potential mortal injury in fish eggs and larvae exposed to impulse noise Recoverable injury in fish with medium hearing sensitivity exposed to impulse noise	207 dB peak	40	40	0	0	0	0	0	0	0	0	40	28	40
Recoverable injury in fish with high or medium hearing sensitivity exposed to seismic sound	203 dB peak	60	60	50	51	51	51	51	51	51	48	60	56	60

Table B.15: Ranges in metres at which SPL has fallen to threshold level along individual transects for fish exposed to Geotiger sound during the month of October (* - maximum range derived from near-field source level model)

Impact	Threshold dB re 1 μPa	Transect bearing (degrees)												Max range m
		0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°	
Auditory injury (PTS) onset in pinnipeds	218 dB peak	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m
Temporary deafness (TTS) onset in pinnipeds and Significant behavioural disturbance	212 dB peak	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m
Avoidance behaviour in pinnipeds exposed to impulsive sounds	190 dB (RMS)[1]	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m
Avoidance behaviour in pinnipeds exposed to impulsive sounds	190 dB (RMS)[2]	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m
Limited disturbance in pinnipeds exposed to impulsive sounds	180 dB (RMS)[1]	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m
Limited disturbance in pinnipeds exposed to impulsive sounds	180 dB (RMS)[2]	1	1	1	1	1	1	1	1	1	1	1	1	1
Limited disturbance in pinnipeds exposed to impulsive sounds	150 dB (RMS)[1]	12	12	10	8	14	0	0	0	0	0	13	12	12
Limited disturbance in pinnipeds exposed to impulsive sounds	150 dB (RMS)[2]	20	20	20	16	14	0	0	0	0	0	13	12	20

Table B.16: Ranges in metres at which SPL has fallen to threshold level along individual transects for pinnipeds exposed to VGSA sound during the month of June (* - maximum range derived from near-field source level model;
[1] – based on Peak level – 15 dB; [2] - based on Peak level – 10 dB)

Impact	Threshold dB re 1 μPa	Transect bearing (degrees)												Max range m
		0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°	
Auditory injury (PTS) onset in pinnipeds	218 dB peak	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m
Temporary deafness (TTS) onset in pinnipeds and Significant behavioural disturbance	212 dB peak	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m
Avoidance behaviour in pinnipeds exposed to impulsive sounds	190 dB (RMS)[1]	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m
Avoidance behaviour in pinnipeds exposed to impulsive sounds	190 dB (RMS)[2]	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m
Limited disturbance in pinnipeds exposed to impulsive sounds	180 dB (RMS)[1]	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m
Limited disturbance in pinnipeds exposed to impulsive sounds	180 dB (RMS)[2]	1	1	1	1	1	1	1	1	1	1	1	1	1
Limited disturbance in pinnipeds exposed to impulsive sounds	150 dB (RMS)[1]	12	12	10	8	14	0	0	0	0	0	13	12	12
Limited disturbance in pinnipeds exposed to impulsive sounds	150 dB (RMS)[2]	20	20	20	16	14	0	0	0	0	0	13	12	20

Table B.17: Ranges in metres at which SPL has fallen to threshold level along individual transects for pinnipeds exposed to VGSA sound during the month of July (* - maximum range derived from near-field source level model;
[1] – based on Peak level – 15 dB; [2] - based on Peak level – 10 dB)

Impact	Threshold dB re 1 µPa	Transect bearing (degrees)												Max range m
		0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°	
Auditory injury (PTS) onset in pinnipeds	218 dB peak	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m
Temporary deafness (TTS) onset in pinnipeds and Significant behavioural disturbance	212 dB peak	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m
Avoidance behaviour in pinnipeds exposed to impulsive sounds	190 dB (RMS)[1]	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m
Avoidance behaviour in pinnipeds exposed to impulsive sounds	190 dB (RMS)[2]	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m
Limited disturbance in pinnipeds exposed to impulsive sounds	180 dB (RMS)[1]	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m
Limited disturbance in pinnipeds exposed to impulsive sounds	180 dB (RMS)[2]	1	1	1	1	1	1	1	1	1	1	1	1	1
Limited disturbance in pinnipeds exposed to impulsive sounds	150 dB (RMS)[1]	12	12	10	8	14	0	0	0	0	0	13	12	12
Limited disturbance in pinnipeds exposed to impulsive sounds	150 dB (RMS)[2]	20	20	20	16	14	0	0	0	0	0	13	12	20

Table B.18: Ranges in metres at which SPL has fallen to threshold level along individual transects for pinnipeds exposed to VGSA sound during the month of August (* - maximum range derived from near-field source level model;
[1] – based on Peak level – 15 dB; [2] - based on Peak level – 10 dB)

Impact	Threshold dB re 1 μPa	Transect bearing (degrees)												Max range m
		0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°	
Auditory injury (PTS) onset in pinnipeds	218 dB peak	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m
Temporary deafness (TTS) onset in pinnipeds and Significant behavioural disturbance	212 dB peak	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m
Avoidance behaviour in pinnipeds exposed to impulsive sounds	190 dB (RMS)[1]	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m
Avoidance behaviour in pinnipeds exposed to impulsive sounds	190 dB (RMS)[2]	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m
Limited disturbance in pinnipeds exposed to impulsive sounds	180 dB (RMS)[1]	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m
Limited disturbance in pinnipeds exposed to impulsive sounds	180 dB (RMS)[2]	1	1	1	1	1	1	1	1	1	1	1	1	1
Limited disturbance in pinnipeds exposed to impulsive sounds	150 dB (RMS)[1]	12	12	10	8	14	0	0	0	0	0	13	12	12
Limited disturbance in pinnipeds exposed to impulsive sounds	150 dB (RMS)[2]	20	20	20	16	14	0	0	0	0	0	13	12	20

Table B.19: Ranges in metres at which SPL has fallen to threshold level along individual transects for pinnipeds exposed to VGSA sound during the month of September (* - maximum range derived from near-field source level model; [1] – based on Peak level – 15 dB; [2] - based on Peak level – 10 dB)

Impact	Threshold dB re 1 μPa	Transect bearing (degrees)												Max range m
		0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°	
Auditory injury (PTS) onset in pinnipeds	218 dB peak	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m
Temporary deafness (TTS) onset in pinnipeds and Significant behavioural disturbance	212 dB peak	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m
Avoidance behaviour in pinnipeds exposed to impulsive sounds	190 dB (RMS)[1]	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m
Avoidance behaviour in pinnipeds exposed to impulsive sounds	190 dB (RMS)[2]	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m
Limited disturbance in pinnipeds exposed to impulsive sounds	180 dB (RMS)[1]	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m	<1 m
Limited disturbance in pinnipeds exposed to impulsive sounds	180 dB (RMS)[2]	1	1	1	1	1	1	1	1	1	1	1	1	1
Limited disturbance in pinnipeds exposed to impulsive sounds	150 dB (RMS)[1]	12	12	10	8	14	0	0	0	0	0	13	12	12
Limited disturbance in pinnipeds exposed to impulsive sounds	150 dB (RMS)[2]	20	20	20	16	14	0	0	0	0	0	13	12	20

Table B.20: Ranges in metres at which SPL has fallen to threshold level along individual transects for pinnipeds exposed to VGSA sound during the month of October (* - maximum range derived from near-field source level model;
[1] – based on Peak level – 15 dB; [2] - based on Peak level – 10 dB)

Impact	Threshold dB re 1 μPa	Transect bearing (degrees)												Max range m
		0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°	
Auditory injury (PTS) onset in pinnipeds	218 dB peak	0	0	0	0	0	0	0	0	0	0	0	0	1*
Temporary deafness (TTS) onset in pinnipeds and Significant behavioural disturbance	212 dB peak	0	0	0	0	0	0	0	0	0	0	0	0	6*
Avoidance behaviour in pinnipeds exposed to impulsive sounds	190 dB (RMS)[1]	9	10	0	0	0	0	0	0	0	0	0	12	12
Avoidance behaviour in pinnipeds exposed to impulsive sounds	190 dB (RMS)[2]	18	20	0	0	0	0	0	0	0	0	19	12	20
Limited disturbance in pinnipeds exposed to impulsive sounds	180 dB (RMS)[1]	27	30	0	0	0	0	0	0	0	0	19	24	30
Limited disturbance in pinnipeds exposed to impulsive sounds	180 dB (RMS)[2]	36	40	50	51	51	51	51	51	51	46	38	36	51
Limited disturbance in pinnipeds exposed to impulsive sounds	150 dB (RMS)[1]	333	330	300	306	306	306	306	306	306	322	304	336	336
Limited disturbance in pinnipeds exposed to impulsive sounds	150 dB (RMS)[2]	423	460	400	408	408	408	408	408	408	414	437	420	460

Table B.21: Ranges in metres at which SPL has fallen to threshold level along individual transects for pinnipeds exposed to Bubbles sound during the month of June (* - maximum range derived from near-field source level model;
[1] – based on Peak level – 15 dB; [2] - based on Peak level – 10 dB)

Impact	Threshold dB re 1 μPa	Transect bearing (degrees)												Max range m
		0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°	
Auditory injury (PTS) onset in pinnipeds	218 dB peak	0	0	0	0	0	0	0	0	0	0	0	0	1*
Temporary deafness (TTS) onset in pinnipeds and Significant behavioural disturbance	212 dB peak	0	0	0	0	0	0	0	0	0	0	0	0	6*
Avoidance behaviour in pinnipeds exposed to impulsive sounds	190 dB (RMS)[1]	9	10	0	0	0	0	0	0	0	0	0	12	12*
Avoidance behaviour in pinnipeds exposed to impulsive sounds	190 dB (RMS)[2]	18	20	0	0	0	0	0	0	0	0	19	12	20
Limited disturbance in pinnipeds exposed to impulsive sounds	180 dB (RMS)[1]	27	30	0	0	0	0	0	0	0	0	19	24	30
Limited disturbance in pinnipeds exposed to impulsive sounds	180 dB (RMS)[2]	36	40	50	51	51	51	51	51	51	46	38	36	51
Limited disturbance in pinnipeds exposed to impulsive sounds	150 dB (RMS)[1]	387	360	350	408	306	306	306	357	357	322	342	408	408
Limited disturbance in pinnipeds exposed to impulsive sounds	150 dB (RMS)[2]	522	520	500	510	510	510	510	510	510	506	513	516	522

Table B.22: Ranges in metres at which SPL has fallen to threshold level along individual transects for pinnipeds exposed to Bubbles sound during the month of July (* - maximum range derived from near-field source level model;
[1] – based on Peak level – 15 dB; [2] - based on Peak level – 10 dB)

Impact	**Threshold dB re 1 μPa**	**Transect bearing (degrees)**												**Max range m**
		0°	**30°**	**60°**	**90°**	**120°**	**150°**	**180°**	**210°**	**240°**	**270°**	**300°**	**330°**	
Auditory injury (PTS) onset in pinnipeds	218 dB peak	0	0	0	0	0	0	0	0	0	0	0	0	1*
Temporary deafness (TTS) onset in pinnipeds and Significant behavioural disturbance	212 dB peak	0	0	0	0	0	0	0	0	0	0	0	0	6*
Avoidance behaviour in pinnipeds exposed to impulsive sounds	190 dB (RMS)[1]	9	10	0	0	0	0	0	0	0	0	0	12	12*
Avoidance behaviour in pinnipeds exposed to impulsive sounds	190 dB (RMS)[2]	18	20	0	0	0	0	0	0	0	0	19	12	20
Limited disturbance in pinnipeds exposed to impulsive sounds	180 dB (RMS)[1]	27	30	0	0	0	0	0	0	0	0	19	24	30
Limited disturbance in pinnipeds exposed to impulsive sounds	180 dB (RMS)[2]	36	40	50	51	51	51	51	51	51	46	38	36	51
Limited disturbance in pinnipeds exposed to impulsive sounds	150 dB (RMS)[1]	486	560	450	459	510	612	612	612	510	598	513	636	636
Limited disturbance in pinnipeds exposed to impulsive sounds	150 dB (RMS)[2]	801	900	750	765	765	918	918	918	867	920	931	780	931

Table B.23: Ranges in metres at which SPL has fallen to threshold level along individual transects for pinnipeds exposed to Bubbles sound during the month of August (* - maximum range derived from near-field source level model;
[1] – based on Peak level – 15 dB; [2] - based on Peak level – 10 dB)

Impact	Threshold dB re 1 μPa	Transect bearing (degrees)												Max range m
		0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°	
Auditory injury (PTS) onset in pinnipeds	218 dB peak	0	0	0	0	0	0	0	0	0	0	0	0	1*
Temporary deafness (TTS) onset in pinnipeds and Significant behavioural disturbance	212 dB peak	0	0	0	0	0	0	0	0	0	0	0	0	6*
Avoidance behaviour in pinnipeds exposed to impulsive sounds	190 dB (RMS)[1]	9	10	0	0	0	0	0	0	0	0	0	12	12*
Avoidance behaviour in pinnipeds exposed to impulsive sounds	190 dB (RMS)[2]	18	20	0	0	0	0	0	0	0	0	19	12	20
Limited disturbance in pinnipeds exposed to impulsive sounds	180 dB (RMS)[1]	27	30	0	0	0	0	0	0	0	0	19	24	30
Limited disturbance in pinnipeds exposed to impulsive sounds	180 dB (RMS)[2]	36	40	50	51	51	51	51	51	51	0	38	36	51
Limited disturbance in pinnipeds exposed to impulsive sounds	150 dB (RMS)[1]	513	560	450	510	408	612	612	612	510	598	513	636	636
Limited disturbance in pinnipeds exposed to impulsive sounds	150 dB (RMS)[2]	810	900	900	969	663	918	918	918	867	920	798	960	969

Table B.24: Ranges in metres at which SPL has fallen to threshold level along individual transects for pinnipeds exposed to Bubbles sound during the month of September (* - maximum range derived from near-field source level model; [1] – based on Peak level – 15 dB; [2] - based on Peak level – 10 dB)

Impact	Threshold dB re 1 μPa	Transect bearing (degrees)												Max range m
		0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°	
Auditory injury (PTS) onset in pinnipeds	218 dB peak	0	0	0	0	0	0	0	0	0	0	0	0	1*
Temporary deafness (TTS) onset in pinnipeds and Significant behavioural disturbance	212 dB peak	0	0	0	0	0	0	0	0	0	0	0	0	6*
Avoidance behaviour in pinnipeds exposed to impulsive sounds	190 dB (RMS)[1]	9	10	0	0	0	0	0	0	0	0	0	12	12*
Avoidance behaviour in pinnipeds exposed to impulsive sounds	190 dB (RMS)[2]	18	20	0	0	0	0	0	0	0	0	19	12	20
Limited disturbance in pinnipeds exposed to impulsive sounds	180 dB (RMS)[1]	27	30	0	0	0	0	0	0	0	0	19	24	30
Limited disturbance in pinnipeds exposed to impulsive sounds	180 dB (RMS)[2]	36	40	50	51	51	51	51	51	51	0	38	36	51
Limited disturbance in pinnipeds exposed to impulsive sounds	150 dB (RMS)[1]	1125	1130	1100	1122	1122	1122	1122	1122	1122	1104	1121	1128	1130
Limited disturbance in pinnipeds exposed to impulsive sounds	150 dB (RMS)[2]	1368	1280	1150	2193	1377	2193	1377	1377	1377	1518	1520	2220	2220

Table B.25: Ranges in metres at which SPL has fallen to threshold level along individual transects for pinnipeds exposed to Bubbles sound during the month of October (* - maximum range derived from near-field source level model; [1] – based on Peak level – 15 dB; [2] - based on Peak level – 10 dB)

Impact	Threshold dB re 1 μPa	Transect bearing (degrees)												Max range m
		0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°	
Auditory injury (PTS) onset in pinnipeds	218 dB peak	10	10	0	0	0	0	0	0	0	0	0	0	9*
Temporary deafness (TTS) onset in pinnipeds and Significant behavioural disturbance	212 dB peak	20	20	0	0	0	0	0	0	0	0	20	14	32*
Avoidance behaviour in pinnipeds exposed to impulsive sounds	190 dB (RMS)[1]	40	50	50	51	0	51	51	51	51	48	40	42	51
Avoidance behaviour in pinnipeds exposed to impulsive sounds	190 dB (RMS)[2]	70	80	50	51	51	51	51	51	51	48	80	70	80
Limited disturbance in pinnipeds exposed to impulsive sounds	180 dB (RMS)[1]	110	110	100	102	102	102	102	102	102	96	120	112	120
Limited disturbance in pinnipeds exposed to impulsive sounds	180 dB (RMS)[2]	150	170	150	153	153	153	153	153	153	144	160	154	170
Limited disturbance in pinnipeds exposed to impulsive sounds	150 dB (RMS)[1]	940	950	950	1020	918	867	918	1020	969	960	940	952	1020
Limited disturbance in pinnipeds exposed to impulsive sounds	150 dB (RMS)[2]	1110	1110	1200	1122	1275	1173	1122	1122	1122	1104	1120	1120	1275

Table B.26: Ranges in metres at which SPL has fallen to threshold level along individual transects for pinnipeds exposed to Geotiger sound during the month of June (* - maximum range derived from near-field source level model;
[1] – based on Peak level – 15 dB; [2] - based on Peak level – 10 dB)

Impact	**Threshold dB re 1 μPa**	**Transect bearing (degrees)**												**Max range m**
		0°	**30°**	**60°**	**90°**	**120°**	**150°**	**180°**	**210°**	**240°**	**270°**	**300°**	**330°**	
Auditory injury (PTS) onset in pinnipeds	218 dB peak	10	10	0	0	0	0	0	0	0	0	0	0	9*
Temporary deafness (TTS) onset in pinnipeds and Significant behavioural disturbance	212 dB peak	20	20	0	0	0	0	0	0	0	0	20	14	32*
Avoidance behaviour in pinnipeds exposed to impulsive sounds	190 dB (RMS)[1]	40	50	50	51	51	51	51	51	51	48	40	42	51
Avoidance behaviour in pinnipeds exposed to impulsive sounds	190 dB (RMS)[2]	80	80	50	51	51	51	51	51	51	48	80	70	80
Limited disturbance in pinnipeds exposed to impulsive sounds	180 dB (RMS)[1]	110	110	100	102	102	102	102	102	102	96	100	112	112
Limited disturbance in pinnipeds exposed to impulsive sounds	180 dB (RMS)[2]	170	190	150	153	153	153	153	153	153	144	180	182	190
Limited disturbance in pinnipeds exposed to impulsive sounds	150 dB (RMS)[1]	940	940	950	1020	867	918	918	1020	969	912	940	938	1020
Limited disturbance in pinnipeds exposed to impulsive sounds	150 dB (RMS)[2]	1110	1100	1200	1122	1275	1173	1122	1122	1122	1152	1120	1106	1275

Table B.27: Ranges in metres at which SPL has fallen to threshold level along individual transects for pinnipeds exposed to Geotiger sound during the month of July (* - maximum range derived from near-field source level model;
[1] – based on Peak level – 15 dB; [2] - based on Peak level – 10 dB)

Impact	Threshold dB re 1 μPa	Transect bearing (degrees)												Max range m
		0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°	
Auditory injury (PTS) onset in pinnipeds	218 dB peak	10	10	0	0	0	0	0	0	0	0	0	0	9*
Temporary deafness (TTS) onset in pinnipeds and Significant behavioural disturbance	212 dB peak	20	20	0	0	0	0	0	0	0	0	20	14	32*
Avoidance behaviour in pinnipeds exposed to impulsive sounds	190 dB (RMS)[1]	40	50	50	0	0	51	51	51	51	48	40	42	51
Avoidance behaviour in pinnipeds exposed to impulsive sounds	190 dB (RMS)[2]	70	80	50	51	51	51	51	51	51	48	80	70	80
Limited disturbance in pinnipeds exposed to impulsive sounds	180 dB (RMS)[1]	110	110	100	102	102	102	102	102	102	96	100	112	112
Limited disturbance in pinnipeds exposed to impulsive sounds	180 dB (RMS)[2]	150	160	150	153	153	153	153	153	153	144	160	154	160
Limited disturbance in pinnipeds exposed to impulsive sounds	150 dB (RMS)[1]	1550	1480	1450	1530	1326	1428	1326	1326	1224	1296	1400	1372	1550
Limited disturbance in pinnipeds exposed to impulsive sounds	150 dB (RMS)[2]	1810	1780	1750	1887	1734	1632	1632	1632	1632	1632	1760	1932	1932

Table B.28: Ranges in metres at which SPL has fallen to threshold level along individual transects for pinnipeds exposed to Geotiger sound during the month of August (* - maximum range derived from near-field source level model;
[1] – based on Peak level – 15 dB; [2] - based on Peak level – 10 dB)

Impact	Threshold dB re 1 μPa	Transect bearing (degrees)												Max range m
		0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°	
Auditory injury (PTS) onset in pinnipeds	218 dB peak	10	10	0	0	0	0	0	0	0	0	0	0	9*
Temporary deafness (TTS) onset in pinnipeds and Significant behavioural disturbance	212 dB peak	20	20	0	0	0	0	0	0	0	0	20	14	32*
Avoidance behaviour in pinnipeds exposed to impulsive sounds	190 dB (RMS)[1]	40	40	50	0	0	0	0	51	0	48	40	42	51
Avoidance behaviour in pinnipeds exposed to impulsive sounds	190 dB (RMS)[2]	70	70	50	51	51	51	51	51	51	48	80	70	80
Limited disturbance in pinnipeds exposed to impulsive sounds	180 dB (RMS)[1]	110	110	100	102	102	102	102	102	102	96	100	112	112
Limited disturbance in pinnipeds exposed to impulsive sounds	180 dB (RMS)[2]	150	150	150	153	153	153	153	153	153	144	140	140	153
Limited disturbance in pinnipeds exposed to impulsive sounds	150 dB (RMS)[1]	1560	1570	1550	1530	1326	1428	1377	1377	1275	1440	1400	1554	1570
Limited disturbance in pinnipeds exposed to impulsive sounds	150 dB (RMS)[2]	1950	1940	1750	1938	1785	1836	1836	1836	1785	1728	1760	1960	1960

Table B.29: Ranges in metres at which SPL has fallen to threshold level along individual transects for pinnipeds exposed to Geotiger sound during the month of September (* - maximum range derived from near-field source level model;
[1] – based on Peak level – 15 dB; [2] - based on Peak level – 10 dB)

Impact	Threshold dB re 1 μPa	Transect bearing (degrees)												Max range m
		0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°	
Auditory injury (PTS) onset in pinnipeds	218 dB peak	10	10	0	0	0	0	0	0	0	0	0	0	9*
Temporary deafness (TTS) onset in pinnipeds and Significant behavioural disturbance	212 dB peak	20	20	0	0	0	0	0	0	0	0	20	14	32*
Avoidance behaviour in pinnipeds exposed to impulsive sounds	190 dB (RMS)[1]	40	40	50	0	0	0	0	51	0	48	40	42	51
Avoidance behaviour in pinnipeds exposed to impulsive sounds	190 dB (RMS)[2]	70	70	50	51	51	51	51	51	51	48	80	70	80
Limited disturbance in pinnipeds exposed to impulsive sounds	180 dB (RMS)[1]	110	110	100	102	102	102	102	102	102	96	100	112	112
Limited disturbance in pinnipeds exposed to impulsive sounds	180 dB (RMS)[2]	150	150	150	153	153	153	153	153	153	144	140	140	153
Limited disturbance in pinnipeds exposed to impulsive sounds	150 dB (RMS)[1]	1970	1990	1950	3264	3366	3366	3366	3366	3315	3360	3360	3318	3366
Limited disturbance in pinnipeds exposed to impulsive sounds	150 dB (RMS)[2]	4020	4290	4200	4590	6579	6579	6579	6579	6579	6576	6640	4718	6640

Table B.30: Ranges in metres at which SPL has fallen to threshold level along individual transects for pinnipeds exposed to Geotiger sound during the month of October (* - maximum range derived from near-field source level model; [1] – based on Peak level – 15 dB; [2] - based on Peak level – 10 dB)

Threshold	Threshold dB re 1 μPa	Transect bearing (degrees)												Max range m
		0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°	
Background noise level	120 dB (RMS)[1]	152	152	150	152	140	153	153	102	102	138	143	144	153
	120 dB (RMS)[2]	204	276	275	200	210	204	204	204	204	207	208	204	276
	110 dB (RMS)[1]	324	328	300	328	294	306	306	255	255	276	286	336	336
	110 dB (RMS)[2]	456	456	450	456	448	408	408	459	459	437	455	444	459
	100 dB (RMS)[1]	564	560	560	560	546	561	561	612	561	529	546	540	612
	100 dB (RMS)[2]	764	764	765	760	756	765	765	714	714	667	754	648	765

Table B.31: Ranges in metres at which SPL from VGSA array has fallen to background noise levels along individual transects during June
([1] – based on Peak level – 15 dB; [2] - based on Peak level – 10 dB)

Threshold	Threshold dB re 1 μPa	Transect bearing (degrees)												Max range m
		0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°	
Background noise level	120 dB (RMS)[1]	180	180	175	176	168	153	153	102	102	138	169	168	180
	120 dB (RMS)[2]	244	248	250	248	336	204	204	255	255	253	338	252	338
	110 dB (RMS)[1]	404	400	355	352	350	306	306	255	255	414	351	348	414
	110 dB (RMS)[2]	624	520	520	520	462	510	459	510	510	506	442	504	624
	100 dB (RMS)[1]	704	696	810	696	686	612	561	714	561	644	689	672	810
	100 dB (RMS)[2]	848	880	855	856	868	765	765	765	765	759	871	852	880

Table B.32: Ranges in metres at which SPL from VGSA array has fallen to background noise levels along individual transects during July
([1] – based on Peak level – 15 dB; [2] - based on Peak level – 10 dB)

Threshold	Threshold dB re 1 μPa	Transect bearing (degrees)												Max range m
		0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°	
Background noise level	120 dB (RMS)[1]	140	140	130	128	126	153	153	102	102	115	130	132	153
	120 dB (RMS)[2]	356	348	445	344	336	306	306	306	255	322	338	336	445
	110 dB (RMS)[1]	540	664	660	656	574	408	612	612	459	621	468	624	664
	110 dB (RMS)[2]	928	920	880	880	812	765	765	816	765	943	793	936	943
	100 dB (RMS)[1]	1384	1260	1270	1264	1288	1275	1275	1275	1275	1265	1534	1272	1534
	100 dB (RMS)[2]	1704	1624	1740	1744	1918	1734	1734	1734	1632	1725	1794	1740	1918

Table B.33: Ranges in metres at which SPL from VGSA array has fallen to background noise levels along individual transects during August
([1] – based on Peak level – 15 dB; [2] - based on Peak level – 10 dB)

Threshold	Threshold dB re 1 μPa	Transect bearing (degrees)												Max range m
		0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°	
Background noise level	120 dB (RMS)[1]	136	136	130	128	126	153	153	102	102	115	130	132	153
	120 dB (RMS)[2]	356	348	445	344	336	306	306	306	255	322	455	396	455
	110 dB (RMS)[1]	540	664	660	552	574	408	612	612	459	621	481	624	664
	110 dB (RMS)[2]	936	968	990	888	966	816	816	816	765	943	910	936	990
	100 dB (RMS)[1]	1388	1420	1430	1432	1512	1275	1275	1275	1275	1288	1560	1284	1560
	100 dB (RMS)[2]	1816	1760	1745	1752	1932	1734	1734	1734	1734	1725	1807	1752	1932

Table B.34: Ranges in metres at which SPL from VGSA array has fallen to background noise levels along individual transects during September
([1] – based on Peak level – 15 dB; [2] - based on Peak level – 10 dB)

Threshold	Threshold dB re 1 μPa	Transect bearing (degrees)												Max range m
		0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°	
Background noise level	120 dB (RMS)[1]	136	136	130	136	126	153	153	102	102	115	130	120	153
	120 dB (RMS)[2]	288	276	270	264	252	204	204	255	255	276	273	276	288
	110 dB (RMS)[1]	912	976	975	976	854	816	816	816	816	851	975	864	976
	110 dB (RMS)[2]	1228	1716	1760	1648	1680	2193	2193	2193	2193	2185	1664	2184	2193
	100 dB (RMS)[1]	2240	2408	2495	2848	3206	3927	3927	3927	3927	3933	3055	3936	3936
	100 dB (RMS)[2]	2628	3076	3295	3360	5446	7599	7752	7752	6987	7705	5967	6744	7752

Table B.35: Ranges in metres at which SPL from VGSA array has fallen to background noise levels along individual transects during October
([1] – based on Peak level – 15 dB; [2] - based on Peak level – 10 dB)

Threshold	**Threshold dB re 1 μPa**	**Transect bearing (degrees)**												**Max range m**
		0°	**30°**	**60°**	**90°**	**120°**	**150°**	**180°**	**210°**	**240°**	**270°**	**300°**	**330°**	
Background noise level	120 dB (RMS)[1]	1197	1210	1450	1275	1479	1428	1428	1326	1377	1150	1197	1200	1479
	120 dB (RMS)[2]	1368	1380	1750	1683	1836	1836	1785	1683	1632	1334	1368	1380	1836
	110 dB (RMS)[1]	1611	1570	2300	2091	2091	2295	2295	2040	1989	1564	1558	1620	2300
	110 dB (RMS)[2]	2016	1970	2500	2550	2754	2703	2652	2499	2244	1932	1938	1956	2754
	100 dB (RMS)[1]	2304	2300	3300	3009	3162	3111	3111	3009	2754	2208	2261	2292	3300
	100 dB (RMS)[2]	2853	2840	3600	3519	3621	3825	3825	3519	3213	2622	2603	2628	3825

Table B.36: Ranges in metres at which SPL from Bubbles array has fallen to background noise levels along individual transects during June
([1] – based on Peak level – 15 dB; [2] - based on Peak level – 10 dB)

Threshold	**Threshold dB re 1 μPa**	**Transect bearing (degrees)**												**Max range m**
		0°	**30°**	**60°**	**90°**	**120°**	**150°**	**180°**	**210°**	**240°**	**270°**	**300°**	**330°**	
Background noise level	120 dB (RMS)[1]	1404	1410	1450	1326	1479	1428	1530	1326	1377	1334	1349	1404	1530
	120 dB (RMS)[2]	1611	1530	1750	1683	1785	1836	1785	1683	1632	1610	1615	1608	1836
	110 dB (RMS)[1]	1746	1720	2250	2091	2091	2244	2295	2091	1989	1748	1843	1812	2295
	110 dB (RMS)[2]	2025	2020	2500	2550	2805	2703	2754	2550	2295	2070	2052	2028	2805
	100 dB (RMS)[1]	2304	2300	3250	3009	3162	3111	3213	3009	2703	2254	2280	2292	3250
	100 dB (RMS)[2]	2826	2640	3600	3519	3621	3825	3825	3519	3162	2622	2603	2628	3825

Table B.37: Ranges in metres at which SPL from Bubbles array has fallen to background noise levels along individual transects during July
([1] – based on Peak level – 15 dB; [2] - based on Peak level – 10 dB)

Threshold	Threshold dB re 1 μPa	Transect bearing (degrees)												Max range m
		0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°	
Background noise level	120 dB (RMS)[1]	3465	3400	3200	3366	3417	3366	3366	3417	3417	3404	3401	3384	3465
	120 dB (RMS)[2]	3906	4060	3850	3825	3876	3825	3825	4080	4080	3910	3914	3900	4080
	110 dB (RMS)[1]	4356	4600	4600	4437	4590	4590	4590	4590	8160	4600	4617	4524	8160
	110 dB (RMS)[2]	4977	5090	5050	5100	5100	5100	5100	5151	8160	5152	5130	5124	8160
	100 dB (RMS)[1]	5616	5550	5550	5865	5865	5865	5865	5916	8160	5888	5890	5736	8160
	100 dB (RMS)[2]	5994	6260	6000	6375	6477	6426	6426	6477	8160	6440	6422	6240	8160

Table B.38: Ranges in metres at which SPL from Bubbles array has fallen to background noise levels along individual transects during August ([1] – based on Peak level – 15 dB; [2] - based on Peak level – 10 dB)

Threshold	Threshold dB re 1 μPa	Transect bearing (degrees)												Max range m
		0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°	
Background noise level	120 dB (RMS)[1]	3510	3440	3400	3468	3468	3468	3468	3723	3723	3680	3496	3696	3723
	120 dB (RMS)[2]	4275	4190	4200	4182	4182	4182	4182	4233	4233	4232	4237	4212	4275
	110 dB (RMS)[1]	4734	4740	4650	4947	4692	4896	4947	4998	4998	5014	5035	4956	5035
	110 dB (RMS)[2]	5211	5300	5400	5508	5508	5508	5559	5559	5508	5520	5510	5496	5559
	100 dB (RMS)[1]	5931	5960	5850	6171	6324	6324	6324	6324	6324	6348	6289	5988	6348
	100 dB (RMS)[2]	6255	6410	6250	6783	6885	6885	6936	6936	6936	6946	6878	6612	6946

Table B.39: Ranges in metres at which SPL from Bubbles array has fallen to background noise levels along individual transects during September ([1] – based on Peak level – 15 dB; [2] - based on Peak level – 10 dB)

Threshold	Threshold dB re 1 μPa	Transect bearing (degrees)												Max range m
		0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°	
Background noise level	120 dB (RMS)[1]	6786	7190	6850	9078	25551	37281	37128	38097	38913	23046	16340	8640	38913
	120 dB (RMS)[2]	7434	7710	7400	9741	39372	50949	50949	50949	50949	25024	17423	9744	50949
	110 dB (RMS)[1]	8145	8230	7800	10149	50949	50949	50949	50949	50949	32246	18031	10776	50949
	110 dB (RMS)[2]	8829	8540	8100	10455	50949	50949	50949	50949	50949	40894	18411	11712	50949
	100 dB (RMS)[1]	8991	8780	8400	10710	50949	50949	50949	50949	50949	45954	18677	11988	50949
	100 dB (RMS)[2]	8991	9010	8600	10914	50949	50949	50949	50949	50949	45954	18886	11988	50949

Table B.40: Ranges in metres at which SPL from Bubbles array has fallen to background noise levels along individual transects during October
([1] – based on Peak level – 15 dB; [2] - based on Peak level – 10 dB)

Threshold	Threshold dB re 1 μPa	Transect bearing (degrees)												Max range m
		0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°	
Background noise level	120 dB (RMS)[1]	2820	2710	3400	3060	3315	3264	3315	3060	2856	2832	2820	2716	3400
	120 dB (RMS)[2]	3320	3320	3600	3519	3621	3876	4029	3570	3366	3312	3320	3318	4029
	110 dB (RMS)[1]	4020	4020	4550	4182	4590	4743	4590	4029	3672	3744	3960	3990	4743
	110 dB (RMS)[2]	4250	4240	4800	4590	5355	5355	5151	4641	4335	4224	4220	4242	5355
	100 dB (RMS)[1]	5080	5070	5800	5457	5916	6579	6273	5508	5151	5088	5040	5068	6579
	100 dB (RMS)[2]	5850	5860	6750	6426	6681	6987	6732	6375	5406	5808	5760	5852	6987

Table B.41: Ranges in metres at which SPL from Geotiger array has fallen to background noise levels along individual transects during June
([1] – based on Peak level – 15 dB; [2] - based on Peak level – 10 dB)

Threshold	Threshold dB re 1 μPa	Transect bearing (degrees)												Max range m
		0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°	
Background noise level	120 dB (RMS)[1]	2940	2950	3350	3060	3315	3264	3315	3060	2856	2688	2920	2940	3350
	120 dB (RMS)[2]	3300	3290	3650	3519	3774	3927	3978	3570	3366	3312	3280	3290	3978
	110 dB (RMS)[1]	4020	4020	4650	4182	4641	4743	4590	4233	3672	3984	4000	4018	4743
	110 dB (RMS)[2]	4240	4230	4800	4743	5100	5202	5100	4641	4335	4224	4220	4228	5202
	100 dB (RMS)[1]	5040	5030	5800	5457	5967	6579	6273	5508	5151	5040	5020	5026	6579
	100 dB (RMS)[2]	5850	5850	6750	6426	6681	6987	6732	6426	5355	5760	5800	5852	6987

Table B.42: Ranges in metres at which SPL from Geotiger array has fallen to background noise levels along individual transects during July
([1] – based on Peak level – 15 dB; [2] - based on Peak level – 10 dB)

Threshold	Threshold dB re 1 μPa	Transect bearing (degrees)												Max range m
		0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°	
Background noise level	120 dB (RMS)[1]	4670	4670	4650	4641	4641	4131	4131	4029	3978	4176	4700	4690	4700
	120 dB (RMS)[2]	5260	5410	5400	5406	5406	4692	4692	4539	4335	4656	5260	5460	5460
	110 dB (RMS)[1]	6030	5960	5950	5967	5967	5253	5253	5100	4998	5136	5840	5992	6030
	110 dB (RMS)[2]	6550	6580	6700	6732	6732	5814	5814	5508	5406	5616	6680	6720	6732
	100 dB (RMS)[1]	7420	7310	7300	7344	7344	6579	6273	6069	6018	6096	7300	7378	7420
	100 dB (RMS)[2]	7980	8030	8050	8058	8058	6987	6783	6579	6528	6720	7920	7994	8058

Table B.43: Ranges in metres at which SPL from Geotiger array has fallen to background noise levels along individual transects during August ([1] – based on Peak level – 15 dB; [2] - based on Peak level – 10 dB)

Threshold	Threshold dB re 1 μPa	Transect bearing (degrees)												Max range m
		0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°	
Background noise level	120 dB (RMS)[1]	4950	5030	4850	4998	5049	4437	4437	4386	4131	4272	5080	5040	5080
	120 dB (RMS)[2]	5620	5810	5800	5610	5814	5049	5049	4896	4641	4992	5660	5586	5814
	110 dB (RMS)[1]	6380	6410	6400	6375	6375	5610	5610	5355	5253	5568	6240	6398	6410
	110 dB (RMS)[2]	7030	7090	7100	7191	7242	6273	6222	5967	6018	6048	7180	7084	7242
	100 dB (RMS)[1]	7850	7780	7750	7803	7803	6834	6834	6477	6579	6816	7780	7854	7854
	100 dB (RMS)[2]	8480	8550	8550	8619	8619	7497	7242	7038	7089	7152	8440	8428	8619

Table B.44: Ranges in metres at which SPL from Geotiger array has fallen to background noise levels along individual transects during September ([1] – based on Peak level – 15 dB; [2] - based on Peak level – 10 dB)

Threshold	Threshold dB re 1 μPa	Transect bearing (degrees)												Max range m
		0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°	
Background noise level	120 dB (RMS)[1]	9990	9990	11500	17595	50949	50949	50949	50949	50949	36144	19840	13328	50949
	120 dB (RMS)[2]	9990	9990	13250	29682	50949	50949	50949	50949	50949	45312	19980	13636	50949
	110 dB (RMS)[1]	9990	9990	14700	47736	50949	50949	50949	50949	50949	47760	19980	13944	50949
	110 dB (RMS)[2]	9990	9990	19150	50949	50949	50949	50949	50949	50949	47952	19980	13986	50949
	100 dB (RMS)[1]	9990	9990	31550	50949	50949	50949	50949	50949	50949	47952	19980	13986	50949
	100 dB (RMS)[2]	9990	9990	49950	50949	50949	50949	50949	50949	50949	47952	19980	13986	50949

Table B.45: Ranges in metres at which SPL from Geotiger array has fallen to background noise levels along individual transects during October ([1] – based on Peak level – 15 dB; [2] - based on Peak level – 10 dB)