APPENDIX E:
UNDERWATER SOUND PROPAGATION FROM SHALLOW CORING OPERATIONS IN BAFFIN BAY
Underwater Sound Propagation from Shallow Coring Operations in Baffin Bay

Shell 2012 Shallow Coring Operations in Baffin Bay.

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2012 March 12

P001170-001
Document Version Control

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Executive Summary

JASCO Applied Sciences (JASCO) carried out a modelling study for LGL Limited (LGL) to predict the underwater sound levels propagating from the operation of a vertical seismic profile (VSP) airgun array and a vessel in dynamic positioning (DP) mode at three shallow coring sites, located offshore of western Greenland.

The VSP array consists of two airguns with a total volume of 500 in\(^3\). The underwater acoustic signature of the array was predicted with JASCO’s Airgun Array Source Model (AASM, MacGillivray 2006a). This model is based on the physics of the oscillation and radiation of airgun bubbles described by Ziolkowski (1970). AASM produces a set of “notional” signatures for each array element based on:

- Array layout,
- Volume, tow depth, and firing pressure of each airgun, and
- Interactions between different airguns in the array.

The signatures are also summed with the appropriate phase delays to obtain the far-field source signature of the entire array in different directions. This far-field array signature is filtered into 1/3-octave passbands to compute the source levels of the array as a function of frequency band and azimuthal angle in the horizontal plane.

The source levels for a vessel in DP mode were estimated based JASCO’s source levels database and the specifications of the coring vessel proposed by Shell Global Solutions International B.V. (Shell), i.e., the M/V JOIDES Resolution.

Sound levels at distances from the sources were predicted using JASCO’s Marine Operations Noise Model (MONM). MONM treats sound propagation in range-varying acoustic environments through a wide-angled parabolic equation (PE) solution to the acoustic wave equation, based on a version of the US Naval Research Laboratory’s Range-dependent Acoustic Model (RAM) (Collins et al. 1996). The model fully accounts for depth and/or range dependence of several environmental parameters, including bathymetry and sound speed profiles in the water column and the sub-bottom. In this study, sound level predictions were made for water temperature profiles representative of the three operational months (August to October), accounting for the source directivity and the range-dependent environmental properties in the area.

Full-Waveform Range-dependent Acoustic Model (FWRAM) was used to determine the acoustic pulse time integration periods as a function of range from the sources, and consequently, the range-dependent conversion factor between sound exposure level (SEL) and root mean square sound pressure level (rms SPL), and between SEL and Peak sound pressure level (SPL).

Marine mammal frequency weighting (M-weighting), based on Southall et al. (2007), was applied for four functional hearing groups to weight the importance of received sound levels at particular frequencies.

The predicted distances to specific sound levels were computed from the maximum-over-depth sound fields. The acoustic metrics considered include SEL, rms SPL, Peak SPL (zero to Peak and Peak to Peak), and cumulative SEL. Results are presented in two formats: tables of maximum and 95% distances to threshold sound levels, and sound field contour maps showing the directivity and range to various threshold levels. Aggregate maps of cumulative SEL and received rms SPLs from concurrent seismic operations by Shell, ConocoPhillips, and Maersk are also presented.
1. Introduction

1.1. Project Overview

JASCO Applied Sciences (JASCO) carried out a modelling study for LGL Limited (LGL) to predict the underwater sound levels propagating from the operation of a vertical seismic profile (VSP) airgun array and a vessel in dynamic positioning (DP) mode at three shallow coring sites, located offshore of western Greenland.

The VSP array consists of two air guns with a total volume of 500 in³. The underwater acoustic signature of the array was predicted using a specialized computer model that accounts for individual airgun volumes and the array geometry. The source levels for the vessel in DP mode were estimated based JASCO’s source levels database and the specifications of the coring vessel proposed by Shell Global Solutions International B.V. (Shell), the M/V JOIDES Resolution.

Sound levels at distances from the sources were predicted using an underwater acoustic propagation model and the modelled source levels. These predictions were made for water temperature profiles representative of the three operational months (August to October), accounting for source directivity and the range-dependent environmental properties in the area.

Section 2 discusses the methodology for predicting the source levels and modelling sound propagation. Section 3 describes the specifications of the sources, the source locations, and all environmental parameters required by the propagation model. Section 4 presents the results of the modelling study in two formats: tables of maximum and 95% distances to sound level thresholds, and sound field contour maps showing the directivity and range to various sound level thresholds. In accordance with the Danish Centre for Environment and Energy’s Guidelines to Environmental Impact Assessment of Seismic Activities in Greenland Waters (Kyhn et al. 2011), distances from the airgun array to sound level thresholds are provided for:

- un-weighted SELs of 200 through 120 dB re 1 µPa²·s,
- M-weighted SEL of 198 dB re 1 µPa²·s for each marine mammal functional hearing group,
- rms SPLs of 200 through 120 dB re 1 µPa, and
- zero-to-peak and peak-to-peak SPLs of 230, 218, 210, 200, 190, and 180 dB re 1 µPa.

Maps of cumulative SELs from two source arrays operating for 24 h are provided. The cumulative SELs were also considered in combination with those from other seismic survey sources planned for concurrent use in the area (Section 4.5).

1.2. Acoustic Metrics

Underwater sound amplitude is measured in decibels (dB), relative to a standard reference pressure of 1 µPa. Several sound level metrics are commonly used to evaluate loudness or effects of impulsive noise. The primary sound level metrics of importance to this report are zero-to-peak sound pressure level (often called peak SPL), peak-to-peak SPL, 90% rms sound pressure level (rms SPL), and sound exposure level (SEL). Zero-to-peak SPL (dB re 1 µPa, ANSI symbol $L_{pk}$) is the maximum instantaneous sound pressure level attained by a time varying pressure signal, $p(t)$:

$$L_{pk} = 20 \log_{10} \left( \max \left| p(t) \right| \right)$$
The 90% energy rms SPL \( (dB \text{ re } 1 \mu Pa, \text{ symbol } L_{p90}) \) is the root-mean-square pressure level over the time window \( T_{90} \):

\[
L_{p90} = 10 \log_{10} \left( \frac{1}{T_{90}} \int_{T_{90}} p^2(t) dt / p_0^2 \right)
\]  

(2)

where \( T_{90} \) is the time interval containing the central 90% (from 5% to 95% of the total) of the pulse energy. The rms SPL can be thought as a measure of the average pressure or as the “effective” pressure over the duration of an acoustic event, such as the emission of one acoustic pulse. Because the window length, \( T_{90} \), is used as a divisor, pulses that are more spread out in time have a lower rms SPL for the same total acoustic energy.

The SEL \( (dB \text{ re } 1 \mu Pa^2\cdot s, \text{ ANSI symbol } L_E) \) is the time integral of the squared pressure over a fixed time window containing the entire pulse, \( T_{100} \):

\[
L_E = 10 \log_{10} \left( \int_{T_{100}} p^2(t) dt / T_o p_0^2 \right)
\]  

(3)

where \( T_o \) is a reference time interval of 1 s. The per-pulse SEL is measured in units of dB re 1 \( \mu Pa^2\cdot s \) or equivalently dB re 1 \( \mu Pa^2\cdot s \). This measure is represents the total energy delivered over the duration of an acoustic event at a receiver location. It is related to sound energy (or exposure) rather than sound pressure. SEL can be a metric that describes the sound level for a single sound pulse, or a cumulative metric if applied over time periods containing multiple pulses. The cumulative SEL can be computed by summing (in linear units) the SELs of individual pulses:

\[
L_{EC} = 10 \log\left( \sum \frac{L_E}{10} \right)
\]  

(4)

Because the 90% rms SPL and SEL are both computed from the integral of square pressure, these metrics are related numerically by a simple expression, which depends only on the duration of the 90% integration time window, \( T_{90} \):

\[
L_{p90} = L_E - 10 \log(T_{90}/T_o) - 0.458
\]  

(5)

where the 0.458 dB factor accounts for the rms SPL containing 90% of the total energy from the per-pulse SEL (Malme et al. 1986; Greene 1997; McCauley et al. 1998).

1.3. Acoustic Impact Criteria

1.3.1. Marine mammal frequency weighting

The potential for seismic survey noise to impact marine species depends on how well the species can hear the sounds produced (Southall et al. 2007). Noises are less likely to disturb or injure animals if they are at frequencies outside the animal’s hearing range. For non-injurious sound levels, frequency weighting based on audiograms may be applied to weight the importance of sound levels at particular frequencies in a manner reflective of the receiver’s sensitivity to those frequencies (Nedwell and Turnpenny 1998; Nedwell et al. 2007).

Based on a review of literature on marine mammal hearing and on physiological and behavioral responses to anthropogenic sound, Southall et al. (2007) proposed standard
Marine mammal frequency weighting (M-weighting) functions for five functional hearing groups of marine mammals:

- Low-frequency cetaceans (LFCs)—mysticetes (baleen whales),
- Mid-frequency cetaceans (MFCs)—some odontocetes (toothed whales),
- High-frequency cetaceans (HFCs)—odontocetes specialized for using high-frequencies,
- Pinnipeds in water—seals, sea lions and walrus, and
- Pinnipeds in air (not addressed here).

The amount of discount applied by M-weighting functions for less-audible frequencies is less than that indicated by the corresponding audiograms for member species of these hearing groups. The rationale for applying a smaller discount is due in part to an observed characteristic of mammalian hearing where by perceived equal loudness curves have increasingly less rapid roll-off outside the most sensitive hearing frequency range as sound levels increase. This is the reason that C-weighting curves for humans, used for assessing effects of loud sounds such as blasts, are flatter than A-weighting curves used for quiet to mid-level sounds. Additionally, out-of-band frequencies, though less audible, can still cause physical injury if pressure levels are high enough. The M-weighting functions therefore are intended to be applied primarily at high sound levels where impacts such as temporary or permanent hearing threshold shifts may occur. The use of M-weighting should be considered precautionary (in the sense of overestimating the potential impact) particularly when applied to lower level impacts such as onset of behavioural response. Figure 1 shows the decibel frequency weighting of the M-weighting functions for each functional hearing group underwater.

![Figure 1. Standard M-weighting functions for low-, mid-, and high-frequency cetaceans and for pinnipeds in water.](image)

These functions have unity gain (0 dB) through the passband and high and low frequency roll-off is approximately –12 dB per octave. The amplitude response of the M-weighting functions is defined in the frequency domain by the following function:

$$G(f) = -20 \log_{10} \left[ \left(1 + \frac{f_{lo}^2}{f^2} \right) \left(1 + \frac{f^2}{f_{hi}^2} \right) \right]$$

The roll-off and passband of these functions are controlled by parameters $f_{lo}$ and $f_{hi}$; estimated upper and lower hearing limits specific to each functional hearing group (Table 1).
Table 1. Low- and high-frequency cut-off parameters of M-weighting curves for each marine mammal functional hearing group.

<table>
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<th>$f_{lw}$ (Hz)</th>
<th>$f_{hi}$ (Hz)</th>
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<tr>
<td>Low-frequency cetaceans (LFC)</td>
<td>7</td>
<td>22 000</td>
</tr>
<tr>
<td>Mid-frequency cetaceans (MFC)</td>
<td>150</td>
<td>160 000</td>
</tr>
<tr>
<td>High-frequency cetaceans (HFC)</td>
<td>200</td>
<td>180 000</td>
</tr>
<tr>
<td>Pinnipeds (underwater)</td>
<td>75</td>
<td>75 000</td>
</tr>
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</table>

1.3.2. Exposure criteria

The Guidelines to Environmental Impact Assessment of Seismic Activities in Greenland Waters (Kyhn et al. 2011, §5.1.2) state: “Each pulse should not exceed the peak pressure criterion [provided by Southall et al. (2007)], but in addition, the summed energy of all pulses the animal is exposed to should not exceed the limits suggested by Southall et al. (2007)”.

Distances to these Southall criteria, as well as distances to the thresholds of SELs and zero-to-peak and peak-to-peak SPLs of 200 through 120 dB, in 10 dB increments, are provided in this report.

The Guidelines also discuss the US mitigation standard of 180 dB re 1 µPa rms SPL (NMFS 2003, Miller et al. 2005), so distances to this threshold are provided for completeness, as well as distances to the thresholds of rms SPLs of 200 through 120 dB re 1 µPa in 10 dB increments.

For impulsive sound sources, a broadband received rms SPL of 160 dB re 1 µPa or greater is estimated to cause disruption of behavioural patterns (i.e., harassment) to marine mammals (MMPA 2007). Furthermore, concerns about temporary and/or permanent hearing impairment to cetaceans exist at a broadband received rms SPL of 180 dB re 1 µPa or greater; this level is higher (190 dB re 1 µPa) for pinnipeds (MMPA 2007). This harassment criterion (the most cautionary injury impact criterion) was thought to be well understood by the public and easily calculated from standard propagation models (NMFS 2005). Being expressed in rms units, the criterion accounts for not only the energy of the pulse, but also the length of the pulse (see Equation 2). The disadvantage of such a criterion is that it does not account for certain important attributes of exposure such as exposure duration, sound frequency composition and pulse repetition rate. Also, these exposure levels are calculated using un-weighted acoustic signals, i.e., the criterion does not account for the different hearing ability of animals at different frequencies.

1.3.3. Southall criteria

The Noise Criteria Group, sponsored by NMFS, was established in 2005 to address shortcomings of the 180–160 dB rms SPL criteria. The goal of the Noise Criteria Group was to review literature on marine mammal hearing and on their behavioural and physiological responses to anthropogenic noise, as well as to propose new noise exposure criteria. In 2007, the findings of the Noise Criteria Group were published by an assembly of experts (Southall et al. 2007). The publication introduced new noise impact threshold levels, now commonly referred to as the “Southall criteria”.

These so-called “dual-criteria” are based on both zero-to-peak (peak) SPL of acoustic waves, expressed in dB re 1 µPa, and total SEL, expressed in dB re 1 µPa²·s. A received sound exposure is assumed to cause injury if it exceeds either the peak SPL, or SEL criterion, or both. The peak SPL is not frequency weighted, whereas the SEL is M-weighted for the given marine mammal group (see Section 1.3.1).
Different levels were established for cetaceans and pinnipeds, with the levels for pinnipeds being lower. During the calculations of SEL, the length of the pulse is not considered, only the total energy released during the pulse event (see Equation 3).

Table 2. Southall criteria for injury and behavioural disturbance (Southall et al. 2007). The zero-to-peak SPL criterion is un-weighted (i.e., flat weighted), whereas the SEL criterion is M-weighted for the given marine mammal functional hearing group.

<table>
<thead>
<tr>
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<th>Injury</th>
<th>Behavioral disturbance</th>
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<tr>
<td></td>
<td>Peak SPL (dB re 1 µPa)</td>
<td>SEL (dB re 1 µPa²·s)</td>
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<tr>
<td>Low-frequency cetaceans (LFC)</td>
<td>230</td>
<td>198 (M_LFC)</td>
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<td>Mid-frequency cetaceans (MFC)</td>
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<td>198 (M_MFC)</td>
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</tr>
<tr>
<td>Pinnipeds underwater</td>
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</table>
2. Methods

Two complementary acoustic models were used to predict the underwater acoustic field for the studied Vertical Seismic Profile (VSP) airgun array. The airgun array pressure signatures and directional source levels (SLs) were predicted with JASCO’s Airgun Array Source Model (AASM), described in Section 2.1.1. The acoustic fields around the source were modelled with JASCO’s Marine Operations Noise Model (MONM), described in Section 2.2, based on the computed signatures and SLs. The model input parameters for the source and environment are described in Section 3.

The frequency-dependent SLs associated with a shallow coring vessel keeping on-station, using an onboard dynamic positioning (DP) system, were estimated from measured data available in JASCO’s internal database (see Section 2.1.2). Acoustic fields were also modelled with MONM. No sound levels from the drilling operation (including sound from mechanical actions of the drill bit, the string and casing, and the drill platform) were modelled since SLs from the vessel’s propulsion system while in DP mode is estimated to be substantially higher (> 18 dB) than that of the drilling operation (Gales 1982).

JASCO’s Full-Waveform Range-dependent Acoustic Model (FWRAM) was used to determine the acoustic pulse time integration periods as a function of range from the VSP array, and consequently the range-dependent conversion factor between SEL and rms SPL, as described in Section 1.2. The methodology is described in Section 2.3. Results from FWRAM were also used to determine distances to zero-to-peak and peak-to-peak SPL thresholds (see Section 2.4).

M-weighting was applied to four functional hearing groups to weight the importance of received sound levels at particular frequencies. M-weighting is described in Section 1.3.1.

2.1. Acoustic Source Model

2.1.1. Vertical Seismic Profile airgun array

The SLs and directivity of the airgun array were predicted with JASCO’s Airgun Array Source Model (AASM, MacGillivray 2006a). This model is based on the physics of oscillation and radiation of airgun bubbles, which is described by Ziolkowski (1970). The model solves the set of parallel differential equations governing bubble oscillations. AASM also accounts for nonlinear pressure interactions among airguns, port throttling, bubble damping, and generator-injection (GI) gun behaviour, that are discussed by Dragoset (1984), Laws et al. (1990), and Landro (1992). AASM includes four empirical parameters that were tuned so that the model output matches observed airgun behaviour. The model parameters fit to a large library of empirical airgun data using a “simulated annealing” global optimization algorithm. These airgun data were measurements of the signatures of Bolt 600/B guns ranging in volume from 5 to 185 in³ (Racca and Scrimger 1986).

AASM is based on the physics of the oscillation and radiation of airgun bubbles, described by Ziolkowski (1970). AASM produces a set of “notional” signatures for each array element based on:

- Array layout,
- Volume, tow depth, and firing pressure of each airgun, and
- Interactions between different airguns in the array.

The notional signatures are pressure waveforms of individual airguns at a standard reference distance of 1 m, and account for the interactions with other airguns in the array. The
signatures are output for use by full-wave sound propagation models. The signatures are also summed with the appropriate phase delays to obtain the far-field source signature of the entire array in different directions. This far-field array signature is filtered into 1/3-octave passbands to compute the SLs of the array as a function of frequency band and azimuthal angle in the horizontal plane (at the source depth). It can then be treated as a directional point source in the far field.

The interactions between individual elements of the array create directionality in the overall acoustic emission. Generally, this directionality is prominent mainly at frequencies in the mid-range of several tens to several hundred hertz; at lower frequencies, with acoustic wavelengths much larger than the inter-airgun separation distances, directivity is small. At higher frequencies the pattern of lobes is too finely spaced to be resolved and the effective directivity is less.

2.1.2. Vessel in Dynamic Positioning mode
Dynamic positioning (DP) systems allow for the automatic control of a vessel’s propellers and/or thrusters to maintain the position and heading during various marine activities. In DP mode, the propulsion system handles a large variation in power demand to counter forces such as currents and wind. Consequently, the broadband source level from a vessel in DP mode is expected to be higher than for transiting at constant speed.

JASCO recorded the dive support vessel *DSV Fu Lai* while operating in DP mode, with DP levels of 25%, i.e., at approximately 3000 HP (MacGillivray 2006b). The calculated source levels were used to estimate the source levels for a vessel in DP mode in the present study.

To produce cautionary estimates of distances to threshold sound levels, the modelled vessel was assumed to operate at DP levels of 100%. The final spectrum was adjusted for the difference in total horsepower between the *DSV Fu Lai* and the modelled shallow coring vessel using the following equation:

\[
SL = SL_{FuLai} + 10 \log(\frac{HP}{HP_{ref}})
\]

where \( HP_{ref} \) is the level of reference, i.e., 3000 HP.

2.2. Sound Propagation Models
Underwater sound propagation (i.e., transmission loss) at frequencies of 10 Hz to 5 kHz was predicted with JASCO’s Marine Operations Noise Model (MONM) and Full Waveform Range Dependent Acoustic Model (FWRAM). MONM computes received per-pulse SEL for impulsive sources at a specified source depth. FWRAM is used to determine distances to zero-to-peak and peak-to-peak SPL thresholds and to convert the SELs modelled with MONM to rms SPLs.

MONM computes acoustic propagation via a wide-angle parabolic equation solution to the acoustic wave equation (Collins 1993) based on a version of the US Naval Research Laboratory’s Range-dependent Acoustic Model (RAM), which has been modified to account for an elastic seabed. The parabolic equation method has been extensively benchmarked and is widely employed in the underwater acoustics community (Collins et al. 1996). MONM accounts for the additional reflection loss at the seabed due to partial conversion of incident compressional waves to shear waves at the seabed and sub-bottom interfaces, and it includes wave attenuations in all layers. MONM incorporates the following site-specific environmental properties: a bathymetric grid of the modelled area, underwater sound speed as
a function of depth, and a geoacoustic profile based on the overall stratified composition of the seafloor.

MONM computes acoustic fields in three dimensions by modelling transmission loss within two-dimensional (2-D) vertical planes aligned along radials covering a 360° swath from the source, an approach commonly referred to as N×2-D. These vertical radial planes are separated by an angular step size of $\Delta \theta$, yielding $N = \frac{360°}{\Delta \theta}$ number of planes.

The model fully accounts for depth and/or range dependence of several environmental parameters including bathymetry and sound speed profiles in the water column and the sub-bottom. It also accounts for the additional reflection loss due to partial conversion of incident compressional waves to shear waves at the seabed and sub-bottom interfaces. It includes wave attenuations in all layers, and the acoustic environment is sampled at a fixed range step along radial traverses.

MONM calculates transmission loss from an equivalent point-like acoustic source to receiver locations at various distances, depths, and bearings. However, a seismic array consists of many sources and so the point-source assumption is not valid in the near field where the array elements do not add coherently. The maximum extent of the near field of an array ($R_{nf}$) is:

$$R_{nf} < \frac{l^2}{4\lambda},$$

where $\lambda$ is the sound wavelength and $l$ is the longest dimension of the array (Lurton 2002, §5.2.4). For example, for the airgun array described in Section 3.1, $l \approx 2$ m and so the maximum near-field range is 1.3 m at 2 kHz. Beyond this range it is assumed that an array radiates like a directional point source and is treated as such for propagation modelling with MONM.

MONM treats frequency dependence by computing acoustic transmission loss at the centre frequencies of 1/3-octave bands, from 10 to 2000 Hz for the current project. This frequency range includes the important bandwidth of noise emissions for the seismic airgun arrays. Third-octave band received levels are computed by subtracting band transmission loss values from the corresponding directional SLs. Broadband received levels are then computed by summing the received band levels.

MONM’s predictions have been compared to experimental data in several sound source verification programs conducted by JASCO (Hannay and Racca 2005; Aerts et al. 2008; Funk et al. 2008; Ireland et al. 2009; O’Neill et al. 2010; Warner et al. 2010). An inherent variability in the measured sound level is caused by temporal variability in the environment and the variability in the signature of the repeated acoustic impulse (an example of sound source verification results is presented in Figure 2). While MONM’s predictions correspond to the averaged received levels, cautionary estimates of the threshold radii are obtained by shifting the best fit line (solid line in Figure 2) upwards so that the trend line encompasses 90% of all the data (dashed line in Figure 2).
In the regions of the Beaufort and Chukchi Seas, sound source verification results show that this 90th percentile best-fit is, on average, 3 dB higher than the original best fit line for sources in water depths greater than 20 m (Aerts et al. 2008; Funk et al. 2008; Ireland et al. 2009; O’Neill et al. 2010; Warner et al. 2010). Consequently, a safety factor of 3 dB was added to the predicted received levels to provide cautionary results reflecting the inherent variability of sound levels in the modelled area.

FWRAM conducts time-domain calculations and is therefore appropriate for computing time-averaged rms SPL and peak SPL values for impulsive sources. FWRAM computes synthetic pressure waveforms versus range and depth for range-varying marine acoustic environments using the parabolic equation approach to solving the acoustic wave equation. Like MONM, FWRAM accounts for range-varying properties of the acoustic environment. It uses the same $N \times 2$-D algorithmic engine as MONM and uses the same environmental inputs (bathymetry, water sound speed profile, and seabed geoaoustic profile). However, FWRAM computes pressure waveforms via Fourier synthesis\(^1\) of the modelled acoustic transfer function in closely spaced frequency bands.

### 2.3. Estimating 90% rms SPL from SEL

Existing safety radius regulations for impulsive sound sources are based on the rms SPL metric. An objective definition of pulse duration is needed when measuring the rms level for a pulse. Following suggestions by Malme et al. (1986), Greene (1997), and McCauley et al. (1998), pulse duration is conventionally taken to be the interval during which 90% of pulse energy is received. Although one can easily measure the 90% rms SPL \textit{in situ}, this metric is generally difficult to model because the adaptive integration period, implicit in the definition of the 90% rms SPL, is highly sensitive to the specific multipath arrival pattern from an acoustic source and can vary greatly with distance from the source or with depth of the receiver. To predict the 90% rms SPL, it is necessary to model the full-waveform of acoustic

\(^1\) Fourier synthesis is the operation of rebuilding a function from simpler pieces (Fourier series).
pressure, but full-wave models are computationally expensive for large-depth range-dependent environments and modelling can be prohibitive due to the extensive time required to complete model runs, especially when multiple ocean sound speed profiles must be considered.

Accurate estimates of airgun array safety ranges must account for the acoustic energy that is returned to the water column by bottom and surface reflections. This is especially important in the case of shallow water conditions.

MONM computes SEL in 1/3-octave bands but does not directly predict rms SPL required for evaluation against accepted noise threshold criteria. The 1/3-octave band SEL values from MONM can be summed to compute broadband SEL, equivalent to the SPL that would occur if the energy for a single airgun array pulse were spread evenly over a nominal time window of 1 s. The 90% rms SPL can be computed from the modelled SEL values using Equation 5 if the $T_{90}$ integration period is known; however $T_{90}$ is generally unknown and must be predicted. The prediction of $T_{90}$ is complicated by variation in this time parameter with distance from the source and its dependence on multipath arrival times that in turn depend on water depth and seabed geoacoustic properties.

Two approaches can be used to determine the integration time period $T_{90}$: (a) the use of empirical values based on field measurements made in similar environments, and (b) the use of a full-wave acoustic model to predict the range-dependent pressure waveform from which the difference between SEL and 90% rms SPL can be directly extracted. In various studies where the rms SPL, SEL, and duration have been measured for individual airgun pulses, the offset between rms SPL and SEL is typically found to be 5–15 dB, with considerable variation depending on water depth and geoacoustic environment (Greene 1997; McCauley et al. 1998; Blackwell et al. 2007; MacGillivray et al. 2007). On average, the measured rms SPL–SEL offsets tend to be larger at closer distances, where the pulse duration is short ($\ll 1$ s), and smaller at farther distances, where pulse duration tends to increase because of propagation effects.

A full-waveform acoustic propagation model, such as JASCO’s FWRAM, can be used to determine range-dependent estimates of rms SPL and SEL for a small set of representative transects. The rms SPL–SEL offsets obtained in this manner can then be interpolated between transects and applied to the set of SEL predictions from MONM. This approach combines the accurate pulse length information available from FWRAM with the greater computational efficiency of MONM. For the conversion of the acoustic field in SEL units to rms SPL units, appropriate rms SPL–SEL range dependent functions are selected from the set of representative transects on the basis of similarity of water depth and bottom type.

For this study the second approach, the use of a full-wave acoustic modelling, was chosen. The full-waveform sound propagation was modelled with FWRAM along two transects at each site. These transects are perpendicular to the tow direction, toward shallower water and toward deeper water, up to a range of 20 km from the source. The resulting range-dependent rms SPL–SEL offset functions were calculated from the resulting rms SPL–SEL offsets. Figure 3 presents an example of these results and Figure 4 shows the site-offset functions used in this study.
2.4. Peak SPL Thresholds

Zero-to-peak and peak-to-peak SPLs were calculated from the synthetic pressure waveforms modelled with FWRAM (see Section 2.2). Peak SPLs were maximized over depth and plotted as a function of range along the two transects for each scenario. Distances to SPL thresholds were obtained by selecting the maximum range at which the modelled levels exceeded the threshold value.

2.5. Cumulative Sound Exposure

During shallow coring operations, a concentrated acoustic energy is introduced into the environment with each firing of the seismic source. While some impact criteria are based on per-pulse received energy at the subject’s location, others account for the total acoustic energy to which a marine mammal is subjected over a 24 h period. An accurate assessment of the cumulative acoustic field depends not only on the parameters of each shot, but also on the
number of shots delivered in a given time period and the relative source position of the shots. Quite a different issue, which is not considered here but bears mentioning as a qualifier to any estimates, is that individuals of most species would not remain stationary throughout the accumulation period, so their dose accumulation would depend also on their motion.

Since the VSP array is a stationary source, the cumulative sound field is simply estimated by adding a constant value (in dB) to the per-shot field, accounting for the maximum number of shots fired within 24 h. Sound levels were extrapolated beyond the edges of the modelled regions by assuming cylindrical spreading transmission loss, \( TL = 10 \cdot \log(R) \), which is consistent with the rate of decay predicted by the modelling. This method provides cautionary estimates of the cumulative sound exposure levels (cSEL) from the acoustic events during the given time period.

### 2.6. Aggregate Sound Exposure

Regional cSEL footprints were computed for each separate activity, extending over a full regional model area. These footprints were then combined into an aggregate exposure map, representing the sum of the received levels in areas of overlap.

Requirements for cumulative sound exposure at a regional scale were also addressed by generating aggregate exposure maps that show combined noise contributions from concurrent seismic activities. This includes contributions from seismic operations planned by Shell, ConocoPhillips, and Maersk.

### 2.7. Sound Propagation Beyond the Regional Scale

Noise exposure beyond the regional scale was estimated using MONM to compute sound propagation along single transects connecting several source and receiver locations. The sources include the two 4240 m\(^3\) Shell arrays, a ConocoPhillips array, a Maersk array and the Shell vertical seismic profiling array. Sound was propagated from each source to a set of receivers over distances of several hundred kilometers. Ice-free conditions were assumed, so scattering at the sea surface due to ice was not accounted for. The presence of sea ice would result in a reduction of the received sound levels, so the values presented provide a cautionary estimate in ideal propagation conditions.
3. Model Parameters

3.1. Acoustic Sources

The shallow coring vessel considered in the study is the *M/V JOIDES Resolution*. During shallow coring operations, the main source of underwater noise is expected to be airgun shots from the VSP array and the cavitation from the vessel’s thrusters.

The VSP array will be used to determine the depth of the wellbore in relation to the acoustics layering below the seafloor, and verify data from previous “checkshot” velocity surveys. It is estimated that 5 to 10 shots from stationary VSP array, lowered to depths of 2–7 m, may be required to gather this information at each site. Since the lower-frequencies in the source spectrum may be significantly attenuated at shallower tow depth, the depth of the VSP array was set to the deepest possible value, 7 m, to estimate cautionary (larger) distances to sound level thresholds.

The *M/V JOIDES Resolution* was assumed to operate at DP levels of 100%. It’s estimated spectrum was adjusted for the difference in total horsepower between the surrogate vessel (*DSV Fu Lai*) as detailed in Section 2.1.2.

Table 3. Vessel specifications.

<table>
<thead>
<tr>
<th></th>
<th><em>M/V JOIDES Resolution</em></th>
<th><em>DSV Fu Lai</em> (surrogate vessel)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Ocean coring research vessel</td>
<td>Dive support vessel</td>
</tr>
<tr>
<td>Length × Breadth (m)</td>
<td>143.4 × 21.3</td>
<td>107 × 19</td>
</tr>
<tr>
<td>Draft (m)</td>
<td>7.5</td>
<td>6.6</td>
</tr>
<tr>
<td>Gross tonnage (GT)</td>
<td>10 282</td>
<td></td>
</tr>
<tr>
<td>Propulsion system</td>
<td>12 × thrusters; each 750 HP</td>
<td>3 × bow thrusters (2×800-1200 BHP, 1×816BHP)</td>
</tr>
<tr>
<td></td>
<td>2 × shafts (main screws)</td>
<td>3 × stern thrusters (2×700 BHP, 1×816 BHP)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 × 3700 BHP engines each driving a single variable pitch propeller</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Main props diameter: 4 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Thrusters diameter: 2 m – 2.5 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>11 732 (estimated)</td>
</tr>
<tr>
<td>Total horse power (HP)</td>
<td>19 400 (estimated)</td>
<td></td>
</tr>
<tr>
<td>VSP array (maximum volume)</td>
<td>2 × 250-in³ Sercel G guns in parallel cluster 1 m apart, lowered to 2–7 m depth</td>
<td></td>
</tr>
</tbody>
</table>
3.2. Modelled Scenarios

3.2.1. Shallow Coring Operations

Shell’s shallow coring operations will take place to the northwest of Exploration License Qamut and within Exploration License Anu in Baffin Bay, south of Thule Air Base, Greenland (see Figure 6). Sound propagation from the VSP array and vessel in DP mode was modelled at the three sites representing the north, centre, and south sectors for shallow coring. Table 4 present the coordinates and water depth at each site.

Table 4. Location and water depth of the modelled sites for the VSP array and vessel in DP mode.

<table>
<thead>
<tr>
<th>Site</th>
<th>Description</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>North sector</td>
<td>75°44'37.064&quot; N</td>
<td>66°17'01.630&quot; W</td>
<td>543</td>
</tr>
<tr>
<td>2</td>
<td>Centre sector</td>
<td>75°35'17.586&quot; N</td>
<td>65°05'06.359&quot; W</td>
<td>184</td>
</tr>
<tr>
<td>3</td>
<td>South sector</td>
<td>74°45'52.834&quot; N</td>
<td>62°36'29.830&quot; W</td>
<td>289</td>
</tr>
</tbody>
</table>
Figure 6. The three modelled sites for the VSP array and vessel in DP mode, in Baffin Bay, western Greenland.
3.2.2. Aggregate Sound Exposure from Five Sources

In addition to the modelling of shallow coring operations, JASCO has also modelled sound propagation for the following scenarios:

- Shell 2012 seismic surveys in Baffin Bay Block 5 & 8 (Matthews 2012)
- ConocoPhillips’ planned 2012 2-D seismic survey (Austin et al. 2012a) and
- Maersk’s planned 2012 3-D seismic survey (Austin et al. 2012b).

The sound contribution from all activities planned for the 2012 open water period in northeast Baffin Bay were modelled using a scenario that includes simultaneous operation of these four sources and the VSP array operating at site 2 (mentioned in Section 3.2.1). This aggregate scenario provides a cautionary estimate of overall sound exposure from concurrent operations in sensitive areas such as Melville Bay.

For each seismic source, modelled single-pulse sound fields were used to compute cSEL for multiple airgun array shots fired within a 24 h period, following the approach described in Section 2.5. The results for each seismic source are provided in individual reports to the various operators.

To assess noise levels beyond a regional scale, sound propagation from each source was modelled along point-to-point transects for single airgun shots. These transects extend from each of the five source locations to four receiver locations in: (R1) Melville Bay, (R2) the northern waters at the border between Greenland and Canada, (R3) Lancaster Sound, and (R4) the southern waters near Disko Island (Figure 7). Table 5 presents the coordinates of the source and receiver sites for modelling beyond the regional scale.

Table 5. Location of modelled sources and receivers for modelling beyond the regional scale.

<table>
<thead>
<tr>
<th>Site</th>
<th>Description</th>
<th>Latitude</th>
<th>Longitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sources</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S1</td>
<td>ConocoPhillips’ seismic airgun array</td>
<td>75° 00’ 18.525” N</td>
<td>65° 28’ 56.015” W</td>
</tr>
<tr>
<td>S2</td>
<td>Maresk’s seismic airgun array</td>
<td>74° 41’ 17.508” N</td>
<td>63° 13’ 16.072” W</td>
</tr>
<tr>
<td>S3</td>
<td>Shell’s seismic airgun array</td>
<td>73° 49’ 15.372” N</td>
<td>62° 33’ 13.807” W</td>
</tr>
<tr>
<td>S4</td>
<td>Shell’s seismic airgun array</td>
<td>73° 54’ 18.337” N</td>
<td>59° 47’ 41.054” W</td>
</tr>
<tr>
<td>S5</td>
<td>Shell’s vertical seismic profiling array</td>
<td>75° 35’ 17.565” N</td>
<td>65° 05’ 06.368” W</td>
</tr>
<tr>
<td>Receivers</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R1</td>
<td>Melville Bay</td>
<td>75° 41’ 58.419” N</td>
<td>61° 06’ 37.248” W</td>
</tr>
<tr>
<td>R2</td>
<td>Canada-Greenland Border</td>
<td>76° 00’ 01.786” N</td>
<td>74° 50’ 50.335” W</td>
</tr>
<tr>
<td>R3</td>
<td>Lancaster Sound</td>
<td>74° 29’ 57.959” N</td>
<td>78° 57’ 11.209” W</td>
</tr>
<tr>
<td>R4</td>
<td>Southern modelled area</td>
<td>71° 02’ 44.154” N</td>
<td>55° 51’ 23.045” W</td>
</tr>
</tbody>
</table>
3.3. Environmental Parameters

3.3.1. Bathymetry
The bathymetry for the modelled area was extracted from the SRTM30+ (v7.0) data grid. This set is a 30 arc-second grid (~300 × 900 m at the studied latitude), rendered for the entire Globe (Rodriguez et al. 2005). The bathymetry data were re-gridded to cover a 388 × 460 km region with a horizontal resolution of 50 × 50 m.

3.3.2. Geoacoustics
While the seabed is covered by poorly sorted coarse sand and gravel, the main surficial sediment layers found along the west coast of Greenland are composed of clay (Codispoti and Kravitz 1968; Marlowe 1968; Henriksen et al. 2000; Griffiths et al. 2011). In some areas,
these layers have been scared by the passage of glaciers and icebergs. Close to the shore (< 100 km), a single shallow horizon increases in thickness (5–60 m) with water depths generally deepening toward the west. Below this surficial layer are found stratified horizons that dip to the south. Further from the shore, on the continental shelf, little to no surficial (softer) sediment is found. In these areas, the seafloor consist of stratified horizons, made of denser muds, which dip to the south (Griffiths et al. 2011).

The geoaoustic properties of the surficial layers depend on the sediment type. As porosity decreases, compressional sound speed and sediment density increase, while the compressional attenuation decreases. Because the modelled area is large and limited geoaoustic information is available, two simplified geoaoustic profiles were constructed to represent the major features of the sediment column at the modelled sites. Geoaoustic properties were estimated from the average parameters based on empirical formulas presented by Hamilton (1980) and Buckingham (2005), and from layer thickness data (Codispoti and Kravitz 1968; Marlowe 1968; Henriksen et al. 2000, Griffiths et al. 2011). The resulting profile for Site 1 is shown in Table 7. The resulting profile for Sites 2 and 3 is shown in Table 7.

<table>
<thead>
<tr>
<th>Depth below seafloor (m)</th>
<th>Density (g/cm³)</th>
<th>Compressional sound speed (m/s)</th>
<th>Compressional attenuation (dB/λ)</th>
<th>Shear sound speed (m/s)</th>
<th>Shear attenuation (dB/λ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–40</td>
<td>1.45–1.48</td>
<td>1462–1600</td>
<td>0.16–0.17</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40–160</td>
<td>1.80–1.97</td>
<td>1612–1777</td>
<td>1.05–0.88</td>
<td></td>
<td></td>
</tr>
<tr>
<td>160–380</td>
<td>2.05–2.29</td>
<td>1819–2030</td>
<td>0.85–0.77</td>
<td>113</td>
<td>1.49</td>
</tr>
<tr>
<td>380–500</td>
<td>2.44–2.55</td>
<td>2155–2250</td>
<td>0.70–0.64</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt;500</td>
<td>2.55</td>
<td>2250</td>
<td>0.64</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 7. Estimated geoaoustic profile representing a multi-layered clay bottom at Sites 2 and 3.

<table>
<thead>
<tr>
<th>Depth below seafloor (m)</th>
<th>Density (g/cm³)</th>
<th>Compressional sound speed (m/s)</th>
<th>Compressional attenuation (dB/λ)</th>
<th>Shear sound speed (m/s)</th>
<th>Shear attenuation (dB/λ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–20</td>
<td>1.77–1.80</td>
<td>1574–1600</td>
<td>0.90–1.05</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20–160</td>
<td>1.80–1.97</td>
<td>1612–1777</td>
<td>1.05–0.88</td>
<td></td>
<td></td>
</tr>
<tr>
<td>160–380</td>
<td>2.05–2.29</td>
<td>1819–2030</td>
<td>0.85–0.77</td>
<td>305</td>
<td>4.02</td>
</tr>
<tr>
<td>380–500</td>
<td>2.44–2.55</td>
<td>2155–2250</td>
<td>0.70–0.64</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt;500</td>
<td>2.55</td>
<td>2250</td>
<td>0.64</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.3.3. Sound speed profile

The sound speed profiles for the modelled sites were obtained from the US Naval Oceanographic Office’s Generalized Digital Environmental Model (GDEM) database (Teague et al. 1990). The current release of the GDEM database (version 3.0) provides average monthly profiles of temperature and salinity for the world’s oceans on a latitude-longitude grid with 0.25° resolution, based on global historical observations from the US Navy’s Master Oceanographic Observation Data Set (MOODS). The profiles include 78 fixed depth points up to a maximum depth of 6800 m (where the ocean is that deep), including 55 standard depths between 0 and 2000 m. The GDEM temperature-salinity profiles were converted to sound speed profiles according to the equations of Coppens (1981):

...
where $z$ is water depth (m), $T$ is water temperature ($^\circ$C), $S$ is salinity (psu), and $\phi$ is latitude (radians). Since shallow coring operations are expected to start at the southern sites in August and carry on until October, sound speed profiles used for sound propagation modelling are based on GDEM data for August at Sites 2 and 3, and October at Site 1. The structure is similar for all profiles: high speed at the surface, followed by a minimum at about 50 m below the sea surface and a gradual increase with depth.

Figure 8. Estimated sound speed profiles from GDEM data at each site.
3.4. Geometry and Modelled Volumes

The sound fields from single seismic shots and for continuous sound from the vessel in DP mode were modelled over two areas at different resolutions. The first area was $5 \times 5$ km centred on the source, with a horizontal separation of 5 m between receiver points along the modelled radials. The second area was $100 \times 100$ km centred on the source, with a horizontal separation of 20 m between receiver points. In both cases, sound fields were modelled with a horizontal angular resolution of $\Delta \theta = 2.5^\circ$, for a total of $N = 144$ radial planes. Sound fields extending beyond the regional scale were modelled with a horizontal separation of 25 m between receiver points.

The receiver depths span the entire water column over the modelled areas, from 1 to 3000 m, with step sizes that increase with depth. For all sites, the vertical step size increased from 1.5 to 500 m, with increasing depth. To estimate the cumulative sound fields, the single-shot sound fields were extrapolated over a $450 \times 450$ km area (as described in Section 2.5), with a horizontal separation of 500 m between receiver points.
4. Results

4.1. Source Levels and Directivity

4.1.1. Vertical Seismic Profile airgun array

The pressure signatures of the individual airguns and the composite 1/3-octave band source levels of the array, as functions of azimuthal angle, were computed with AASM as described in Section 2.1. These source levels and signatures respectively acted as the acoustic source for the MONM and FWRAM (used to estimate the SEL to rms SPL conversion factors) sound propagation models. While the effect of source depth on bubble interactions is accounted for in the AASM source model, the surface-reflected signal (i.e., surface ghost) is not included in the far-field source signatures. The surface reflections, a property of the medium rather than the source, are accounted for by the acoustic propagation models.

The overpressure signatures and corresponding power spectrum levels for the JOIDES Resolution VSP array (500 in³) at 7 m depth are shown in Figure 9 for the broadside (perpendicular to the tow direction) and endfire (parallel to the tow direction) directions. The signatures consist of a strong primary peak related to the initial firing of the airguns, followed by a series of pulses associated with bubble oscillations. Most of the energy is produced at frequencies below 200 Hz (see Figure 9b). The spectrum contains peaks and nulls resulting from interference among airguns in the array, where the frequencies at which they occur depend on the volumes of the airguns and their locations within the array. The maximum (horizontal) 1/3-octave band sound levels over all directions are plotted in Figure 10. The horizontal 1/3-octave band directivities are shown in Figure 11.

![Figure 9](image-url)

Figure 9. Predicted (a) overpressure signature and (b) power spectrum for the VSP array (500 in³) in the broadside and endfire (horizontal) directions. Surface ghosts (effects of the pulse reflection at the water surface) are not included in these signatures, as they are accounted for by the MONM propagation model.
Table 8. Source level specifications (10 Hz to 2 kHz) for the VSP array at 7.0 m tow depth computed with AASM in the broadside and endfire directions. Surface ghost effects are not included, as they are accounted for by the MONM propagation model.

<table>
<thead>
<tr>
<th>Tow depth (m)</th>
<th>Direction</th>
<th>Zero-to-peak SPL (dB re 1 µPa @ 1 m)</th>
<th>SEL (dB re 1 µPa² @ 1 m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>10 Hz to 2 kHz</td>
<td>10 Hz to 1 kHz</td>
</tr>
<tr>
<td>7.0</td>
<td>Broadside</td>
<td>238.1</td>
<td>218.6</td>
</tr>
<tr>
<td></td>
<td>Endfire</td>
<td>237.8</td>
<td>218.6</td>
</tr>
</tbody>
</table>

Figure 10. Maximum directional source level (SL) in each 1/3-octave band for the VSP array, at 7 m tow depth.
Figure 11. VSP array: Directionality of predicted source levels (SLs, dB re 1 µPa²·s) in 1/3-octave bands. Third-octave band centre frequencies are indicated above each plot.
4.1.2. Vessel in Dynamic Positioning mode

The omnidirectional SLs for the JOIDES Resolution in DP mode were estimated based on Equation (7), resulting in an increase of 7.6 dB from the calculated SL for the reference vessel, DSV Fu Lai. The estimated 1/3-octave band spectrum is presented in Figure 12.

![Figure 12. Estimated source levels in each 1/3-octave band for the M/V JOIDES Resolution in dynamic positioning (DP) mode.](image)

4.2. Single-Shot Sound Fields—Vertical Seismic Profile array

The tow direction of the VSP array was set to 0°, i.e., UTM north. Because of the directivity in the array source levels, this tow direction is expected to estimate cautionary distances to threshold levels. The tow depth at all other sites was 7.0 m.

The underwater sound fields predicted by the propagation model were sampled such that the received sound level at each point in the horizontal plane was taken to be the maximum value over all modelled depths for that point (see Section 2.2). The resultant “maximum-over-depth” sound fields for each site are presented below.

The predicted distances to specific SEL and rms SPL thresholds were computed from the maximum-over-depth sound fields. Two distances, relative to the source, are reported for each sound level: (1) \( R_{\text{max}} \), the maximum range at which the given sound level was encountered in the modelled sound field; and (2) \( R_{95\%} \), the maximum range at which the given sound level was encountered after exclusion of the 5% farthest such points. This definition is meaningful in terms of impact on marine mammals, because, regardless of the noise footprint’s geometric shape for a given sound level threshold, \( R_{95\%} \) is the predicted range beyond which no more than 5% of a uniformly distributed population would be exposed to sound at or above that level.

The model results are presented as tables of \( R_{\text{max}} \) and \( R_{95\%} \) to specified maximum-over-depth SEL, and rms SPL thresholds and as contour maps of the sound field that show the directivity in sound propagation. While \( R_{\text{max}} \) and \( R_{95\%} \) are highly relevant, they may vary slightly, depending on the orientation of the source array and its location within the modelled area. By considering the distances to the sound level thresholds in combination with the maps of the propagated sound field, one can better predict the variations that occur in realistic scenarios. The modelled area was limited to 100 × 100 km, centred on the source. This area is not large
enough to predict the full extent of the ≤ 130 dB re 1 µPa²·s thresholds. Consequently, some contour lines on the maps are cut-off at the 100 km limit.

Distances to peak SPL thresholds were calculated using FWRAM along two transects (see Section 2.4). These results are presented as tables of radii to specific maximum-over-depth zero-to-peak and peak-to-peak SPL thresholds, and as contour maps. Since only two transects were modelled, the maps present circular (omnidirectional) thresholds based on the estimated peak-to-peak radii.

Table 9. Distances to SEL thresholds at each site: Maximum ($R_{\text{max}}$, m) and 95% ($R_{95\%}$, m) horizontal distances from the source to modelled maximum-over-depth sound level thresholds (10 Hz to 2 kHz).

<table>
<thead>
<tr>
<th>SEL (dB re 1 µPa²·s)</th>
<th>Site 1</th>
<th>Site 2</th>
<th>Site 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$R_{\text{max}}$</td>
<td>$R_{95%}$</td>
<td>$R_{\text{max}}$</td>
</tr>
<tr>
<td>200</td>
<td>18</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>190</td>
<td>22</td>
<td>22</td>
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<tr>
<td>180</td>
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<td>67</td>
</tr>
<tr>
<td>170</td>
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</tr>
<tr>
<td>160</td>
<td>705</td>
<td>678</td>
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<tr>
<td>150</td>
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<td>2 725</td>
<td>3 895</td>
</tr>
<tr>
<td>140</td>
<td>16 174</td>
<td>10 900</td>
<td>19 548</td>
</tr>
<tr>
<td>130</td>
<td>87 296</td>
<td>48 915</td>
<td>90 820</td>
</tr>
<tr>
<td>120</td>
<td>&gt; 100 000</td>
<td>&gt; 100 000</td>
<td>&gt; 100 000</td>
</tr>
</tbody>
</table>

Table 10. Distances to M-weighted SEL thresholds at each site: Maximum ($R_{\text{max}}$, m) and 95% ($R_{95\%}$, m) horizontal distances from the source to modelled maximum-over-depth sound level thresholds (10 Hz to 2 kHz).

<table>
<thead>
<tr>
<th>SEL (dB re 1 µPa²·s)</th>
<th>Site 1</th>
<th>Site 2</th>
<th>Site 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$R_{\text{max}}$</td>
<td>$R_{95%}$</td>
<td>$R_{\text{max}}$</td>
</tr>
<tr>
<td>198 M_{LFC}</td>
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<td>18</td>
<td>18</td>
</tr>
<tr>
<td>198 M_{MFC}</td>
<td>&lt; 14</td>
<td>&lt; 14</td>
<td>&lt; 14</td>
</tr>
<tr>
<td>198 M_{HFC}</td>
<td>&lt; 14</td>
<td>&lt; 14</td>
<td>&lt; 14</td>
</tr>
<tr>
<td>186 M_{Pw}</td>
<td>18</td>
<td>18</td>
<td>18</td>
</tr>
</tbody>
</table>
Table 11. Distances to rms SPL thresholds at each site: Maximum ($R_{max}$, m) and 95% ($R_{95\%}$, m) horizontal distances from the source to modelled maximum-over-depth sound level thresholds (10 Hz to 2 kHz).

<table>
<thead>
<tr>
<th>rms SPL (dB re 1 µPa)</th>
<th>Site 1</th>
<th>Site 2</th>
<th>Site 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$R_{max}$</td>
<td>$R_{95%}$</td>
<td>$R_{max}$</td>
</tr>
<tr>
<td>200</td>
<td>18</td>
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<tr>
<td>190</td>
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<td>2 351</td>
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</tr>
<tr>
<td>140</td>
<td>36 876</td>
<td>23 436</td>
<td>69 299</td>
</tr>
<tr>
<td>130</td>
<td>87 296</td>
<td>62 367</td>
<td>&gt; 100 000</td>
</tr>
<tr>
<td>120</td>
<td>&gt; 100 000</td>
<td>&gt; 100 000</td>
<td>&gt; 100 000</td>
</tr>
</tbody>
</table>

Table 12. Distances to zero-to-peak and peak-to-peak SPL thresholds at each site: Maximum ($R_{max}$, m) horizontal distances from the source to modelled maximum-over-depth sound level thresholds (10 Hz to 2 kHz).

<table>
<thead>
<tr>
<th>SPL (dB re 1 µPa)</th>
<th>Site 1</th>
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<th>Site 3</th>
</tr>
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<tr>
<td></td>
<td>0-pk</td>
<td>Pk-pk</td>
<td>0-pk</td>
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<td>230</td>
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</tr>
<tr>
<td>218</td>
<td>&lt; 10</td>
<td>60</td>
<td>&lt; 10</td>
</tr>
<tr>
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<td>120</td>
<td>200</td>
<td>120</td>
</tr>
<tr>
<td>200</td>
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<td>360</td>
</tr>
<tr>
<td>190</td>
<td>1080</td>
<td>1900</td>
<td>1180</td>
</tr>
</tbody>
</table>

Table 13. Distances to SEL thresholds at Site 1: Horizontal distances (m) from the VSP array (7.0 m depth) to modelled maximum-over-depth SEL thresholds, with and without M-weighting applied.

<table>
<thead>
<tr>
<th>SEL (dB re 1 µPa$^2$·s)</th>
<th>Un-weighted</th>
<th>LFC</th>
<th>MFC</th>
<th>HFC</th>
<th>Pinnipeds</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{max}$</td>
<td>$R_{95%}$</td>
<td>$R_{max}$</td>
<td>$R_{95%}$</td>
<td>$R_{max}$</td>
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<td>&lt; 15</td>
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<tr>
<td>180</td>
<td>67</td>
<td>65</td>
<td>63</td>
<td>61</td>
<td>22</td>
</tr>
<tr>
<td>170</td>
<td>207</td>
<td>199</td>
<td>197</td>
<td>190</td>
<td>73</td>
</tr>
<tr>
<td>160</td>
<td>705</td>
<td>678</td>
<td>689</td>
<td>659</td>
<td>233</td>
</tr>
<tr>
<td>150</td>
<td>3 357</td>
<td>2 725</td>
<td>3 116</td>
<td>2 677</td>
<td>786</td>
</tr>
<tr>
<td>140</td>
<td>16 174</td>
<td>10 900</td>
<td>14 983</td>
<td>10 468</td>
<td>7 060</td>
</tr>
<tr>
<td>130</td>
<td>87 296</td>
<td>48 915</td>
<td>87 296</td>
<td>48 070</td>
<td>43 172</td>
</tr>
<tr>
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<td>&gt; 100 000</td>
<td>&gt; 100 000</td>
<td>&gt; 100 000</td>
<td>&gt; 100 000</td>
</tr>
</tbody>
</table>

Version 3.0
Table 14. Distances to SEL thresholds at Site 2: Horizontal distances (m) from the VSP array (7.0 m depth) to modelled maximum-over-depth SEL thresholds, with and without M-weighting applied.

<table>
<thead>
<tr>
<th>SEL (dB re 1 µPa²·s)</th>
<th>Un-weighted</th>
<th>LFC</th>
<th>MFC</th>
<th>HFC</th>
<th>Pinnipeds</th>
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<tr>
<td></td>
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<td>$R_{95%}$</td>
<td>$R_{\text{max}}$</td>
<td>$R_{95%}$</td>
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<td>18</td>
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</tr>
<tr>
<td>190</td>
<td>21</td>
<td>21</td>
<td>20</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>180</td>
<td>67</td>
<td>65</td>
<td>64</td>
<td>62</td>
<td>22</td>
</tr>
<tr>
<td>170</td>
<td>256</td>
<td>243</td>
<td>244</td>
<td>230</td>
<td>73</td>
</tr>
<tr>
<td>160</td>
<td>928</td>
<td>834</td>
<td>923</td>
<td>829</td>
<td>244</td>
</tr>
<tr>
<td>150</td>
<td>3 895</td>
<td>3 140</td>
<td>3 843</td>
<td>3 066</td>
<td>1 385</td>
</tr>
<tr>
<td>140</td>
<td>19 548</td>
<td>11 428</td>
<td>19 548</td>
<td>11 356</td>
<td>6 592</td>
</tr>
<tr>
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<td>90 820</td>
<td>59 153</td>
<td>90 820</td>
<td>58 768</td>
<td>70 226</td>
</tr>
<tr>
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<td>&gt; 100 000</td>
<td>&gt; 100 000</td>
<td>&gt; 100 000</td>
<td>&gt; 100 000</td>
<td>&gt; 100 000</td>
</tr>
</tbody>
</table>

Table 15. Distances to SEL thresholds at Site 3: Horizontal distances (m) from the VSP array (7.0 m depth) to modelled maximum-over-depth SEL thresholds, with and without M-weighting applied.

<table>
<thead>
<tr>
<th>SEL (dB re 1 µPa²·s)</th>
<th>Un-weighted</th>
<th>LFC</th>
<th>MFC</th>
<th>HFC</th>
<th>Pinnipeds</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$R_{\text{max}}$</td>
<td>$R_{95%}$</td>
<td>$R_{\text{max}}$</td>
<td>$R_{95%}$</td>
<td>$R_{\text{max}}$</td>
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<tr>
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<td>18</td>
<td>18</td>
<td>&lt; 15</td>
</tr>
<tr>
<td>190</td>
<td>21</td>
<td>21</td>
<td>20</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>180</td>
<td>67</td>
<td>65</td>
<td>64</td>
<td>61</td>
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<td>943</td>
<td>1 004</td>
<td>928</td>
<td>242</td>
</tr>
<tr>
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<td>4 313</td>
<td>3 041</td>
<td>4 282</td>
<td>3 006</td>
<td>1 462</td>
</tr>
<tr>
<td>140</td>
<td>16 800</td>
<td>11 086</td>
<td>16 800</td>
<td>10 956</td>
<td>8 200</td>
</tr>
<tr>
<td>130</td>
<td>93 894</td>
<td>51 082</td>
<td>93 894</td>
<td>49 428</td>
<td>30 382</td>
</tr>
<tr>
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<td>&gt; 100 000</td>
<td>&gt; 100 000</td>
<td>&gt; 100 000</td>
<td>&gt; 100 000</td>
<td>&gt; 100 000</td>
</tr>
</tbody>
</table>
Figure 13. Sound exposure levels (SELS) at Site 1: Received maximum-over-depth sound levels from the VSP array for a single shot. Blue contours indicate water depth (m).
Figure 14. rms sound pressure levels (SPLs) at Site 1: Received maximum-over-depth sound levels from the VSP array for a single shot. Blue contours indicate water depth (m).
Figure 15. Peak-to-peak sound pressure levels (SPLs) at Site 1: Received maximum-over-depth sound levels from the VSP array for a single shot. Blue contours indicate water depth (m).
Figure 16. Sound exposure levels (SELs) at Site 2: Received maximum-over-depth sound levels from the VSP array for a single shot. Blue contours indicate water depth (m).
Figure 17. rms sound pressure levels (rms SPLs) at Site 2: Received maximum-over-depth sound levels from the VSP array for a single shot. Blue contours indicate water depth (m).
Figure 18. Peak-to-peak sound pressure levels (SPLs) at Site 2: Received maximum-over-depth sound levels from the VSP array for a single shot. Blue contours indicate water depth (m).
Figure 19. Sound exposure levels (SELs) at Site 3: Received maximum-over-depth sound levels from the VSP array for a single shot. Blue contours indicate water depth (m).
Figure 20. rms sound pressure level (rms SPLs) at Site 3: Received maximum-over-depth sound levels from the VSP array for a single shot. Blue contours indicate water depth (m).
Figure 21. Peak-to-peak sound pressure levels (SPLs) at Site 3: Received maximum-over-depth sound levels from the VSP array for a single shot. Blue contours indicate water depth (m).
4.3. Sound Fields from Vessel in Dynamic Positioning mode

The model results are presented as tables of distances to specified maximum-over-depth rms SPL thresholds, as well as contour maps of the sound field illustrating the directivity in sound propagation.

Table 16. rms SPL: Maximum ($R_{\text{max}}$, m) and 95% ($R_{95\%}$, m) horizontal distances from the source to modelled maximum-over-depth sound level thresholds (10 Hz to 2 kHz).
Figure 22. Site 1: Maximum-over-depth rms sound pressure levels around the M/V JOIDES Resolution in dynamic positioning mode.
Figure 23. Site 2: Maximum-over-depth rms sound pressure levels around the M/V *JOIDES Resolution* in dynamic positioning mode.
Figure 24. Site 3: Maximum-over-depth rms sound pressure levels around the M/V JOIDES Resolution in dynamic positioning mode.
4.4. Cumulative Sound Fields—Vertical Seismic Profile array

The sound field for each VSP shot at Site 2 was summed over 10 shots to produce the 24 h cSEL field. The model results are presented as tables of distances to specified maximum-over-depth cSEL and contour maps, with and without M-weighting applied. Sounds from the vessel in DP mode were not included in this analysis because they are significantly less than those of the VSP array.

Table 17. Site 2: Horizontal distances (m) from the VSP array (7.0 m depth) to modelled maximum-over-depth cSEL thresholds, with and without M-weighting applied.

<table>
<thead>
<tr>
<th>cSEL (dB re 1 µPa²·s)</th>
<th>Un-weighted</th>
<th>LFC</th>
<th>MFC</th>
<th>HFC</th>
<th>Pinnipeds</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R_max</td>
<td>R_95%</td>
<td>R_max</td>
<td>R_95%</td>
<td>R_max</td>
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<tr>
<td>150</td>
<td>19 548</td>
<td>11 428</td>
<td>19 548</td>
<td>11 356</td>
<td>6 592</td>
</tr>
<tr>
<td>140</td>
<td>90 820</td>
<td>59 149</td>
<td>90 820</td>
<td>58 763</td>
<td>70 226</td>
</tr>
<tr>
<td>130</td>
<td>322 131</td>
<td>254 239</td>
<td>321 955</td>
<td>248 774</td>
<td>109 907</td>
</tr>
<tr>
<td>120</td>
<td>&gt; 500 000</td>
<td>&gt; 500 000</td>
<td>332 243</td>
<td>301 969</td>
<td>330 453</td>
</tr>
</tbody>
</table>
Figure 25. Un-weighted cumulative sound exposure levels (cSELs): Received maximum-over-depth cumulative sound levels from 24 h of seismic survey operations with the VSP array (500 in³).
Figure 26. Low-frequency-cetacean-weighted cumulative sound exposure levels (cSELs): Received maximum-over-depth cumulative sound levels from 24 h of seismic survey operations with the VSP array (500 in³).
Figure 27. Mid-frequency-cetacean-weighted cumulative sound exposure levels (cSELs): Received maximum-over-depth cumulative sound levels from 24 h of seismic survey operations with the VSP array (500 in³).
Figure 28. High-frequency-cetacean-weighted cumulative sound exposure levels (cSELs): Received maximum-over-depth cumulative sound levels from 24 h of seismic survey operations with the VSP array (500 in3).
Figure 29. Pinniped-weighted cumulative sound exposure levels (cSELs): Received maximum-over-depth cumulative sound levels from 24 h of seismic survey operations with the VSP array (500 in3).

**Description:** Estimated maximum-over-depth cumulative sound exposure levels (cSEL) for 10 shots from the VSP array at Site 2. Pinnipeds (in water) M-weighting applied.

**Project:** Shell 2012 Shallow Coring Operation in Baffin Bay.

**Projection:** UTM Zone 21  
**Datum:** WGS 1984
4.5. Aggregate Sound Exposure

The modelled cSELs from each seismic operation were combined into aggregate maps presenting the cSEL footprint for all simultaneous operations. Results are presented as aggregate maps of cSEL and M-weighted cSEL in Figures 30–34.

Figure 30. Aggregate un-weighted cumulative sound exposure levels (cSELs): Received maximum-over-depth cSELs from 24 h of seismic operations with five airgun arrays.
Figure 31. Aggregate low-frequency-cetacean-weighted cumulative sound exposure levels (cSELs): Received maximum-over-depth cSELs from 24 h of seismic operations with five airgun arrays.
Figure 32. Aggregate mid-frequency-cetacean-weighted cumulative sound exposure levels (cSELs): Received maximum-over-depth cSELs from 24 h of seismic operations with five airgun arrays.
Figure 33. Aggregate high-frequency-cetacean-weighted cumulative sound exposure levels (cSELs): Received maximum-over-depth cSELs from 24 h of seismic operations with five airgun arrays.
Figure 34. Aggregate pinniped-weighted cumulative sound exposure levels (cSELs): Received maximum-over-depth cSELs from 24 h of seismic operations with five airgun arrays.
4.6. Sound Propagation beyond the Regional Scale

Since the shots of the separate seismic surveys are not synchronized in time, and the sources are widely spaced geographically, it is unlikely that multiple pulses would arrive simultaneously at any receiver location. Therefore the arrivals of these pulses have not been considered cumulatively. Instead, received rms SPLs over a 1 s pulse length for each source are compared in Table 18.

At large ranges from the source, the received pulse lengths may exceed 1 s, due to propagation effects. To provide cautionary estimates of received rms SPLs, a 1 s pulse length was assumed, in which case SEL and rms SPL are equivalent. Therefore, rms SPL values could be as much as 5 dB lower than shown in Table 18.

Table 18. Single-pulse rms SPL (dB re 1 μPa) received from each seismic source at the receivers (see Figure 7).

<table>
<thead>
<tr>
<th>Receiver</th>
<th>Source S1</th>
<th>Source S2</th>
<th>Source S3</th>
<th>Source S4</th>
<th>Source S5</th>
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<td>R1</td>
<td>120.9</td>
<td>126.7</td>
<td>127.2</td>
<td>127.1</td>
<td>122.4</td>
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<tr>
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<td>121.1</td>
<td>122.8</td>
<td>123.7</td>
<td>117.2</td>
</tr>
<tr>
<td>R3</td>
<td>125.2</td>
<td>122.2</td>
<td>128.1</td>
<td>123.0</td>
<td>115.4</td>
</tr>
<tr>
<td>R4</td>
<td>116.9</td>
<td>111.8</td>
<td>116.5</td>
<td>119.8</td>
<td>106.8</td>
</tr>
</tbody>
</table>

Figure 35 shows sound levels as a function of range and depth along the four transects, for the Shell VSP array. Levels are given in SEL (dB re 1 μPa^2·s), so are equal to or greater than rms SPL.
Figure 35. Source S5, Shell’s VSP array: Sound exposure levels (SELs, dB re 1 μPa²s) as a function of range and depth from the VSP array (500 in³) at each receiver. The SEL values are likely greater than the rms SPL values.
Literature Cited


MacGillivray, A. O. 2006a. *Acoustic Modelling Study of Seismic Airgun Noise in Queen Charlotte Basin*, University of Victoria, Victoria, BC.


