Report of the Sound Propagation and Cumulative Exposure Models Technical Working Group

Part of the 2015–2016 Seismic Code of Conduct Review process

New Zealand Government

Department of Conservation
Te Papa Atawhai

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Cover photo: Humpback whale breaching. *Photo: © Blue Planet Marine*

Contents

Preface: background to the Technical Working Group

The review of the Code

In 2012, the Department of Conservation (DOC) developed a voluntary Code of Conduct for Minimising Acoustic Disturbance to Marine Mammals from Seismic Survey Operations ('the Code'), in consultation with international and domestic stakeholders representing industry, operators, observers and marine scientists. The Code (and its supporting reference document) aims to provide effective, practical measures to minimise the acoustic disturbance of marine mammals during seismic surveys. It was updated in 2013 after being incorporated by reference into the Exclusive Economic Zone and Continental Shelf (Environment Effects – Permitted Activities) Regulations 2013 ('the EEZ Regulations'; see SR2013/283).

At the time the 2012 Code was implemented, DOC committed to the Code being reviewed after three years. Accordingly, the review of the 2013 Code began in July 2015, with a request for feedback from numerous stakeholders (the Seismic Code Review Group; SCRG). In August 2015, this feedback was combined with that obtained during the three years since implementation.

Role of the Technical Working Groups

In August 2015, DOC established nine technical working groups (TWGs) to address the technical issues raised in the feedback and to provide expert advice on the most suitable methods for addressing them. It was intended that DOC would then draw on this advice when redrafting the Code. The TWGs were:

1. Marine Mammal Observer/Passive Acoustic Monitoring Requirements
2. Marine Mammal Observer/Passive Acoustic Monitoring Observer Data
3. Marine Mammal Impact Assessments/Marine Mammal Mitigation Plans
4. Consultation Requirements for Operators
5. Sound Propagation and Cumulative Exposure Models
6. Acoustic Ground-truthing
7. Non-Standard Surveys
8. Non-Commercial Surveys
9. Biologically Relevant Sound Levels

The work of these TWGs was supplemented by two workshops that were co-hosted by DOC in association with scientific conferences in 2015, to discuss the appropriate mechanisms to facilitate the integration of methodological and technological advances into the revised Code.

The nine TWGs worked until January 2016 to provide feedback on the issues assigned to them. This is the report of the fifth TWG: Sound Propagation and Cumulative Exposure Models.

Scope of work for the Sound Propagation and Cumulative Exposure Models TWG

A certain amount of feedback on the 2012/2013 Code concerned sound transmission loss modelling – specifically, an acceptable methodology for undertaking such modelling and the application of the results to the mitigation zones outlined in the Code. This TWG was asked to consider the various software solutions for sound profile modelling, the potential need to incorporate oceanographic features that may influence propagation in addition to bathymetric features, and (more generally) the most appropriate methodologies (including model components and considerations and use of weighting, if any) and level of resolution required.

This TWG also discussed the:

- Relative merits and difficulties of modelling levels in sound pressure levels (SPL; both peak and root-mean-square, or rms) and sound exposure level (SEL)
- Potential for multi-project acoustic modelling (as currently undertaken in a rudimentary form by companies seeking permits to operate in Greenland waters)
- Merits of integrating non-seismic sources into acoustic models, given the possible role of multibeam sonar in the 2008 Madagascar melon-headed whale strandings

The output of this TWG will be combined with that of the Acoustic Ground-Truthing TWG to advise DOC and the steering group on Code elements pertaining to impact assessment requirements, field verification and reporting requirements. Advice will be delivered as a report containing two or more options (where appropriate) for addressing the specific issues raised in this subject area in the Revised Code.

Specific issues raised to date have indicated the need for the following tasks:

1) Regarding the merit of sound propagation modelling, provide an opinion on:
    a) Whether experience to date suggests it is necessary to undertake modelling for every survey
    b) How models and ground-truthing (G-T) could be published, if that is considered useful.
2) Considering other recent guidelines and noise exposure criteria proposed internationally (eg in Germany, Greenland, USA and Denmark), establish options for formal guidelines for sound transmission loss modelling in terms of:
    a) Acceptable methodology
    b) Application of results to mitigation zones
    c) The size of area to be included in the models
    d) The unit(s) to be modelled (eg cumulative sound exposure level, peak pressures or some other option)

    e) The need and options for multi-source modelling for any given project
    f) The potential for cross-project exposure modelling
    g) The extent to which topographic, bathymetric and other oceanographic features should be incorporated

3) Outline the applicability of the methodology and other factors above to non-seismic sources such as multibeam sonar, as well as detailing changes needed to expand that methodology to other such sources.
4) The potential for propagation models to assist in early planning stages, regarding siting surveys in ways to potentially reduce exposure of marine mammals
5) The potential for models to include any acoustically-active mitigation efforts, such as soft starts and acoustic alarms

Part 1: Introduction and modelling fundamentals

1. This report offers advice for addressing known Code issues related to sound propagation modelling

This report presents options for ways to address specific sound propagation modelling issues through revisions to the Code. It also provides background information and advice to DOC staff on sound propagation modelling in general: whether is it necessary to undertake modelling for every survey; how models and ground-truthing could be usefully published; and how to incorporate a) different bathymetry, and b) transference between bathymetric environments.

1.1. Part 1: fundamentals of sound source and transmission modelling

Part 1 provides an opinion on useful and practical methodologies for sound source and transmission-loss modelling as necessary to meets the needs of regulatory bodies. Elements would be included in the revised Code as formal guidelines for:

- The unit(s) to be modelled: these include the cumulative sound exposure level, sound exposure level calculation time-window, peak pressures, or some other option
- Inputs
- Acoustic propagation models
- Reverberation
- Accuracy quantification
- Relevance to mitigation
- Animal exposure assessment
- Single shot and accumulated single-survey sound fields

Additionally, opinion is provided for handling multi-source modelling for a given project, focussing on:

- Combining single seismic sources and non-seismic sources
- Regional cumulative assessment

1.2. Part 2: modelling and wider management

Part 2 outlines how modelling can be incorporated into wider survey planning. Topics covered are:

- The potential for propagation models to assist in early planning stages, such as siting surveys in ways to reduce the impact on marine mammals
- Relevance of the modelling to sensitive or protected areas
- Survey classification bands

1.3. Part 3: general guidelines for in-field verification

Part 3 of this report covers some technical aspects of field verification of acoustic models, from the perspective of providing needed feedback from such G-T to modellers. The specific topics are:

- The importance of realistic parameters defining the sound propagation environment
- The quality of a G-T study
- The metrics and receiver locations that should be used
- inter-pulse reverberation and data collection

1.4. Part 4: modelling of non-standard sources

Part 4 addresses the extent to which the established methodologies and approaches above can be applied to non-typical sources, and thus the possibility that non-typical sources could be incorporated into the Code. Case studies were used to achieve this – the viability of modelling several specific non-typical source types was discussed. These source types are:

- Fixed-location surveys (such as vertical seismic profiling)
- Boomers, chirpers and sparkers
- Vibroseis
- Multibeam sonars
- Active acoustic mitigation techniques (such as a soft start)

1.5. General guidance on models used in underwater acoustics

At DOC's request, an introduction and explanation of source and transmission loss models for underwater acoustic modelling is found in **Appendix 2**.

1.6. What the Code applies to

The Code currently applies (through regulation) throughout the EEZ, and is voluntary elsewhere in New Zealand waters. In practice this means that, with few exceptions, all seismic surveys must adhere to the Code if they are to be allowed to operate in the EEZ.

2. Requirements for modelling

Acoustic modelling is conducted to determine the 'footprint' of acoustic sources used in seismic exploration. It is not done simply for its own sake: acoustic modelling increases our understanding of a specific source's acoustic footprint in any given bathymetric environment with unique environmental parameters – such as sound speed profile and geology.

Every individual acoustic footprint is unique due to differences in:

- Source array total operational volume, configuration, operating pressure
- Array tow depth
- Bathymetry
- Substrate
- Sound profile, which depends upon temperature and salinity profiles that may vary between seasons

These variables make it difficult to maintain the current breakdown of survey category by total array volume. Evaluations of surveys involving multiple sources, or proximate concurrent surveys, may require the assessment of both individual and cumulative footprints.

Modelling will need to consider the evolution of seismic sources from airguns to vibroseis and beyond. While the current Code is mainly concerned with high-level sounds, and thus the sound footprint close to the sound source, lower levels that result in behavioural effects may also be important. Potential effects could occur at relatively large distances. The Biological Relevant Sound Levels TWG (Bio Rel TWG) will decide which sound levels are relevant.[1]

2.1. Unit(s) to be modelled

This TWG deferred to the Bio Rel TWG for a decision on the metrics relevant for modelling. However, members noted it would be important to document metrics that are currently applied in modelling assessments, to ensure best practices can be incorporated.

2.1.1. Metrics used under the current Code

All modelling assessments under the code currently require only consideration of single shot SELs of 171 or 186 dB re 1 µPa2.s. These SEL criteria are specified by Southall et al. (2007) for onset of temporary threshold shift (TTS) and permanent threshold shift (PTS) in pinnipeds respectively, for single and multiple shots. The current code does not clarify that when multiple shots are present, multiple shot SELs should be computed to evaluate against these criteria.

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[1] The Bio Rel TWG's work is further detailed in a later report in this series.

2.1.2. Recommended assessment metrics and methods

2.1.2.1. Sound Exposure Level

The SEL metric is an index for accumulated sound energy, and enables the integration of sound energy across multiple sound exposures. The period over which the SEL is accumulated must be specified.

The accumulative exposures are calculated from multiple events over longer time periods than a single shot. The length of this accumulation window needs to be defined. It is recommended that it be:

- A standard period (eg 24 hours)
- The duration of activity (eg a seismic line or the total length of a survey – as recommended in Southall et al. (2007) and Popper et al. (2014)); or
- The total period that any animals will be exposed

The exposure could also be calculated using animat models[2] based on the times that animats receive significant exposures without a recovery period.

A simplistic but often reasonable way to calculate seismic survey exposures is to assume an animal is stationary while the seismic vessel passes. This approach is valid, mainly because most of the exposure accumulates when the animal is closest to the airgun array. With this assumption, the distance from the survey line at which a threshold is reached over a 24-hour period could define the exclusion zone. The resulting summed sound field can therefore be interpreted as the total sound energy an animal would experience at a given range and depth from the survey line, if it did not move as the source travelled past. This is not a conservative estimate (as it doesn't account for the animal moving in the same direction as the survey vessel) but could be considered a reasonable approximation.

Whether an animal is exposed to a full period of sound activity depends on its behaviour, including whether it stays in the vicinity of the sound or moves away. Movement of the source itself also has an effect.

Complete characterisation of SEL is required to understand the biological relevance of the sound. This includes not only the number of sound events, but also the:

- Period over which the summation is performed
- Distribution of sound events within that period
- Changes in the magnitude of the individual sound events

As DOC currently prefers to avoid detailed animat modelling, for simplicity we recommend the period be set at 24 hr or the duration of the activity (Southall et al. 2007, Popper et al. 2014). This is addressed further in **Appendix 2**.

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[2] Animat models are those that deploy 'virtual' animals into a modelled environment containing predicted sound exposure distributions.

Further suggestions when reporting

We suggest the following be included:

1. Single-shot modelling sites:

- Distance to isopleths (210–120 dB SEL in 10 dB increments, unweighted/weighted (as appropriate) – reported as maximum and 95% radius.
- If requiring assessment of a particular single shot – as done in Australia with the 160 dB SEL single shot threshold – provide the maximum and 95% horizontal distances

2. Exposure over activity-duration scenarios (excluding animat methodology):

- Ensonified areas within isopleths – unweighted and weighted (if weighting applied) – reported in km^2. The isopleths considered should include PTS thresholds at a minimum. It may help to report the distances to other isopleths, such as temporary TTS thresholds, in an Appendix. This is because TTS is not typically used for any regulatory assessment, and it is not usually possible to mitigate the impact of TTS during an ongoing survey.
- If requiring assessment of a specific level for exclusion-zone determination purposes (for example a weighted, or unweighted, PTS level), provide the maximum perpendicular distance from the source to the isopleth. This will determine the 'exclusion zone' for PTS impacts. This is the closest point of approach an animal can achieve over the length of the scenario without sustaining PTS.

These should be calculated as 'maximum-over-depth', as this is typically the most conservative assessment. For site-specific fish species that only inhabit the seafloor, it might be more appropriate to report sea-floor levels.

2.1.2.2. RMS Sound Pressure Level

Sound Pressure Level (SPL) is the decibel ratio of the time-mean-square sound pressure, in a stated frequency band, to the square of the reference sound pressure (ANSI S1.1-1994 R2004). Unless otherwise stated, SPL refers to the root-mean-square sound pressure level (rms SPL).

The root-mean-square (rms) SPL (dB re 1 µPa) is the rms pressure level in a stated frequency band over a time window (*T*, s) containing the acoustic event:

$$\text{rms SPL} = 10\log_{10}\left(\frac{1}{T}\int_T p^2(t)dt \Big/ p_0^2\right) \tag{1}$$

The rms SPL is a measure of the average pressure or the effective pressure over the duration of an acoustic event, such as the emission of one acoustic pulse or sweep. Because the window length, *T*, is the divisor, events more spread out in time have a lower rms SPL for the same total acoustic energy density.

In studies of impulsive noise, *T* is often defined as the '90% energy pulse duration' (T_{90}): the interval over which the pulse energy curve rises from 5% to 95% of the total energy. The SPL computed over this T_{90} interval is commonly called the 90% rms SPL (dB re 1 µPa):

$$90\%\ \text{rms SPL} = 10\log_{10}\left(\frac{1}{T_{90}}\int_{T_{90}} p^2(t)dt \Big/ p_0^2\right) \tag{2}$$

Characterisation of rms SPL can be problematic for impulsive sources such as airguns, because the results depend heavily on the integration time chosen. The 90% rms SPL, while commonly used, is difficult to apply in many cases.[3]

It is recommended that an investigation occur in conjunction with the Biologically Relevant Sound Levels Technical Working Group (Bio Rel TWG) about the use of exponential time-weighted average rms SPL with a standardised time weighting, as opposed to attempting to estimate the time spreading of the pulse. This choice has important implications for modelling too: accurate modelling of the temporal distribution of acoustic energy within a pulse is complex, and results can depend on local environmental parameters – many of which are poorly understood. The final 90% rms SPL integration time is also not directly related to the integration period of the mammalian ear. Fixed time-windows, either rectangular or exponentially-weighted, can be defined to be more representative of the hearing integration window.

Definition of exponential time-weighted average SPL

Exponential time-weighted average SPL is the integral, from a point of time in the past to the present, of the squared sound pressure with exponential time-weighting. It is normalised by an exponential time constant (τ, s) and defined as:

$$\text{Time-weighted SPL} = 10\log_{10}\left(\frac{1}{\tau}\int_{-\infty}^{t}\frac{p^2(\xi)}{p_0^2}e^{-(t-\xi)/\tau}d\xi\right) \tag{3}$$

where ξ is the variable of integration (ANSI S1.4-1983 R2006). This means when the pressure signal is averaged, more recent signal levels are given greater emphasis/weight than older ones. The time constant determines the breadth of the weighting curve. When the time constant is large, a sharp rise or fall in sound levels causes a gradual rise or fall in the time-weighted SPL. When the time-weighting constant is small, the time-weighted SPL will respond more rapidly.

Common time constants, τ, include the 'slow' and 'fast' time weightings as defined in the ANSI specification to assess in-air sound loudness for human hearing. For slow time-weighting τ = 1.0 s, and for fast time-weighting τ = 0.125 s.

Relevance of these units to the animals

This metric is typically modelled to determine behavioural response, which is currently accepted by NMFS as generally occurring at 160 dB re 1 µPa. However, there are moves towards a stepped response, as proposed in Wood et al. (2012) and presented in **Table 1**. While the Biol TWG will determine the specific relevant

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[3] This has been examined in Tougaard et al. (2014) and Madsen (2005). Examples of its use for the analysis of airgun sounds are provided in Hermannsen et al. (2015), and in numerous grey literature reports, including Austin et al. (2013).

isopleths, we expect they will consider the 120, 140 and 160 dB isopleths, and whether they are frequency-weighted or not.

Table 1: Behavioural exposure criteria. Probability of behavioural response frequency-weighted sound pressure level (rms SPL dB re 1 μPa). Probabilities are not additive. Adapted from Wood et al. (2012).

Marine mammal group	Probability of response to frequency-weighted rms SPL (dB re 1 μPa)			
	120	140	160	180
Beaked whales	50%	90%		
All other species		10%	50%	90%

The importance of incorporating uncertainty into the impact assessment process through response probabilities or some other means is supported by a recent paper by Nowacek et al. (2015) stating that:

> *…for assessing risk, a probabilistic function with a 50% midpoint at ~140 dBRMS that accounts, even qualitatively, for contextual issues likely affecting response probability (eg whether the animal is feeding or travelling) comes much closer to reflecting the existing data than does the 160 dBRMS step-function that is normally used (see Southall et al. 2007).*

Summary

- If rms SPL is to be modelled accurately, full waveform modelling must be performed.
- The Prop TWG recommends the definition of the way the rms SPL is to be calculated – be that either 90% as defined above or the fast time weighted as recommended in literature (Tougaard et al. 2014, Hermannsen et al. 2015).
- Refer to **Appendix 1** for a real-world example of the difference between the two rms SPL methods.

2.1.2.3. Peak Sound Pressure Level

The zero-to-peak SPL, or peak SPL (dB re 1 μPa), is the maximum instantaneous sound pressure level in a stated frequency band attained by an acoustic pressure signal, $p(t)$:

$$\text{Peak SPL} = 10\log_{10}\left[\frac{\max\left(\left|p^2(t)\right|\right)}{p_0^2}\right] \qquad (4)$$

The peak SPL metric is commonly quoted for impulsive sounds, but it does not account for the duration or bandwidth of the noise. At high intensities, the peak SPL can be a valid criterion for assessing whether a sound is potentially injurious; but because the peak SPL does not account for the duration of a noise event, it is a poor indicator of perceived loudness.

Peak sound pressure (or particle motion) is the maximum absolute value (either positive or negative) of the instantaneous sound pressure (or motion) during a specified time interval, and is properly denoted as $p_{\max}$. Peak is a useful metric for characterising impulsive sounds. Peak-to-peak is the difference between the absolute value of the maximum negative and positive instantaneous peaks of the waveform. Positive and negative peak pressures may have different effects: negative pressures result in expansion and cavitation while positive pressures result in compression.

Peak sound pressure levels are useful for characterising impulsive events but do not account for the total energy of the sound. There are applicable impact assessment metrics related to the peak SPL, although these are only applicable close to the source (injury ranges).

2.2. Inputs

Required inputs to a propagation model include:

1. Seismic source data:

- Output from a model of the seismic source level, for the specific source at the relevant operational depth
- Potential seismic acquisition line locations

2. Environmental data:

- Geoacoustic properties – including bottom sediment types and their layer depths for the region to be modelled, ideally down to several hundred metres into the bottom
- Bathymetry – the recommended minimum resolution to use is the shuttle radar topography mission SRTM15+ grid, which has an approximate grid cell size of 450 m. A higher resolution is preferred
- Sound Speed Profiles (SSPs) – seasonally-relevant SSPs, or salinity, temperature and depth data (in tabulated form)

Modellers should use the most accurate environmental data available, if possible.

2.2.1. Addressing uncertainty in environmental data inputs

Geoacoustics are some of the most important inputs to the modelling process for anywhere on the continental shelf and out to depths of at least 1,000 m. Unfortunately, they are usually also the least well-known – and are ideally required to be understood from the seabed surface to several hundred metres into the bottom. A detailed justification for the parameters used needs to be included. If there is uncertainty about the geoacoustics in situations when they are expected to have a dominant effect on the propagation modelling, an uncertainty analysis may be required.

The operational nature of seismic survey modelling for comprehension of the impact radii might not allow for the sensitivity analysis that could form part of a more detailed examination. If there is uncertainly, modellers should use conservative assumptions based on regional knowledge, and provide justification for their decisions.

While the bathymetry and geoacoustics will be constant for the survey regardless of timing, the SSPs are seasonal. Modelling must be conducted either for the season the survey will be conducted in, or for the most biologically-relevant conservative SSP – accounting for seasonal temperature gradients. Due to the large number of species present in NZ waters, and the use of the entire water column, it may be preferable that the modelling is conducted for the most conservative SSP (ie the one that produces the largest acoustic footprint) for both winter and summer, rather than attempting to estimate a single biologically relevant conservative SSP.

2.2.2. Making input assumptions clear

If assumptions are made about the inputs, they need to be clearly stipulated and justified. This is important for understanding the scientific validity of the assumptions (ie during a review by DOC), or if the results from a ground-truthing study are different and the modelling work needs to be revisited to understand these differences.

2.3. Source and transmission-loss models – choosing, using and applying them

This section summarises the uses and limitations of many of the models currently used in underwater acoustics. These include both source and transmission-loss models.

Modelling projects in NZ waters will cover a wide range of environmental conditions:

- From extremely shallow to deep water
- Highly variable to very constant topography, with specific complex local features like fjords and deep-water canyons
- Significant SSP features
- Varying geoacoustic parameters

In this section, the terms 'low' and 'high' frequencies will be used regularly. Low is defined in this context as below 5 kHz; high refers to 5–200 kHz.

2.3.1. General considerations

It is important to understand that using a reputable model is not enough: modellers need sufficient knowledge of (and experience with) the model(s) they are using, and understand the physics of underwater acoustic propagation well enough to ensure a) they are using the right models, and b) that the models' results are accurate and make physical sense. This will help them choose adjustable parameters and decide input parameters when setting up a model for a given scenario. Proponents of seismic surveys, and DOC, must ensure those completing the modelling reports are experienced.

2.3.1.1. The choice of model should reflect environmental conditions

Models need to be chosen based upon their treatment of environmental conditions above, with an appropriate rationale supplied in the modelling report. In particular, fjords and deep-water canyons may need special consideration. For wide area surveys passing briefly over or past them, it could be argued that no special treatment is required. However, if the survey is focused on or near them, higher resolution 3D models should be considered. This is because of the complex nature of the sound interactions within the bathymetric features, and the location-specific ecology and species (such as beaked whales) that are often present in these locations. 3D models are computationally demanding, but have been used in operational modelling before (examples can be provided upon request).

2.3.1.2. The choice of model should be biologically relevant

Models must be able to handle the wide range of frequencies that are biologically relevant (as defined by the Bio Rel TWG). The requirement to model frequencies from 1 Hz through to 200 kHz is assumed here, to accommodate the wide range of marine mammals in New Zealand waters (eg from blue whales to Māui dolphins). While airguns are commonly referred to as only including components below 1 kHz, studies have shown that considerable energy is also present beyond 10 kHz for ranges beyond 1,300 m, even for only a single airgun (Hermannsen et al. 2015). JASCO has also identified significant components at high frequencies in numerous studies. Although transmission can be modelled over all relevant frequencies, currently airgun source models have an approximate maximum frequency of 25 kHz.[4]

Higher frequencies attenuate rapidly, and therefore are likely only to be relevant for the consideration of the PTS and TTS thresholds, with the longer-range behavioural response thresholds primarily requiring consideration of low frequencies. This will guide the models and techniques used.

2.3.1.3. Relevance and applicability of modelling

Typically modelling is specific to a source, physical location, and environmental conditions such as SSP. Because of this:

- If modelling conditions differ from any previous effort the modelling needs to be redone to accurately characterise the propagation
- You cannot transfer model results across different bathymetric conditions – although you can transfer a model between them

However, what constitutes ‘different’ bathymetric conditions is more substantial in deep water (>700–1,000 m), as greater absolute changes are needed to induce the same percentage change. This allows ‘sampling’, or consistency of large areas of water as you go deeper – typically well off the slope and on the abyssal plain (assuming consistent SSP and geoacoustic properties).

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[4] High frequencies can be extremely computationally intensive to model, although this is no reason to not consider them

When considering slope rate, if gradient and geoacoustics are the same, you can at times compare one area with another along the same isopleth.

Model selection should be paired to frequency range

While the frequency range of biological interest was defined above, selection of acoustic models must be based on the physical properties of sound waves at the different frequencies. The only truly reliable definition would therefore be that ‘high frequencies’ are those for which wave effects are unimportant. In practice, you would find this out by running both model types at successively higher frequencies until they agree; then you can reasonably assume the high frequency model will be accurate at frequencies above this.

As a rough guide, a ray model should be fine in water depths from a few tens of metres to a few hundred metres, for frequencies of 10 kHz and above, and that you'd need to use a wave model for frequencies of 1 kHz or less. Between 1 kHz and 10 kHz the answer would be ‘it depends’. In deeper water, you may or may not be able to push the lower frequency limit of the ray model down, depending on the sound speed profile.

Crossover analysis like this also typically happens between short and long-range transmission loss models, to determine the range at which you change from using one model to the other, while ensuring a smooth transition.

Specific frequencies modelled

Due to the wide range of frequencies to be modelled, the modelling should be done by computing acoustic transmission loss at the centre frequencies of one-third octave bands. Typically, enough one-third octave bands, starting at 10 Hz, are modelled to include most of the acoustic energy emitted by the source.

The one-third octave-band received per-pulse SELs are computed by subtracting the band transmission loss values from the directional source level in that frequency band. Composite broadband received SELs are then computed by summing the received one-third octave-band levels.

Selecting receiver depths

Receiver depths for the model need to be considered in relation to biologically-relevant depths. Ideally the sound field should be sampled at various depths, with the step size between samples increasing with depth. This is because step sizes are chosen to increase coverage near the source’s depth and at relevant depths in terms of the sound speed-profile. If needed, it should also be possible to quantify the sound level at specific depths of interest (eg 10 m or at the sea floor).

If modelling in conjunction with the planning of a ground-truthing study (see the section dealing with incorporation of models into planning) that intends to place sensors at specific depths/locations, these should be included in the model.

Use of transects

Some acoustic models are extremely computationally-intensive, and thus are typically only analysed over specific transects from the source in a particular cardinal direction(s). One common example would be for SEL to SPL conversion transects. While these are typically linked with efforts to model sound in radials covering a

360° swath from the source, it is important to understand the sound propagation in 360° due to source and bathymetric effects. All 360° examinations should thus use tessellation to increase accuracy at greater distances from the source.[5]

2.3.2. Seismic source models

2.3.2.1. Airgun models

Industry standard or peer-reviewed models should be used for close-range source models. These source models should be able to model the source to frequencies above 20 kHz.

For environmental assessment, the source models must characterise the source in a biologically relevant way – which relates particularly to the horizontal plane. As a minimum the models should characterise the:

- Vertical pressure signature and specifications (both with and without surface reflection)
- Horizontal pressure specifications in endfire and broadside directions without surface reflection
- Overpressure signature and power spectrum
- Azimuthal directivity pattern of source level, for both broadband and one-third octave-bands

Industry and scientific source models

While some industry source models have been updated to provide environmental impact modelling capabilities, their accuracy and transparency often still have considerable room for improvement.

On the other hand, specialist propagation modelling for a specific location and scenarios includes many variables and considerations, and uses carefully selected peer-reviewed models. At all stages of the project, modelling results are normally reviewed by experienced modellers with a strong theoretical understanding.

Industry models used by operators resemble 'black box' tools – they typically provide outputs based upon inputs, with little project-specific oversight. The results are often not reviewed by subject matter experts.

Seismic industry source models include:

- Gundalf (https://www.gundalf.com/)
- Nucleus (http://www.norsar.no/seismod/Products/NUCLEUS/)

Some scientific source models:

- JASCO's Airgun Array Source Model (AASM; MacGillivray 2006)
- CMST's Airgun Array Source Model

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[5] Tessellation refers to a mathematical approach using a number of transects (in this case radial) to represent the entire area of interest.

2.3.2.2. *Non-airgun source models*

Peer-reviewed and public source models do not currently exist for marine vibroseis sources. The sizes and types of marine vibroseis transducers can vary widely. At this time, modelling of these sources generally requires an estimate of the source waveform, based on measurements made during testing of the equipment.

2.3.3. Acoustic propagation models

There are five main categories of acoustic propagation model used in underwater acoustics: ray models, normal mode, finite element, wavenumber integration (or fast field), and finite difference (of which parabolic equation (PE) models dominate). Each category represents a different approach to simplifying either the acoustic wave equation (the fundamental mathematical equation that contains all the basic physics of sound propagation) or the model of the environment, or both.

Many propagation models are publicly available as either documented source code or as ready-to-use executables for various computer platforms. The online Ocean Acoustics Library, supported by the U.S. Office of Naval Research, is a valuable repository of a variety of modelling codes and related documentation. It is accessible at the URL http://oalib.hlsresearch.com/. **Table 2** provides a current list, as of this writing, of the acoustic model implementations available on that site.

Table 2: Underwater sound propagation models available from the Ocean Acoustics Library

Category	Models
Ray theory	BELLHOP, HARPO, RAY, TRIMAIN
Normal mode	AW, COUPLE, KRAKEN, MOATL, NLAYER, WKBZ
Wavenumber integration	OASES, RPRESS, SCOOTER, SPARC
Parabolic equation	FOR3D, MMPE, PDPE, PECan, RAM, UMPE

The applicability of these model types is summarised in **Table 3** (from Etter, 1996, and below)**.** For each technique, the possible application regimes are categorised in a binary tree in terms of water depth (shallow or deep), frequency (low or high), and range dependence (range independent or range-dependent ocean environment). We have set the demarcation between low and high frequency at 2,000 Hz, whereas Etter (1996) places it at 500 Hz; this adjustment recognises that increasing computing speed and power makes it more practical to use computationally-intensive methods (like PE) to higher frequencies.

The distinction between shallow and deep water is based on acoustic considerations. It should be assumed that shallow water conditions prevail when the sound is likely to interact significantly with the sea floor. Generally, shallow water refers to water over a continental shelf with a depth of less than 200 m. The environmental range dependence incorporates variability in vertical sound speed profile and/or bathymetry with changing horizontal distance from the source.

Table 3: Domains of applicability of underwater sound propagation models (from Etter (1996)). The cut-off is typically 2,000 Hz.

Model type	Application							
	Shallow water				Deep water			
	Low frequency		High frequency		Low frequency		High frequency	
	R. Ind.	R. Dep.	R. Ind.	R. Dep.	R. Ind.	R. Dep.	R. Ind.	R. Dep.
Ray theory	○	○	⦿	●	⦿	⦿	●	●
Normal mode	●	⦿	●	⦿	●	⦿	⦿	○
Multipath expansion	○	○	⦿	○	⦿	○	●	○
Wavenumber integration	●	○	●	○	●	○	⦿	○
Parabolic equation	⦿	●	○	○	⦿	●	⦿	⦿

Low Frequency: < 1,000 Hz

R. Ind.: Range-Independent Environment

R. Dep.: Range-Dependent Environment

● Modelling approach is both physically applicable and computationally practical

⦿ Modelling approach has limitations in accuracy or computational performance

○ Modelling approach is not applicable

Please note, this is a relative rather than absolute evaluation – there is always at least one method ranked as best applicable in each column, but the performance and/or accuracy of the best model may differ among regimes.

It is also useful to look at the use of different methods in the context of actual oceanic environments, in addition to model applicability based on generalised environment conditions. Etter (1996) outlines some relevant cases, summarised below, based both on theoretical considerations and on reported applications of models in the literature:

Surface duct propagation – characterised by no bottom interaction (sound is refracted upwards at the lower boundary of the duct and reflected at the surface). Models: ray theory, normal mode, PE.

Shallow water duct propagation – dominated by repeated interactions with the sea floor (significant range dependence). Models: ray theory, range dependent normal mode, PE.

Arctic propagation – characterised by ice cover (scattering at the rough surface boundary), rapid loss of high frequencies with range, and little or no bottom interaction because of the strongly upward-refracting water column profile. Models: normal mode, wave number integral, modified ray theory and PE models may all apply if the properties of the ice cover interface are well described.

2.3.4. Reverberation

Reverberation refers to the components of the underwater sound field arising from reflections and scattering of sound off the seabed. It is sometimes divided into coherent and incoherent subcomponents. The coherent subcomponent arises from specular reflections, mainly in the vertical plane of the incident wave propagation direction. The incoherent subcomponent arises from non-specular reflections or scattering, where the vertical incident angle is different from the reflected wave angle, and from out-of-plane scattering where the reflected wave propagates in an entirely different direction from the incident wave.

Coherent reverberation includes all the acoustic multipaths that reflect specularly from the surface and seabed. In deep water these multipaths are separated in time and are often easily distinguishable from each other. In shallow water, they may be identified as separate arrivals at close ranges from the source; at longer distances they generally merge into a continuous signal lasting up to 1–2 seconds. The coherent reverberation usually accounts for most of the sound energy from a seismic pulse. However, seismic pulse measurements in shallow water often include substantial incoherent reverberation that can last more than 15 seconds. This sound energy often keeps the overall signal level above ambient throughout the entire interpulse period (which may be up to 20 seconds).[6]

None of the acoustic models discussed above is designed to deal directly with incoherent reverberation or scattering – they are limited to calculating the coherent reverberation component. However, some of the models can account for acoustic energy lost from seabed and surface reflections due to scattering. Newer models for incoherent reverberation may be available, but we are not aware of them at present. This would be a good research topic for future seismic survey noise analysis.

The low-level sounds arising from incoherent reverberation are likely too low to cause trauma or acute behavioural effects. They could, however, contribute to masking of communications that might produce chronic effects. As current models do not treat incoherent reverberation, this may have to be estimated from measurements made from similar sources in each type of environment.

2.3.5. Accuracy quantification

When underwater noise originates from a single source of specified directivity and with a given transmitted spectral content, high-quality models can predict the spectral levels of the received signal.

2.3.5.1. Propagation model accuracy relies on good geoacoustic data

As mentioned above, propagation models use bathymetric databases, geoacoustic information, oceanographic parameters, and boundary roughness models to estimate the acoustic field at any point far from the source. The estimate's accuracy is directly related to the quality of the environmental information used in the model: for example, in continental shelf waters, geoacoustic parameters like compressional

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[6] Literature on this topic includes a recent publication by Guan et al. (2015).

sound speed, attenuation and sediment density can significantly affect the acoustic propagation. The predicted transmission loss can be incorrect by as much as 20 dB at ranges of several kilometers due to inaccurate geoacoustic parameters.

2.3.5.2. Assessing model sensitivity to parameter uncertainty

A sensitivity analysis (although not typically commissioned for modelling studies at present) focused primarily on the assumed environmental parameters (especially sound speed profile and seabed geoacoustics) would be the most informative way to understand the accuracy of the results. Such an analysis would involve modelling sound levels using the extremities of the parameter space (eg using the most upward refracting and least upward refracting sound speed profile expected in the area, the most reflective and least reflective seabed, etc). This is very time-consuming, as the complete modelling effort needs to be replicated multiple times. To save time and money, modellers often just use what they consider to be the 'worst case' parameter set.

However, it is also important to quantify the uncertainties in the input parameters in the first place. No two measured sound-speed profiles are the same, and modellers cannot be certain their models have captured the most reflective seabed in the area. Virtually all the published shallow geological information for New Zealand waters is from surficial sampling, so it is not possible to know there is not, for example, a layer of highly-reflective coarse sand 50 m below the known surface silt. Finally, there can also be a lot of localised variability in seabed reflectivity, with a 10-dB spread in the SELs of bottom-reflected airgun shots over 50 consecutive shots observed in several data sets from New Zealand (A. Duncan, pers. com.).

One solution is to conduct modelling of many points within a survey region. It is then possible to treat model input parameters as random variables, and to model sound levels from many combinations of those variables to produce distributions of levels or threshold distances. This approach can be used to quantify uncertainty due to source/receiver geometry and environment, assisting with comprehension of the magnitude of uncertainty – which cannot be done with only a few scenarios. It allows the modelling of many radials with different parameters instead of many radials with the same parameters; it also makes it easier to understand and justify model inputs while being simpler to compare to measurements.

A Greenlandic sensitivity analysis

Martin et al. (2015) compared model results to measurements to determine how acoustic propagation models are affected by the fidelity of the available environmental data (temperature/salinity profiles, bathymetry, sub-bottom properties) in Greenland. They found that accurate prediction at any given depth in Greenland waters depends most on the geoacoustic profile of the bottom, with source depth and accurate source-level modelling as second order variables. Interestingly, even dramatically different SSPs did not affect results significantly. In the areas modelled, the bathymetry didn't matter as much. The work confirmed that accurate rms SPL modelling requires full-waveform modelling.

In Greenland, guidelines for environmental impact assessments (EIA) of seismic and drilling activities require each applying company to model the noise exposure expected from its planned activity, and the cumulative noise exposure from all concurrent activities proposed in the same general area (Kyhn et al. 2011). To evaluate the need for this relatively new requirement in Greenland, given the data currently available, Wisniewska et al. (2014) conducted a review of predictive modelling undertaken in the EIA process; conducted their own post-survey 3D modelling using bathymetry during the seismic surveys; and examined the measurements from 21 acoustic data-loggers deployed during the surveys to verify the modelling. This review concluded that estimates of the noise exposure from the planned seismic operations were fairly accurate. It also says that the results indicate that the requirement for predictive modelling as part of the EIA is worthwhile, even for areas that are relatively poorly-characterised in terms of (for example) bathymetry.

2.3.6. Relevance to mitigation

Sound propagation modelling can be used to inform several decisions related to reducing impacts from seismic surveys on marine mammals. These include providing a scientific basis for marine mammal exclusion zones sizes and evaluating relative impacts of different survey designs. A comprehensive impact assessment requires locations chosen for modelling acoustic footprints to have acoustic characteristics that are sufficiently representative of those throughout the survey operating area.

The metrics needed for assessment are linked to either single shots or accumulated footprints, discussed below.

2.3.6.1. Single-shot sound field modelling

The single-shot modelling locations should be representative of the survey region, covering bathymetric and geological regions. They only need to be selected on proximity to biological regions of importance if there is a specific need to understand the single shot sound field at that point; otherwise it is more biologically appropriate to examine the sound field near the relevant region by sampling the results of the accumulated modelling.

2.3.6.2. Estimating the accumulated sound field

Thousands of shots must be modelled to represent appropriate exposure lengths, such as 24 hours of seismic operation. Rather than modelling each shot individually, the process can be shortened by estimating the acoustic fields based on a limited number of single-shot sound fields at representative source locations. The single-shot model sites therefore form a library of representative footprints. The relevant survey regions for assessment are then divided into zones, classified to one of the representative sites based on geographic similarity. The corresponding noise footprint is then applied to each shot point and added to the cumulative grid. It is also possible to interpolate between single shot locations along a slope, if the geoacoustic profile is the same and changes in depth are within a scientifically justifiable range.

Although this approach is not as precise as modelling sound propagation at every shot location, small-scale and site-specific sound propagation features tend to blur and become less relevant when sound fields from adjacent shots are summed. Largerscale sound propagation features dominate the cumulative field, depending on water depth. The present method is accurate enough to reflect those large-scale features, giving a meaningful estimate of a wide area accumulated sound exposure level (aSEL) field in a computationally-feasible framework.

2.3.6.3. Sampling and interpreting modelled sound fields

The sound fields, both single shot and cumulative, can be 'sampled' at specific locations (typically called 'receivers') that are selected on their relevance to impact assessment – for example, placing a receiver at a sanctuary boundary, on a reef, or in a location representing a migration path or area used by marine mammals.

The levels immediately around the seismic track lines (derived from single/accumulated footprints as appropriate) will determine the PTS/TTS impact zones of the survey, while levels at the more distant receivers are useful to determine TTS, along with potential behavioural disturbance or masking.

Mitigation zones around the survey track lines therefore should be determined based upon the footprints related to the levels and measurements stipulated by the Bio Rel TWG.

2.3.7. Animal exposure assessment

2.3.7.1. Frequency weighting

The Biol Rel TWG is expected to examine and possibly recommend relevant frequency-weighting methods (ie M-weighting from Southall 2007).

To meet requirements, model outputs will need to present both unweighted and weighted SELs.

2.3.7.2. Animats

Several models for marine mammal movement have been developed (Ellison et al. 1987, Frankel et al. 2002, Houser 2006). These models use an underlying Markov chain to transition from one state to another, based on probabilities determined from measured swimming behaviour. The parameters may represent simple states, such as the speed or heading of the animal, or complex states, such as likelihood of an animal foraging, playing, resting or travelling. The Marine Mammal Movement and Behavior (3MB) model developed by Houser (2006) is commonly used. This model is included in the Effects of Sound on the Marine Environment (ESME) interface developed by the Office of Naval Research (ONR) and Boston University (Gisiner et al. 2006, Shyu and Hillson 2006). Modifications of 3MB exist for it to use sound fields from specific study areas. The model uses several parameters to simulate realistic animal movement that must be determined from published studies for the species to be simulated.

Several topics central to this subject were discussed by the TWG:

- Modelling of moving animals. The TWG concluded that exposure footprints are simpler and not as data-hungry.[7]
- Whether exposure should be weighted towards the expected number of animals in the area. Here the TWG leaned towards 'no', but noted the most relevant expertise lay within the Bio Rel TWG.
- The 'take' of marine mammals: a crucial driver of US regulation. The TWG noted, given the paucity of data, it may not be possible to apply this concept in New Zealand. The lack of information would make it very hard to produce reliable models of animal distributions, locations and movement in addition to models of sound levels.

2.3.8. Examples of single-shot and accumulated single-survey sound fields

The relationships between the various environmental parameters and the different metrics for exposure is often complicated. **Appendix 2** includes working examples to assist in understanding the implications of some of these relationships. In particular, the influence of water depth and slope bathymetry on sound propagation is discussed in more detail.

3. Multi-source models

It was noted that multi-seismic source modelling for any given project is already being undertaken for seismic surveys, such as with wide-azimuth surveys. This is conducted in the Gulf of Mexico; multi-seismic-source models have not yet been used in New Zealand.

Computing power available is sufficient to model multiple sources – it is done quite frequently and is definitely feasible. It is not simply a GIS exercise, however: more variables need to be considered.

3.1. Single-seismic source combined with non-seismic sources

The costs and benefits of including non-seismic sources from seismic surveys (such as profilers, chirpers, boomers, etc) were discussed. If used concurrently with seismic sources, their contributions to aSEL are probably noticeable but limited. An example for a specific case study is shown in **Table 4**. Non-seismic source contributions to an increase in the between-pulse noise floor might still contribute to chronic impacts on marine mammals (using either the SEL or rms SPL metrics for assessment). They are worth considering in highly-sensitive areas.

One example is the modelling done by JASCO (Zykov et al. 2012) – in conjunction with Wood et al. (2012)'s impact assessment for the Californian coast, which assessed

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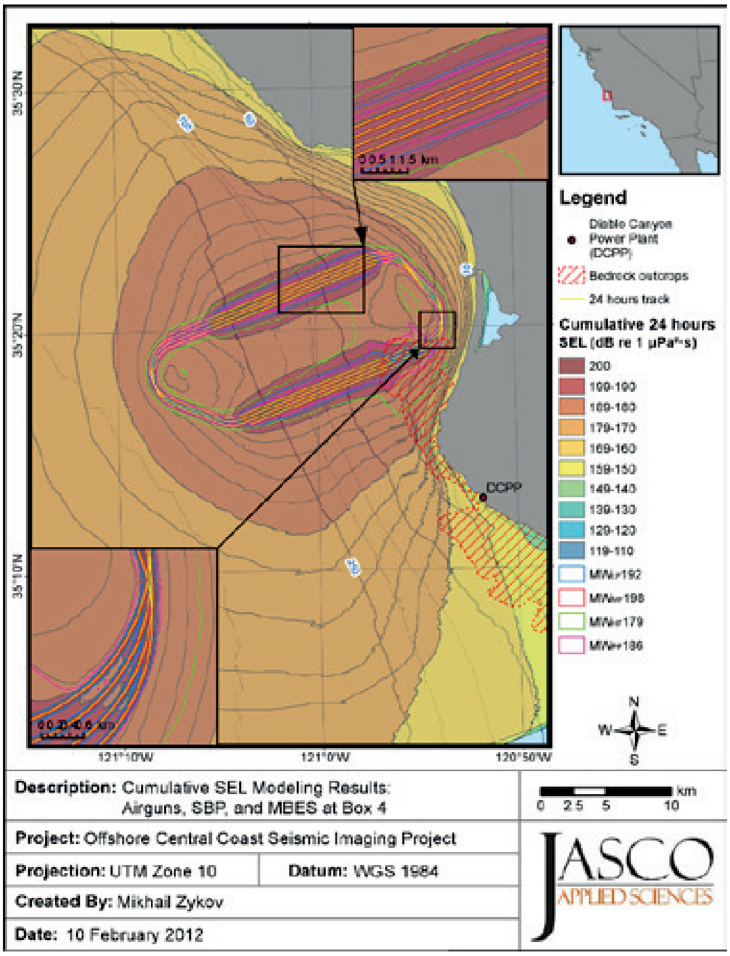
[7] Southall et al. (2007) assumed a stationary receiver, which is extremely simple to implement for accumulated shots.

a 3,300 in^3 seismic array operated simultaneously with a Kongsberg EM 122 multibeam sonar and a Knudsen Chirp 3260 sub-bottom profiler. An extracted example (in **Figure 1**) is associated with Box 4 in **Table 4**.

Table 4: Extent of ensonification (km^2) for maximum-over-depth M-weighted SELs (10 Hz to 200 kHz) around the sources. A break-down for airgun (AG) sources and sonar sources (sub-bottom profiler and multibeam sonar) is also provided.

SEL (dB re 1 µPa2·s)	Box 1			Box 2			Box 3			Box 4		
	All	AG	Sonar	All	AG	Sonar	All	AG	Sonar	All	AG	Sonar
192 M_{LFC}	177	174	5.2	74.1	71.6	4.8	56	54.2	5.3	58.7	55.9	5.4
198 M_{MFC}	9.8	7.7	3.4	10.7	9.3	3.4	8.6	6.0	3.5	7.7	4.9	3.6
179 M_{HFC}	218	119	140	120	33.1	61.3	134	37.6	99.3	156	37.5	116
186 M_{PW}	146	120	34.8	47.2	33.2	19.4	54.1	37.3	32.3	64.0	37.2	3.5

Figure 1: Cumulative maximum-over-depth broadband sound exposure levels for 24 hr of operation of airguns, sub-bottom profiler, and multibeam sonar. Bathymetry contours (m) are shown in blue. (Zykov et al. 2012).



3.2. Single survey, multiple seismic sources

To understand the acoustic footprint of the activity, coil/simultaneous source surveys need to be modelled in a cumulative fashion, with each source considered both independently and in combination. Standard modelling techniques could also be used to achieve this.

3.3. Regional cumulative assessment

The need for this type of modelling depends upon many factors, including:

- Physical proximity of concurrent surveys
- Acoustic propagation factors – sound channelling
- Location sensitivity

The potential for cross-project exposure modelling was discussed. The TWG concluded that:

- For cumulative assessments, a multi-source model is necessary and is reasonably easy to conduct
- While the focus should be on behavioural metrics, both rms SPL and SEL should be calculated

The regulator (eg DOC or the Environmental Protection Authority) can assess the need for such models through a cumulative and chronic effects framework, which would demonstrate the areas and level of activity (eg number of operations) that may need more detailed analysis.[8]

When considering whether a model is necessary, regulators must remember that if two surveys are happening simultaneously, the maximum increase in SEL at any given location (over that produced by whichever survey produces the highest SEL at that location) will be 3 dB.[9] This corresponds to a doubling of received energy.

See **Figure 2** for an example of an accumulated exposure model for multiple surveys.

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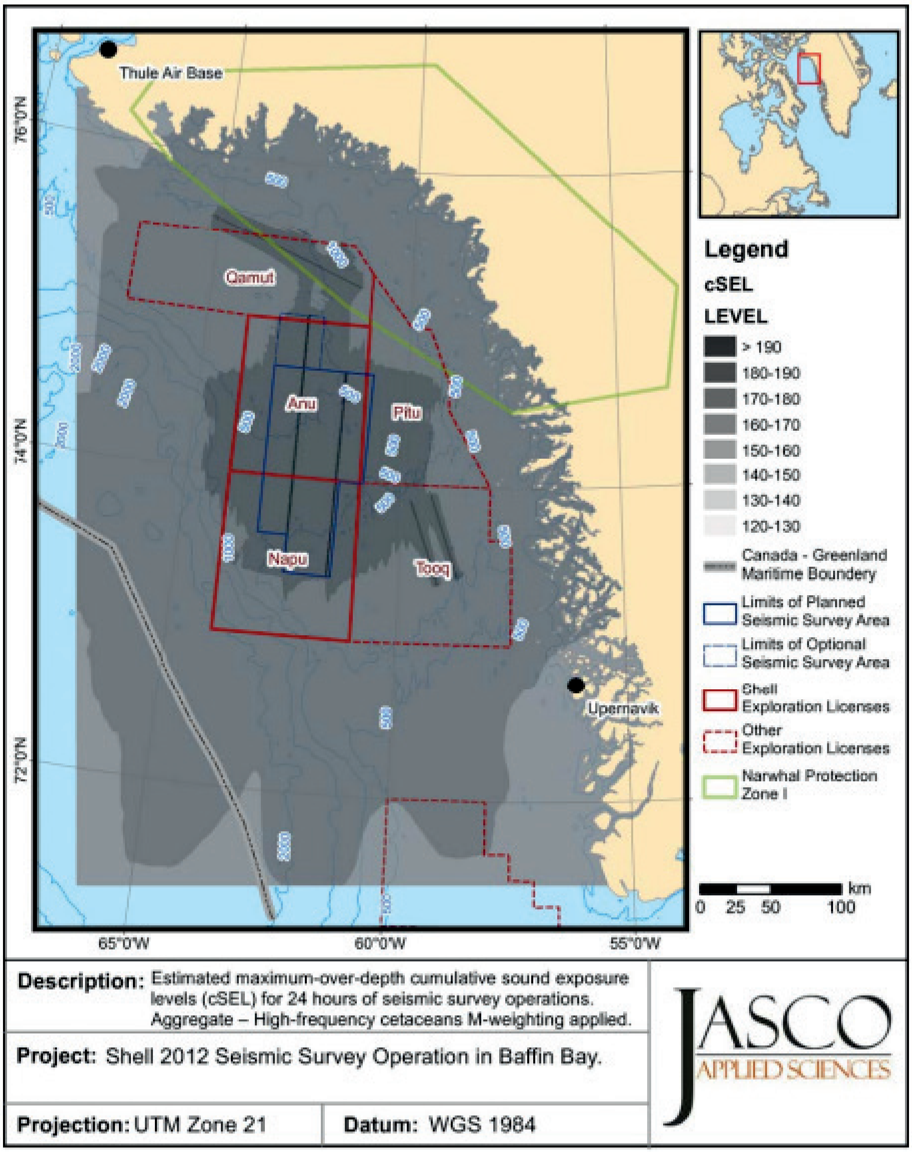
[8] Such studies have been commissioned by NMFS recently.

[9] This 3-dB increase will occur at locations where both surveys, on their own, produce similar SELs.

Figure 2: Aggregate unweighted accumulated sound exposure levels (aSELs) – received maximum-over-depth aSELs from 24 hr of seismic survey operations with five airgun arrays. (Matthews 2012a)



Description: Estimated maximum-over-depth cumulative sound exposure levels (cSEL) for 24 hours of seismic survey operations. Aggregate – High-frequency cetaceans M-weighting applied.

Project: Shell 2012 Seismic Survey Operation in Baffin Bay.

Projection: UTM Zone 21 **Datum:** WGS 1984

Part 2: Modelling and wider management

Modelling of sound propagation from seismic surveys typically centres on assessments of impact for a specific survey plan or the determination of mitigation zones. However, they can be more widely applied in the management and mitigation process: this can most notably be done by providing comparison of different possible survey designs.

4. Incorporation of modelling into survey planning

Survey planning times vary widely. Generally, operators have reasonable internal notice about the survey timing, and can commission the modelling and impact assessments needed.

A typical modelling report may take several weeks to compile, with the modelling work itself reliant upon sourcing and organising input data, which is not often a smooth process. Modelling can thus be delayed if operators are not prepared for data requests from the modellers. Operators should familiarise themselves with the typical data requirements of modelling studies, and should be able to provide an information package in association with the request to commence work. It was noted, however, that final operational details may not be necessary to initiate modelling as assumptions regarding survey planning often occur in cases where, for example, exact track-lines are not known. Best guesses are usually accurate enough for the initial requirements of the studies. In fact, the resulting modelling studies can assist with planning through:

- Information about the footprints of various arrays, if the operator seeks information to assist a choice in survey design. This can be in terms of array size and tow depth, and even vessel speed and shot spacing.
- Information about the ideal orientation/angle/length of line, in relation to minimising biological impact. This of course will be considered by the operator in conjunction with operational considerations, but can be used as an important decision-making tool.
- Information about the line shooting order, and therefore the time between both consecutive and adjacent lines.

5. Relevance to areas of ecological importance and marine mammal sanctuaries

This is a policy decision for DOC – as is any requirement for modelling around marine mammal sanctuaries, etc. However, modelling could be used to plan surveys around any border thresholds set for important areas, such as marine mammal sanctuaries.

6. Recommendations for survey classification bands

Instead of classifying sources simply by array volume, a breakdown by source level could be investigated. However, there are difficulties with this idea. While small sources transiting along a line can be treated in one fashion, the TWG recognised this will not encompass situations where the source is being used for VSP as the localised impacts are quite different.

The TWG therefore recommends VSP modelling be conducted for each survey, as a small array for a longer operation can have a similar impact to a larger array used for a shorter operation.

Please note that detailed investigation of this classification has not yet been conducted. We also need to consider if the breakdown by volume of source (as is currently done) is appropriate.

Part 3: General guidelines for in-field verification

7. Ground-truthing feedback to modellers

The technical aspect of in-field verification of sound propagation model predictions, known as ground-truthing (G-T), will be specifically considered by the Acoustic Ground-Truthing TWG. The purpose of acoustic field measurements is to gauge the validity of acoustic model estimates, not to measure the acoustic properties of the environment directly. However, there is a second type of ground-truthing that is to validate environmental parameters, such as measuring the seabed reflectivity in the frequency bands where it is both most influential and most uncertain.

Regardless, only through a comprehensive G-T exercise it is possible to validate model results, understand and quantify differences, and ultimately identify and refine the parameters that account for the discrepancy. This process is crucial to improve models for future use, but requires that the results be relayed back to modellers in a useful form. Accordingly, we address this subject here from that perspective.

7.1. Realistic parameters are important

The accuracy of an acoustic modelling study's results depends on the realism of the parameters defining the sound propagation environment. Without feedback indicating whether the model predicted the actual sound levels measured at some location from a given activity, it is not possible to judge (and ideally improve) the model's parametrisation.

The primary validator in ground-truthing results of the model is the parameterisation of geoacoustic properties. The seabed geoacoustic model is usually the least well-known of the propagation parameters and, except in very deep water, is also one of the most influential to the results. This parameter is therefore a very important check on the integrity of the modelling.

The TWG recommends:

1. Parametrising models with properties that optimally describe the medium in the algorithm's framework

Knowing the precise physical properties of both the water column and the geophysical layering of the seafloor does not guarantee a model parameterised with those properties will yield accurate results. However, models are often parameterised with properties representing the optimal description of the medium in the numerical approximation framework of the algorithm, rather than those that adhere more precisely to the physical reality.

2. Planning and accounting for verification requirements before configuring and running your model

This applies to the most common paradigm where modelling is performed before assets and resources are mobilised to the field. Assessing the feasibility of operating the source and deploying receivers at locations envisaged in the modelling scenario will make it easier to undertake G-T at the specific sites where predictions have been made. This allows the G-T configuration to precisely match the model scenario geometry, and makes the direct comparison of measured and modelled results possible.

7.2. Quality of ground-truthing study

Even if it is not possible to plan G-T and modelling together, one important consideration for presenting model results is that they should be provided at physical locations where actual receivers can be placed. Model results must therefore consider the depths and locations that could be sampled to facilitate direct comparison with measurements. This might mean providing a separate set of modelling results specifically for G-T, in addition to those results incorporated into the EIA. Modelling studies often focus on maximum exposures of marine mammals or fish, and consequently the results are often presented as 'maximum-over-depth' of sound level on the seabed. G-T studies are typically made with a small number of receivers at fixed depths. For example, sound source verification measurements in deep water are usually made either using a hydrophone suspended less than 100 m from the surface.

7.3. Metrics

The G-T study information must be presented using standardised metrics. These should include:

- Per pulse peak SPL
- Per pulse rms SPL (with a specified integration time window)
- Per pulse 1 s SEL
- Accumulated SEL as appropriate

To enhance the usefulness of these standardised metrics, G-T studies should:

- Clarify the location and depth of both the recorder and the source
- Clearly define ranges as slant or horizontal
- Display the metrics as a function of source location and known receiver location, in the reporting

The immediate ground-truthing would be limited to single-shot SEL and received pressure levels (with third octave bands and spectra). Sound speed profile measurements are also very important.

7.4. Receiver locations

Modelling can predict the sound field at specific geographical locations and depths. Depth sampling points should be distributed through the water column – from 2 m to the bottom, with enough points to accurately estimate the sound field. An example might be using 20 points to represent the water column in 500 m of water. In addition to supporting an accurate model, the use of this many points provides numerous options for undertaking G-T.

It is also important that the modelled depths and G-T measurement depths match at the specific point depth where the G-T occurs – for example:

- A receiver at a depth of the streamers if using a streamer-based G-T method
- A receiver at the bottom if using bottom-based recorders

Furthermore, the geographic locations selected for G-T must be representative of the oceanographic and bathymetric features present in the survey operating area to sufficiently characterise the range of acoustic footprints, and therefore inform a comprehensive impact assessment. This is discussed in **Section 3**.

If the G-T is conducted for the purposes of refining mitigation and to characterise the survey in detail, operators should sample the sound fields at either the extremes of the survey operating range, or at locations where the most disparate modelling footprints are present – either shallowest/deepest, or depth and geologically-dependent. The G-T for mitigation receivers will likely be focused on the biologically-relevant areas (eg placed at the closest location in the survey region if using static receivers). The sound field can be sampled at biologically-relevant depths as the survey approaches the receiver, to indicate the received levels at that location and potentially along an entire track. This can then be compared to the modelling on a shot-by-shot basis, if the recorder location is also treated as a modelled 'receiver' for the distant single shot modelling, and sampled appropriately.

If streamers are used for the receivers, this should be included as a treatment in the footprint modelling, so the chance that the modelling needs to be repeated (to generate results that can be compared with the streamer survey measurements) is minimised. Streamers are also limited in their ability to sample the acoustic field in the near field, and may also be limited in shallow waters.

7.5. Analysis requirements

7.5.1. Standardised integration time – time domain pulse spreading

Integration times need to be consistent across modelling and ground-truthing. Although fixed time-integration windows of between 100 and 200 ms were discussed, the TWG noted that 125 ms integration window for humans would work well for marine mammals (as per Tougaard et al, 2015). See **Section 2.1.2.2** for more detail.

An example of how the time domain spreading of the pulse, and the application of a specific rms SPL window (in this case the 90% energy duration) can be shown in a G-T study is shown in **Figures** 3 and 4, below:

Figure 3: Waveforms of 40 in^3 airgun array pulses received at AMAR A at the CPA (49 m [160 ft], left) and just before the CPA (80 m [260 ft], right) showing the difference in the 90% energy pulse duration (red lines). The pulse on the right has a greater rms SPL than on the left.

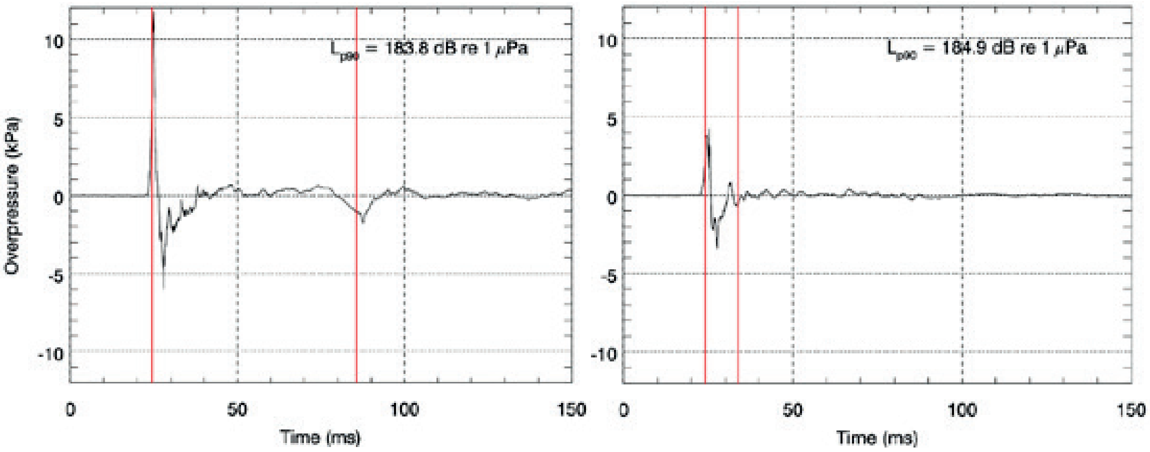
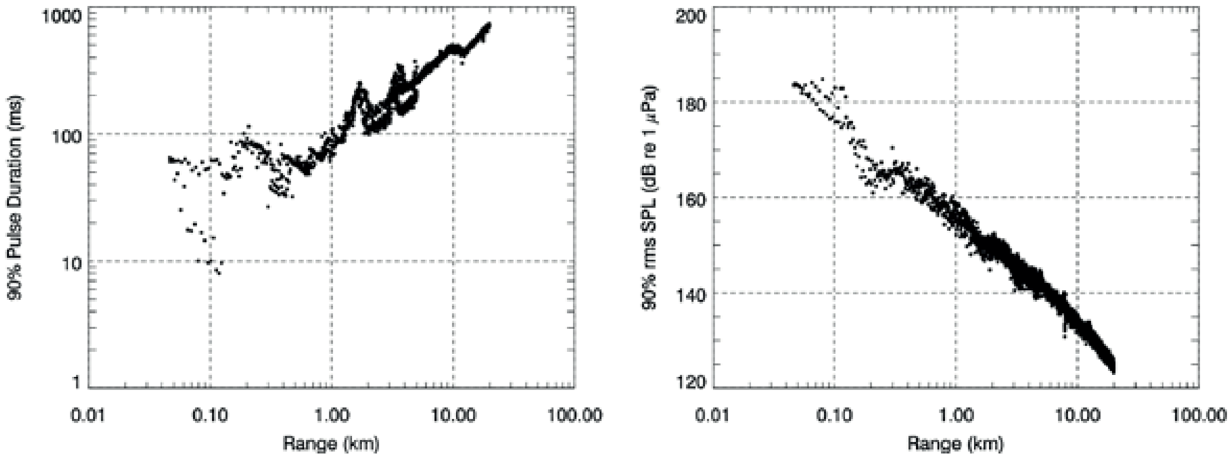


Figure 4: The 90%-rms pulse duration (left) and 90%-rms SPL (right) as functions of range for pulses from the 40 in^3 airgun array received in the endfire direction on AMAR A.



7.5.2. Pulse frequency content

Analysis of the pulse frequency content helps clarify which components propagate the furthest. See **Figures** 5 and **6** below:

Figure 5: Spectrograms of 40 in³ airgun array pulses received at AMAR A at the CPA (46 m [150 ft], left) and at long range (19.9 km [12.4 mi], right). 4,096 pt FFT length. 87.5% overlap, Hanning window.

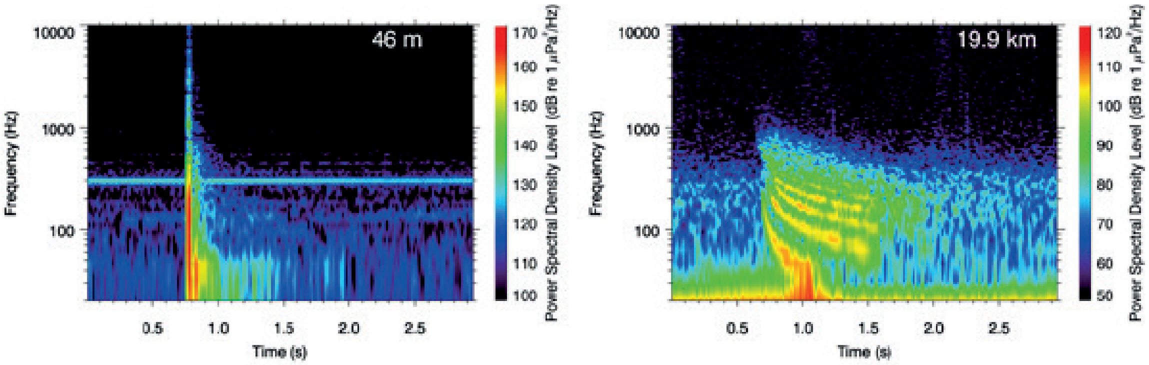
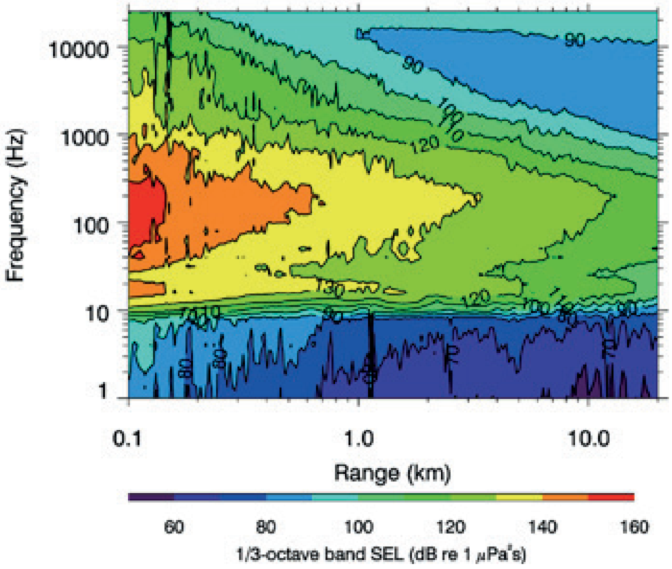


Figure 6: One-third-octave-band SEL as a function of range and frequency for the 40 in^3 airgun array.



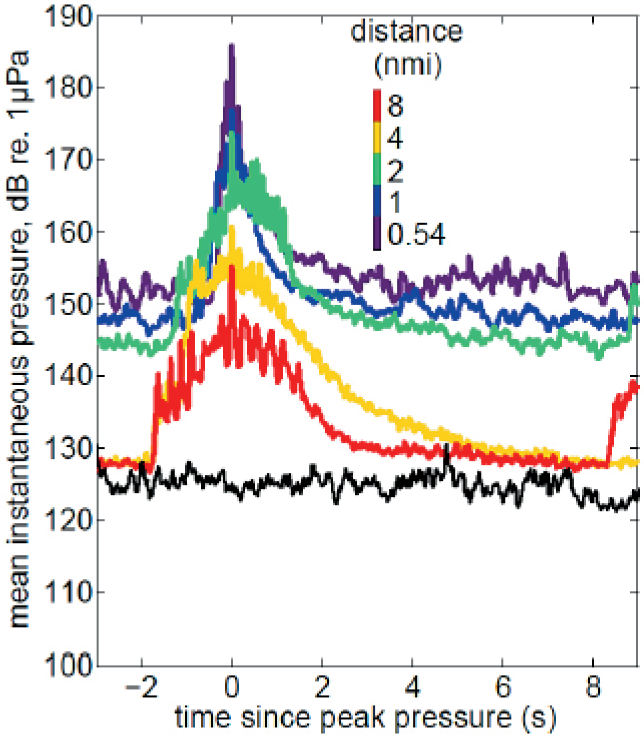
7.6. Inter-pulse reverberation

Studies in Greenland showed that the airgun pulses contained energy up to at least 48 kHz (Wisniewska et al. 2014). The noise level between seismic pulses did not fade to background levels before arrival of the next pulse. New pulses are emitted around every 10 seconds for each survey, resulting in very few (and short) breaks without airgun blasts. On a minute-by-minute basis the background noise level increased by 20 dB on average, but at times up to 70 dB above pre-exposure level.

Wisniewska et al. (2014) examined full-spectrum envelopes of airgun pulses during a 12-second firing interval for ranges of 0.5 to 8 nm from R/V Polarcus Asima (**Figure 7**). This showed that during the interval between pulses (1 pulse every 10 seconds), the instantaneous sound intensity did not fall back to the background level, even at the longest distances. This phenomenon was much more pronounced at ranges below 4 nm.

It was noted that inter-pulse reverberation might feed into potential chronic effects. Accordingly, obtaining more information on inter-pulse levels through G-T would be very helpful.

Figure 7: Figure 31 from (Wisniewska et al. 2014) – Development of mean instantaneous pressure (envelope) as a function of time after a shot, as measured at various distances (0.54 to 8 nm) from the source. The envelopes were calculated using the analytical signal (using the function 'hilbert' in Matlab). For each distance, the envelopes of 12 shots were averaged together and thereafter smoothed with a phase neutral low-pass filter (using 'filtfilt' in Matlab). The lowest (black) line is a similarly-smoothed envelope of the ambient sound recorded during a pause in the seismic operation.



7.7. Data collection

Wisniewska et al. (2014) noted that the quality and quantity of the input data are limiting factors for model precision. They recommend collecting high-quality environmental data and making them available to companies prior to the EIA-process.

The value of data quality was also illustrated through the ground-truthing of models for seismic surveys undertaken in Baffin Bay, where there was very little prior hydrographical and bathymetric information available. The comparison between sound speed profiles used in the EIA-models (Austin et al. 2012a, 2012b, Matthews 2012b) and the actual measurements showed that the magnitude of the near-surface low-sound-speed channel had been underestimated (MacDonnell et al. 2014). It was also clear in this study that the bathymetry had not been mapped in detail – as evidenced by the large deviations of the depths measured during the seismic surveys from the depth charts available for predictive modelling.

Part 4: Modelling of non-standard sources

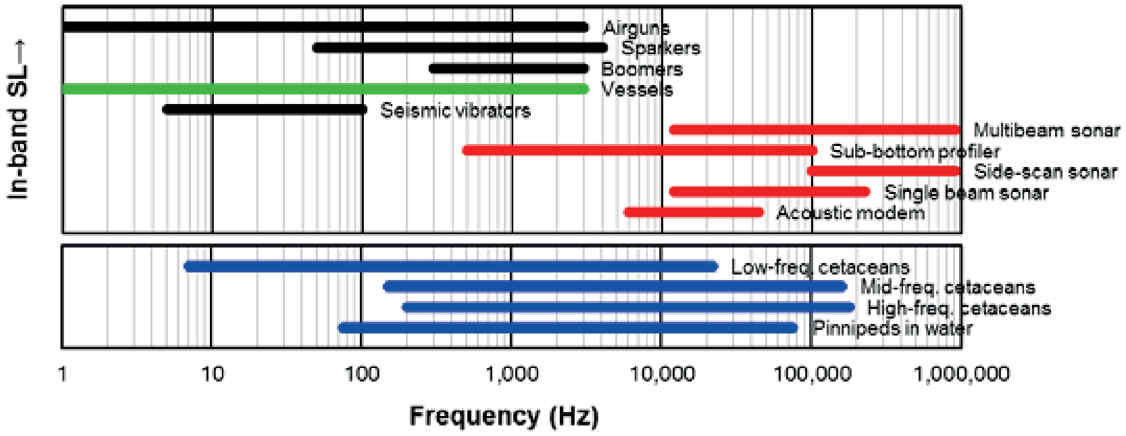
8. Modelling of non-standard seismic sources

Before a new source can be modelled, that source needs to be fully characterised, or at very least information regarding it provided, to allow for some level of understanding about its properties. A summary of frequency content for sources used during seismic surveys, and how they overlap with the hearing of marine mammals, is set out in **Figure 8**).

On this point the TWG discussed the need to model and measure horizontal noise propagation from novel sources, not just operational source characteristics. The TWG concluded that operators who plan to use novel high-amplitude sources must invest in horizontal noise propagation acoustic modelling and measurements, to inform impact assessments with a solid understanding of emission levels and directivity.

Figure 8: (Top) Approximate frequency ranges of sound emitted by vessels (green), E&P seismic sources (black), and E&P Engineering sources (red), ordered from top to bottom by approximate maximum in-band source level (SL, dB re 1 µPa @ 1 m).

(Bottom) Estimated auditory bandwidth of the four (underwater) functional marine mammal hearing groups (Southall et al. 2007), (Chorney and Carr 2011).



8.1. In-water vertical seismic profiling/borehole seismic survey/check-shot surveys

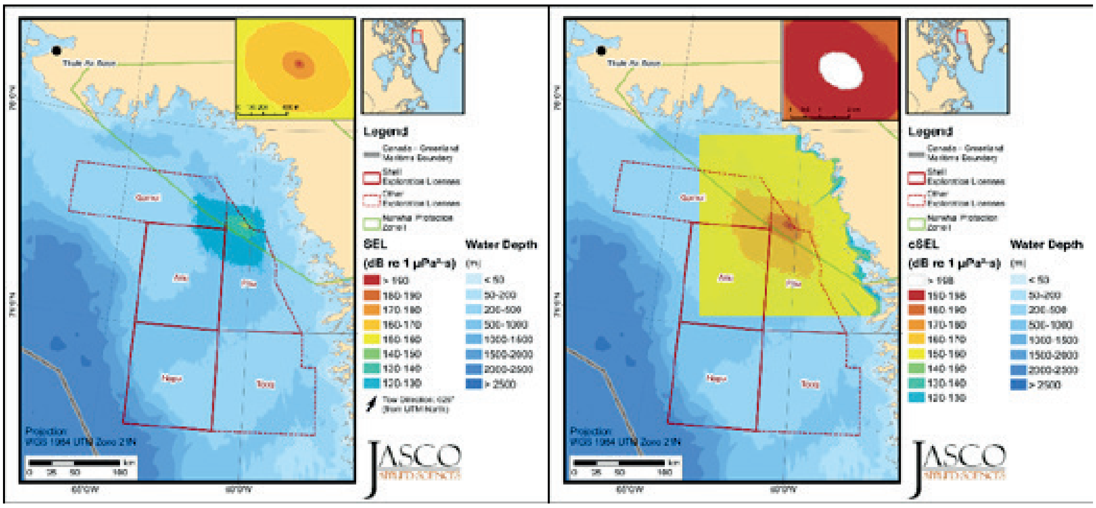
TWG considered modelling in-water vertical seismic profiling (VSP)/borehole seismic survey/check-shot surveys to be the same as for standard seismic modelling, but stationary or constrained to a particular area. While most within-hole sources for VSP are unlikely to generate much in-water noise, this is not necessarily true for explosives, which may also be used for these purposes.

The modelling methods applied to VSP and other stationary source surveys will be the same as those for standard surveys. VSP results are likely to be more re-usable due to the static/constrained location of the survey; however the ability to re-use results will depend upon:

- Array size consistency
- Sound speed profile consistency (seasonal variations)
- Length of VSP survey

An example of a small VSP array (140 in^3, compared to some VSP arrays of 500 in^3) towed behind a vessel in a localised area 1 × 2 km area of 639 m depth is shown in **Figure 9**.

Figure 9: Sound exposure levels (SELs) for a 140 in^3 airgun array, single shot (left) and aSELs from 24 h of seismic survey operations within a 1 × 2 km area (right), received maximum-over-depth sound levels. Blue contours indicate water depth in metres (Matthews 2012a).



8.2. Alternative sources: boomers, chirpers and others

Boomers, chirpers, sparkers and sub-bottom profilers are other sources that should be considered in addition to seismic sources. While they will produce lower SELs than airgun arrays, the SPL (rms and peak) can be significant at short ranges. Like multibeam sonars, modelling studies of these sources should account for the beam pattern of the source, and provide details about it. There is limited information about beam patterns, and all information relating to determining them and any assumptions used in determining on and off-axis levels should be provided.

An example is provided for a Knudsen Chirp 3260 sub-bottom profiler (**Figures 10** and **11** below), with ranges shown in **Table 5**. **Table 4** above shows the additional ensonification from a multibeam sonar and a sub-bottom profiler relative to an airgun survey alone.

Figure 10: ***Knudsen Chirp 3260 sub-bottom profiler*****: Maximum-over-depth broadband (3.5, 12, and 200 kHz) sound pressure levels around the source. Bathymetry contours (m) are shown in blue. (Zykov et al. 2012)**

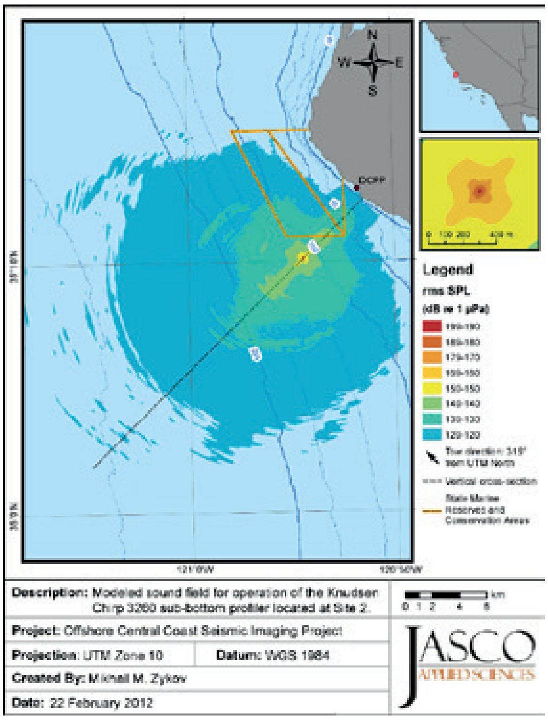


Figure 11: ***Knudsen Chirp 3260 sub-bottom profiler:*** **Vertical cross-section of the broadband (3.5, 12, and 200 kHz) sound pressure levels, up to 22 km from the source. (Zykov et al. 2012)**

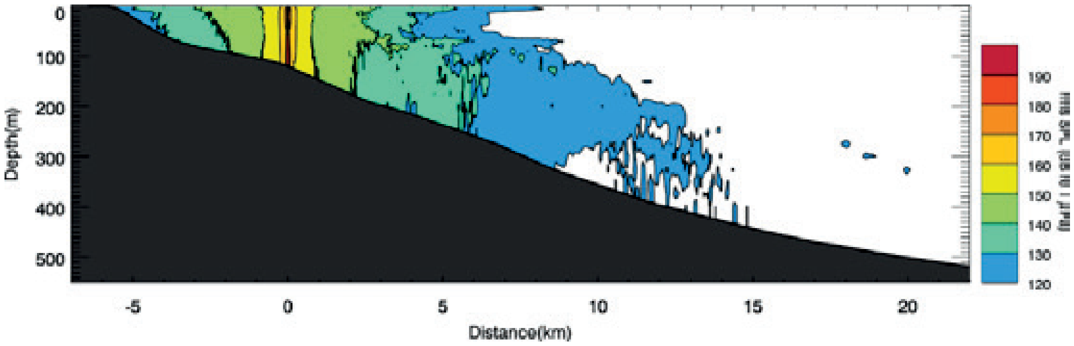


Table 5: Knudsen Chirp 3260 sub-bottom profiler: Maximum (Rmax, m) and 95% (R95%, m) horizontal distances from the source to modelled maximum-over-depth sound level thresholds (3.5, 12, and 200 kHz simultaneously), with and without M-weighting applied. (Zykov et al. 2012)

	Un-weighted		LFC		MFC		HFC		Pinnipeds	
	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
SEL (dB re 1 μPa^2·s)										
198										
192										
186										
179	< 10	< 10	–	–	< 10	< 10	< 10	< 10	< 10	< 10
rms SPL (dB re 1 μPa)										
208	< 10	< 10								
190	14	14	10	10	14	14	14	14	14	14
180	36	36	32	32	36	36	36	36	36	36
160	276	230	226	191	276	228	276	228	269	227
140	3,926	3,575	3,883	3,147	3,926	3,574	3,926	3,574	3,925	3,570
120	21,748	14,425	21,063	13,956	21,744	14,393	21,741	14,376	21,744	14,386

9. Modelling of non-airgun sources

9.1. Vibroseis

Vibroseis (or marine vibrator) sources are discussed in detail in the Non-Standard Surveys TWG report. Regarding modelling vibroseis, much depends on the source, with many sources operating at extremely low frequencies (ie sub-20 Hz). This is because marine vibrator sources either produce an acoustic signal through volume displacement using a vibratory plate, or are shell-driven by hydraulic or electro-mechanical actuators. This source produces an acoustic signal of controllable frequencies and duration, unlike an impulse source like the airgun. This signal is typically a swept sine wave, but can be any other controlled wave shape. Because of the inherent control over the vibrating surface, the output signal from a vibroseis strongly decreases (at rates as high as 50–100 dB per decade) in source level as frequency increases beyond those typically useful for seismic surveying (~100 Hz). The only energy emitted at frequencies above the selected maximum is created by the harmonic resonance of the vibrator.

Given all of this, sound propagation modelling for marine vibroseis sources may not need to extend as far into the higher frequency bands (above 1 kHz), as would be the case for an airgun-based source.

9.2. Multibeam sonars

The TWG noted that directly within the beam of a large multibeam sonar (eg 12 kHz EMN120 system) animals would be exposed to sound levels greater than most airgun-based seismic surveys. It was also noted that, compared to standard seismic sources, these sonars have a standard, defined source and beam patterns, burst shapes, etc.

Relevant impact zones will be determined by the Bio Rel TWG. However, while the SELs are much lower than those for airgun arrays, the peak and/or rms SPL levels over the pulse duration may be similar. Modelling studies of multibeams should account for, and detail, the beam pattern of the source.

The acoustic radiation pattern, or beam pattern, of a transducer is the relative measure of acoustic transmitting or receiving power as a function of spatial angle. Directionality is generally measured in decibels relative to the maximum radiation level along the central axis perpendicular to the transducer surface. The pattern is defined largely by the operating frequency of the device, and the size and shape of the transducer.

From a modelling perspective, a multibeam is much easier to model than an airgun array because its acoustic characteristics and beam pattern are well defined, the frequency bandwidth is narrow, and the frequencies are high enough that ray models are applicable. See **Figure 12** and **Figure 13** for examples of single shots, with corresponding radii shown in **Table 6**. **Figure 14** shows zones associated with an accumulated track line from the Madagascar stranding investigation (Zykov 2012).

Table 4 above shows the additional ensonification from a multibeam sonar and a sub-bottom profiler in relation to an airgun survey.

Figure 12: *Kongsberg EM 122 multibeam sonar* Maximum-over-depth (12 kHz) sound pressure levels around the source in 109 m (left) and 385 m (right). Bathymetry contours (m) are shown in blue. (Zykov et al. 2012)

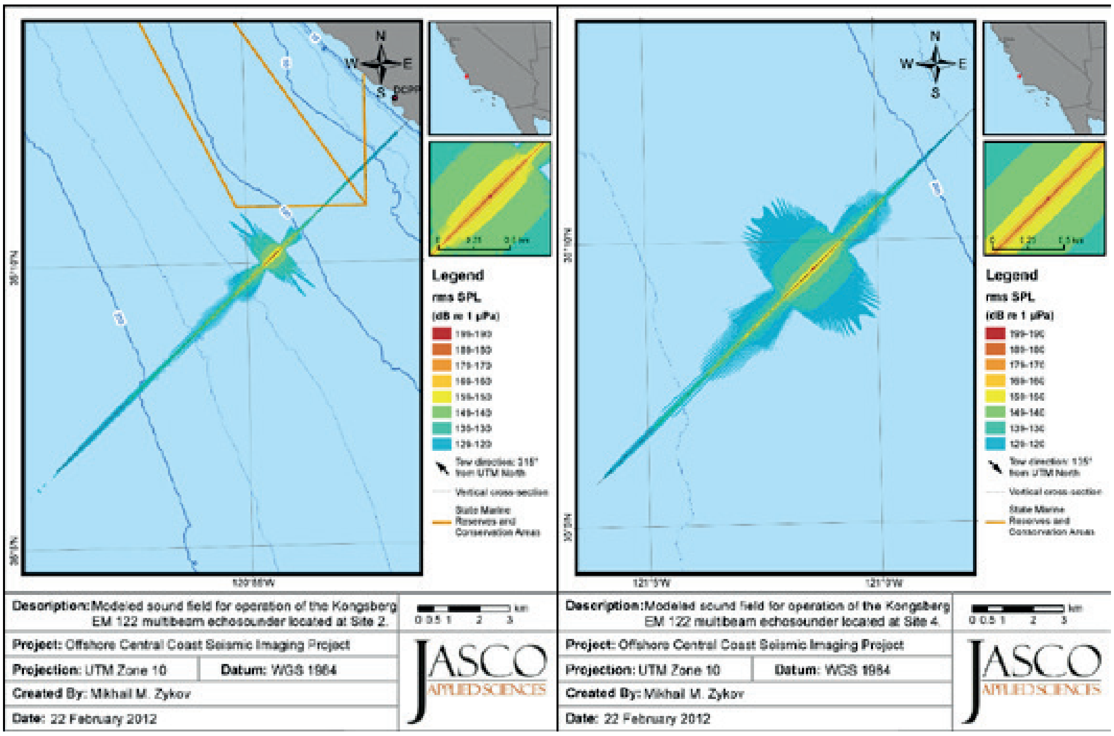
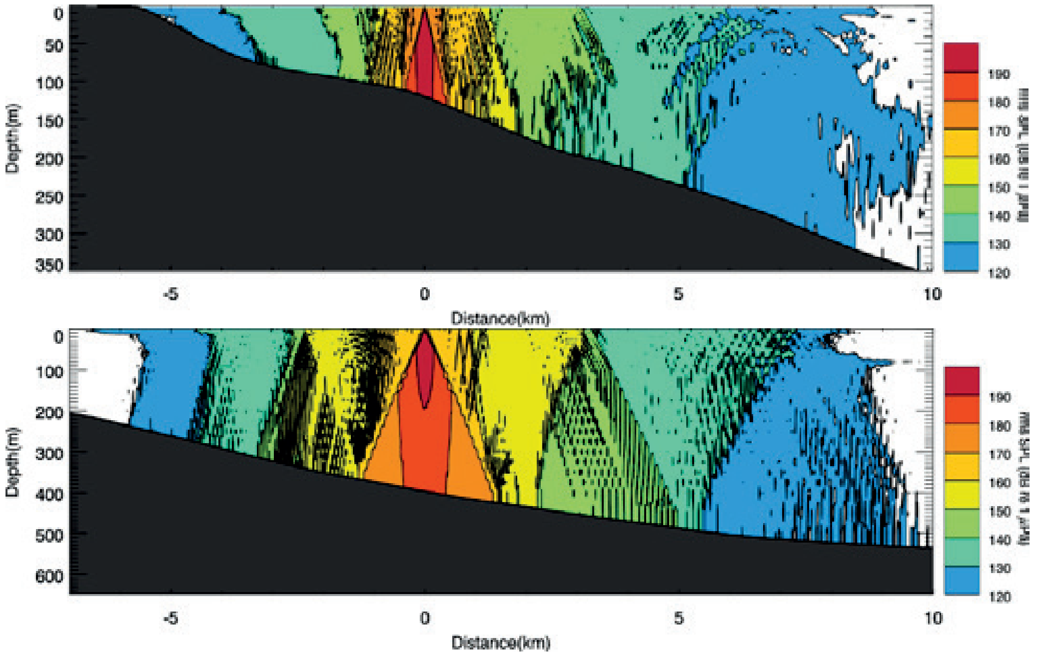


Figure 13: *Kongsberg EM 122 multibeam sonar*: Vertical cross-section of the (12 kHz) sound pressure levels, up to 10 km from the source in 109 m (top) and 385 m (bottom). (Zykov et al. 2012)

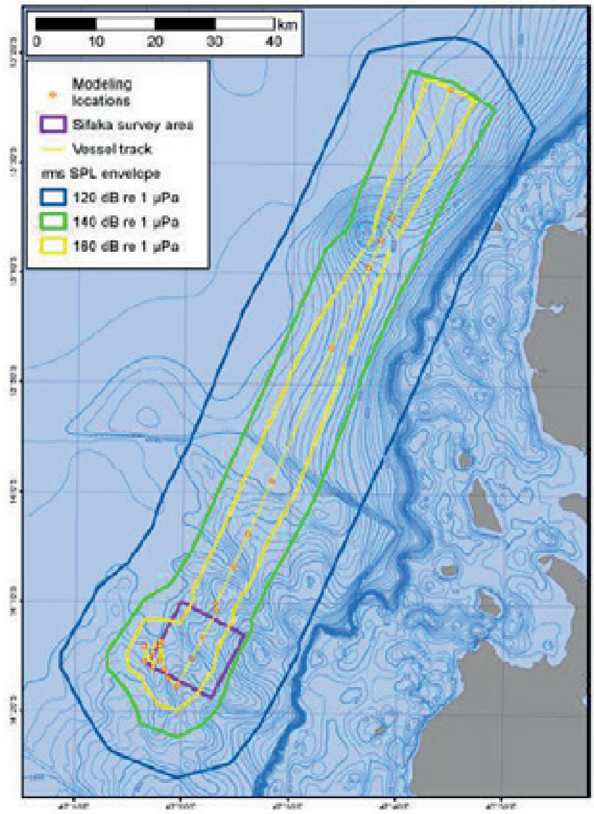


Modelling of this source is possible. However, DOC should decide if this should become a requirement, perhaps based on the sensitivity of the area the source is being used in. Due to the expected source levels and resultant sound fields, it is likely that behavioural disturbances, rather than injury, will be more important for assessing the overall effect of this source.

Table 6: *Kongsberg EM 122 multibeam sonar*: Maximum (R_{max}, m) and 95% ($R_{95\%}$, m) horizontal distances from the source to modelled maximum-over-depth sound level thresholds (12 kHz), with and without M-weighting applied.

	Un-weighted		LFC		MFC		HFC		Pinnipeds	
	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
109 m depth										
SEL (dB re 1 μPa²·s)										
198										
192										
186	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10
179	36	36	22	22	36	36	36	36	36	36
rms SPL (dB re 1 μPa)										
208	< 10	< 10								
190	164	162	121	119	164	162	164	162	164	162
180	430	388	416	374	430	388	430	388	430	388
160	1,477	1,180	1,222	1,016	1,477	1,180	1,477	1,180	1,477	1,159
140	3,966	2,905	3,570	2,622	3,966	2,905	3,966	2,905	3,966	2,891
120	11,376	8,378	10,627	7,537	11,306	8,357	11,306	8,364	11,291	8,272
385 m depth										
SEL (dB re 1 μPa²·s)										
198										
192										
186	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10
179	36	36	22	22	36	36	36	36	36	36
rms SPL (dB re 1 μPa)										
208	< 10	< 10								
190	164	162	121	119	164	162	164	162	164	162
180	531	501	404	388	531	501	531	501	515	487
160	1,760	1,385	1,434	1,237	1,760	1,378	1,760	1,378	1,675	1,364
140	4,963	3,839	4,899	3,839	4,963	3,839	4,963	3,839	4,963	3,839
120	9,891	5,927	9,503	5,387	9,891	5,918	9,891	5,920	9,891	5,883

Figure 14: Maximum extension of distances to specific maximum-over-depth root-mean-square (rms) sound pressure level (SPL) thresholds around the vessel while it was operating the multibeam sonar (Zykov 2012).



10. Active Acoustic Mitigation

10.1. Soft starts

The merits of modelling soft starts (or ‘ramp-ups’) appear limited, in terms of total sound input when compared to the full airgun array. The total contributions to aSEL would be minimal, and they are designed to induce disturbance and behavioural reactions. Modelling would not reveal much that we did not already know, and be largely limited to academic investigations.

However, when modelling a soft start, the assessment is more complex than simply repeating one source at many locations. There might be some merit in modelling this on a one-off basis for specific scenarios where a non-standard or new method of soft start is proposed, to see whether a soft start is achieving the desired changes in sound levels.

Model-based assessments of airgun soft-start operations have been conducted previously (eg Hannay et al. 2010). This report examined an industry-standard airgun array configuration of 28 active airgun elements, of varying sizes, with a total volume of approximately 3,100 in^3. The modelled soft-start sequence followed UK JNCC guidelines, and began with the smallest airgun, with additional airgun elements introduced at each step of the soft-start.

The synthetic pressure results were analysed to directly compute per-pulse SEL and cumulative SEL over all 230 source points of the soft-start. Example results are presented below in **Figures 15** and **16**.

Figure 15: Per-pulse and cumulative SEL for receivers on Profile 1 at 100 m depth (Hannay et al. 2010).

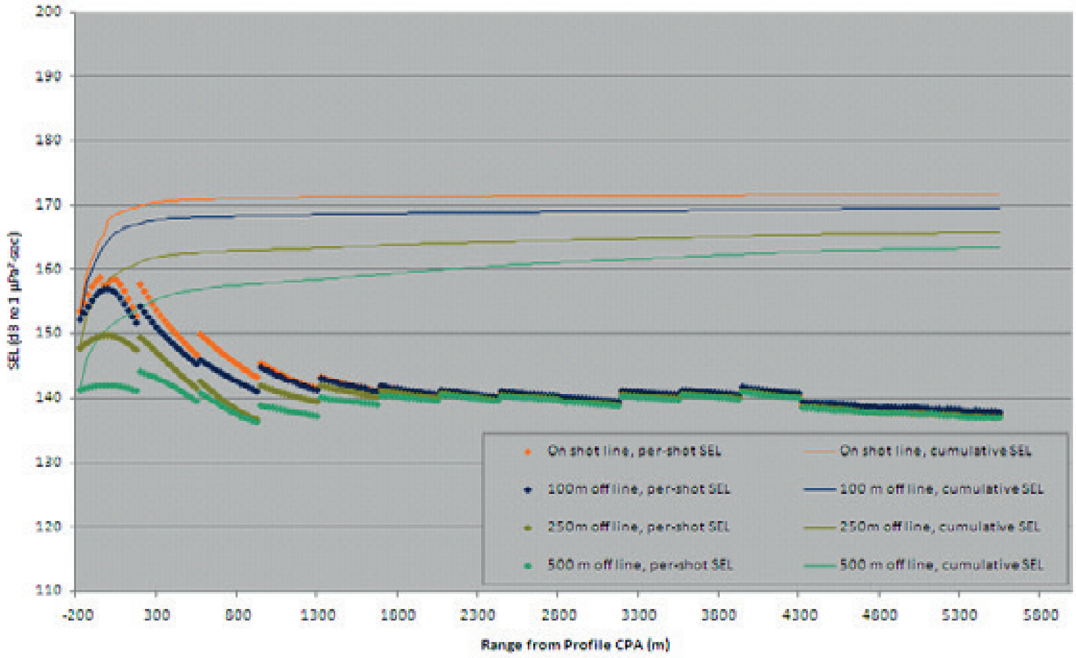
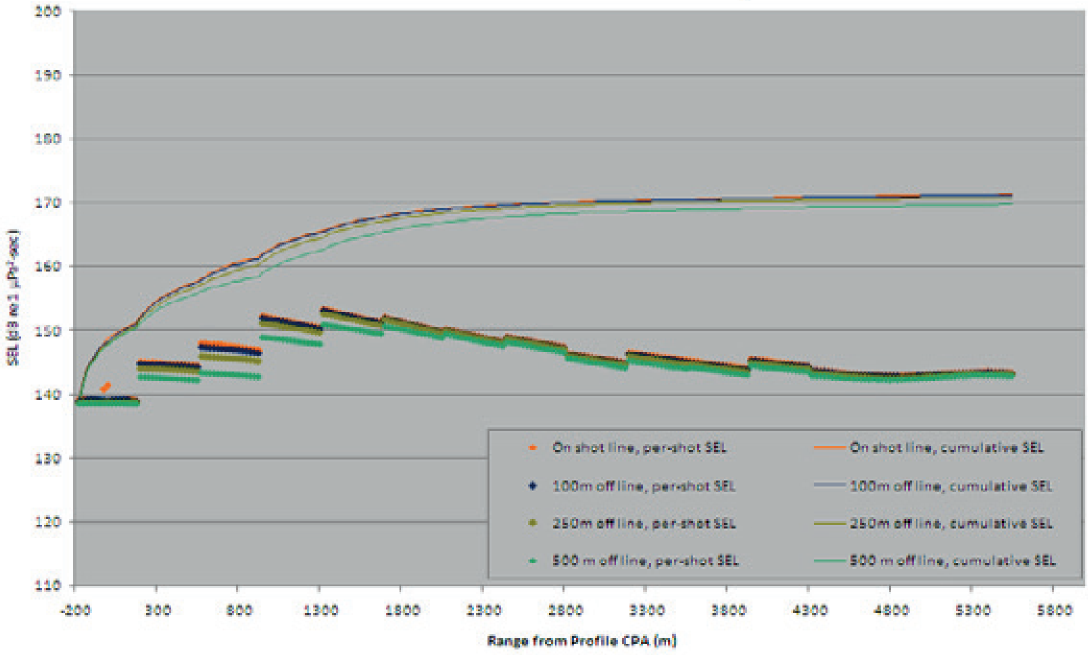


Figure 16: Per-pulse and cumulative SEL for receivers on Profile 1 at 1,000 m depth (Hannay et al. 2010).



10.2. Repellents (ie seal scarers)

Many secondary sources would contribute little to overall source levels, as is the case for soft-starts, leaving little need for modelling. The only possible exceptions are loud secondary sources, such as seal scarers, active acoustic monitoring, or whale-finding sonar. Modelling may be useful in these cases, depending upon the source level and beam patterns.

If modelling high-amplitude repellents, we suggest treating them as non-standard sources. These types of source are often poorly defined, with little information from the manufacturer. Studies on acoustic alarms have found that they vary widely (Erbe et al. 2011). Accordingly, manufacturer information should be tested, as these sources are not tested to the same level as others (eg seismic arrays or multibeam sonars).

10.3. Active sonar

Some success in detecting baleen whales with active sonar has been reported (eg Lucifredi and Stein, 2007). However, the feasibility of active acoustic detection has not been demonstrated for deep-diving whales, and the increased sound energy needed to detect these species may increase risk to the well-being of the animals (Zimmer 2011).

The TWG recommends operators should model the sound footprint of the multiple sources combined, if they plan to use whale-finding sonar on vessels– as per **Section 3.1**.

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Appendix 1: Example of the difference between the two rms SPL methods

The following is an edited extract from Austin et al. (2013). The full extract is available at http://www.nmfs.noaa.gov/pr/pdfs/permits/shell_chukchi_openwater_90dayreport.pdf

Extract: Airgun Pulse rms SPLs: 90%-Energy v. Fast Time-Weighted

The NMFS level A and B harassment thresholds for airgun sources are typically defined in the 90%-rms SPL metric, although no specific integration time is specified. With this metric, the SPL of an airgun pulse is the dB level of the root-mean-square pressure averaged over a time window containing 90% of the pulse energy (ie the 90%-energy pulse duration). This pulse duration changes with range from the source because of multipath dispersion of sound energy.

Depending on the relative strength of the multipath arrivals that constitute the received pulse, the 90%-energy pulse duration of some pulses can be longer or shorter than the nominal trend. These SSV measurements contained pulses with very short 90%-energy pulse durations (<30 ms), which yielded high rms SPLs at ranges of approximately 70–130 m (230–427 ft). Marine mammal mitigation for this survey applied harassment threshold distances based on the maximum measured ranges, which are influenced by this anomalous peak in the 90%-rms SPL, instead of ranges based on the nominal trend. In practical terms these 90%-energy pulse durations are much shorter than integration times of mammalian auditory systems – assumed to be around 200 ms for cetaceans (Madsen 2005). The resulting 90%-rms SPL magnitudes probably do not reflect how these very short impulses would be perceived.

Fast-time-weighted rms SPLs, computed over a fixed time window of 125 ms, better represent perceived sound levels than the 90%-rms SPL. Also, the constant integration time window makes the fast-time-weighted level a more consistent estimator of SPL as a function of range, because propagation effects do not influence this metric as they do the 90%-rms SPL.

Figure 17 compares the 90%-rms and fast-time-weighted rms SPL as functions of range for the 40 in^3 airgun array configurations, respectively. **Table 7** lists the corresponding distances to the SPL thresholds computed from the curve-fits present in **Figure 17**. For the 40 in^3 airgun array, the fast-time-weighted rms SPLs at ranges less than 200 m were fit separately from the data at longer ranges to match the trend in the data.

The two rms SPL metrics converge at ranges where the 90%-energy pulse durations are close to the 125 ms integration time. There is substantially less scatter in the fast time-weighted levels between 70 and 130 m than in the 90%-rms SPLs, and the fast-time-weighted rms SPLs are approximately 10 dB lower than the 90%-rms SPLs for each pulse. These results indicate that the maximum measured ranges to the 90%-rms SPL thresholds that were applied in the survey for marine mammal mitigation are precautionary in terms of sound perception by marine mammals.

Figure 17: Peak SPL, rms SPL, and SEL v. range for 40 in³ airgun array pulses at the SSV site using the 90%-energy pulse duration (left) and the fast time-weighting pulse duration of 125 ms (right). Solid line is the best fit of the empirical function to the rms SPLs. Dashed line is the best-fit line shifted up to exceed 90% of the rms SPLs (ie the 90th-percentile fit).

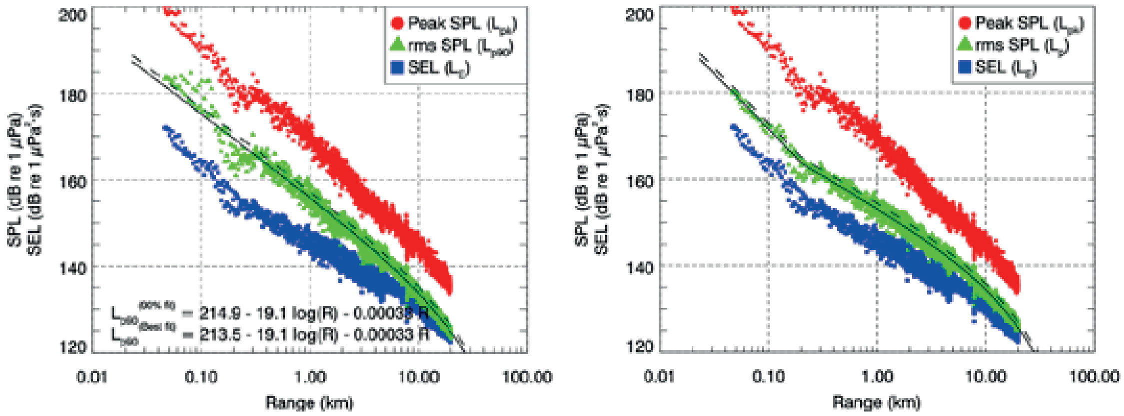


Table 7: Distances to rms SPL thresholds at the SSV site for the 40 in³ airgun array as determined from fits to the rms SPLs in Figure 23.

	90%-rms SPL		Fast-Time-Weighted SPL	
SPL Threshold (dB re 1 µPa)	Best-fit distance (m)	90th-percentile distance (m)	Best-fit distance (m)	90th-percentile distance (m)
190	17†	20†	19†	21†
180	56 (123*)	67 (123*)	47	53
170	190	220	120	130
160	620	720	350	430
150	1,900	2,300	1,600	1,900
140	5,600	6,400	5,600	6,500
130	14,000	15,000	15,000	16,000
120	27,000†	29,000†	28,000†	30,000†

* Not from fit—maximum range at which the measured rms SPL exceeded the threshold.

† Extrapolated beyond the measurement range.

Appendix 2: Incorporating oceanographic features

To inform discussion of results in a typical environment, examples of a single shot (**Figure 18**) and accumulated single survey (**Figure 19**) sound fields are shown below.

Figure 18: Sound exposure levels (SELs) at Site 2: Received maximum-over-depth sound levels from the 3D airgun array (4,240 in^3) for a single shot. Blue contours indicate water depth in metres. (Matthews 2012a).

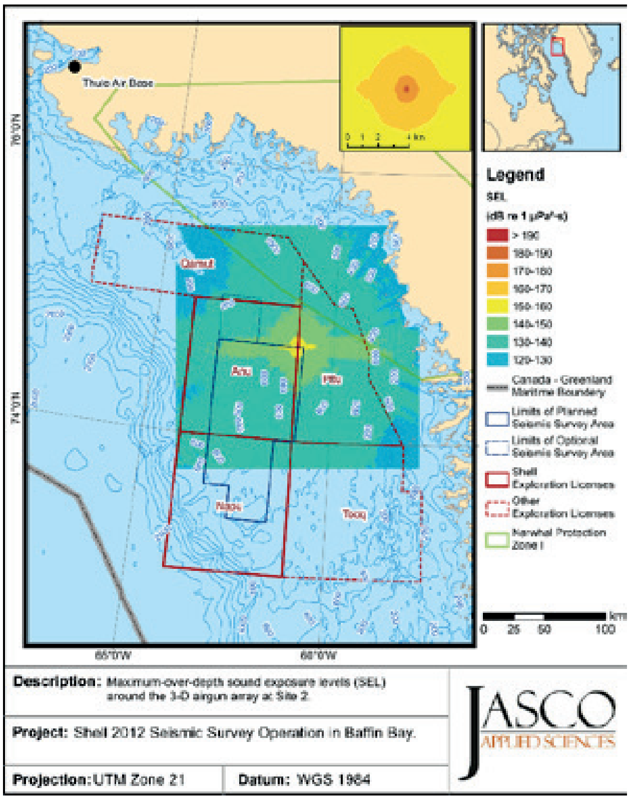
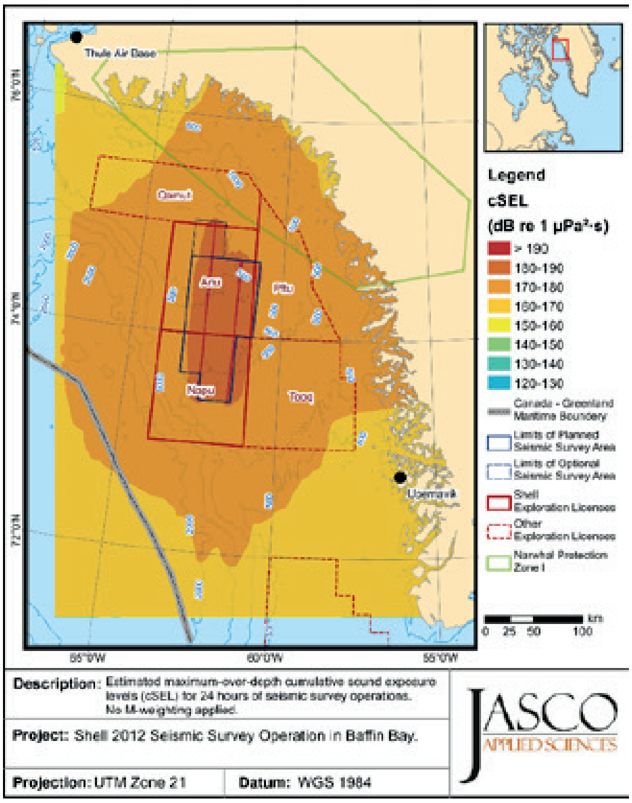


Figure 19: Unweighted accumulated sound exposure levels (aSELs): Received maximum-over-depth aSELs from 24 hr of seismic survey operations with the 4,240 in^3 airgun array. (Matthews 2012a).



Sound transmission: shallow v. deep water

Seismic sound propagation is strongly influenced by water depth. In deep waters, sound may propagate a significant distance before interacting with the seabed. In these cases, sound levels at distances corresponding with injurious effects could be primarily due to direct-path propagation, because the bottom reflection will have travelled much further and will consequently be much weaker. Conversely, in waters of a depth less than 50 m, the seabed reflects substantial energy back into the water – considerably increasing sound levels even at short distances from the source. This additional reflected sound energy often leads to substantially larger injury zones (see **Table 8** for an illustration of this effect).

To complicate matters, the distances from seismic sources corresponding to behavioural effects may occasionally be greater in deep water than shallow water. For instance, this can occur when sound speeds at depth are greater than those nearer to the surface. This condition leads to an upward-refracting environment, which turns relatively shallow-angle propagating sound energy back up before it interacts with the seabed. The sound then essentially skips along under the surface, turning upward from depth on each skip. As (in calm conditions) there is almost no energy lost from the surface reflections, and because the sound avoids reflections from the seabed, it loses very little energy and can propagate relatively uninhibited to very large distances. In shallower water, sounds propagating to large distances must reflect multiple times from the seabed, losing some energy on each reflection. Attenuation is also generally greater in shallow water than in deeper water due to the multiple interactions of the sound with the surface.

However, there are some special cases where sound may propagate well in shallow waters. It was, for example, noted that when you move into shallow water of less than 10 m you get into areas of trauma zone; in slightly deeper areas (that are still shallow) however, this does not occur.

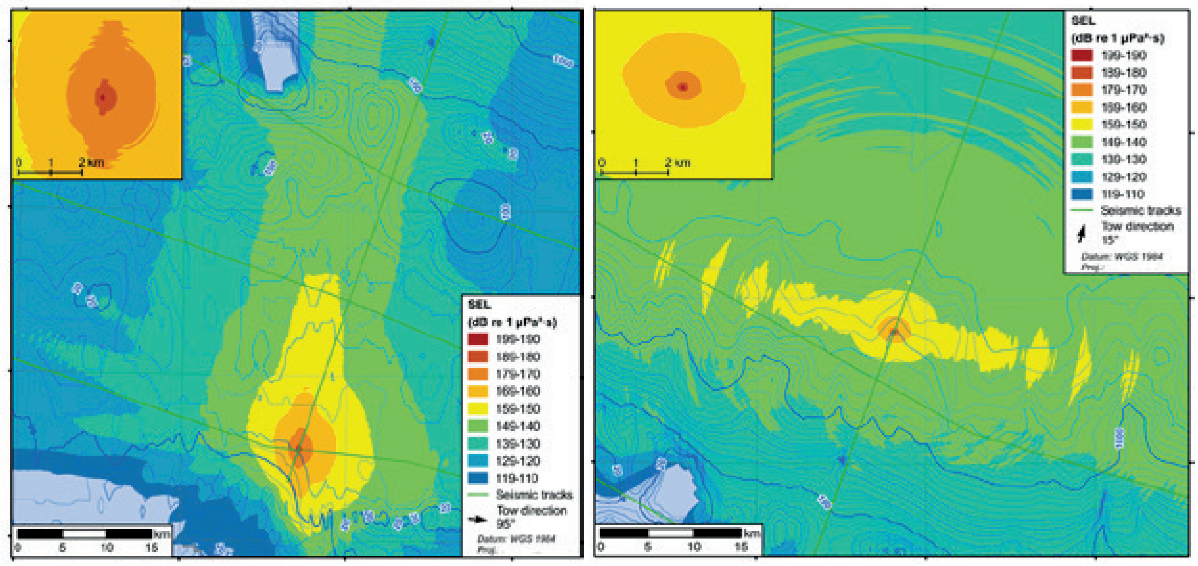
Unfortunately, it is difficult to consistently predict which environments lead to longer or shorter distances for sound pressure levels to reach injurious and behaviour-effects levels. In deep waters the sound speed profile plays a more important role than seabed type. In shallow waters the seabed reflectivity is most important. At intermediate depths the combinations of these parameters must be considered. Models can be extremely good at predicting the complex refraction and reflection characteristics that influence sound levels at distance from seismic programs. However, influence of sea state and tidal volumes (especially in shallow water) can result in modelling that deviates from real-world situations. In many such situations, there is little alternative to taking measurements at the same location with the same source to replace model predictions.

A comparison of shallow and deep sites from a modelling study is provided in **Table 8** and **Figure 20**, below. The sites are in the same area, however three different geoacoustic models were constructed, for the depth categories of <100 m, 100–1,000 m and >1,000 m.

Table 8: Example single shot radii for a >4,000 in^3 array, 10 dB conversion factor between SEL and rms SPL.

		$R_{95\%}$		
rms SPL (dB re. 1 µPa)	SEL (dB re. 1 µPa^2·s)	30 m water depth	500 m water depth	1,500 m water depth
210	200	20	20	20
200	190	110	60	60
190	180	530	170	170
180	170	2,000	600	550
170	160	5,300	2,400	1,800
160	150	17,000	20,000	25,000

Figure 20: Single shot SEL examples for a >4,000 in^3 array, 30 m depth (left) and 1,500 m (right)



Slope

It is not possible in general to transfer model results across different bathymetric conditions. However, what constitutes ‘different’ conditions is more substantial in deep water (>700–1,000 m), as greater absolute changes are needed to induce the same percentage change in parameters. Sampling of larger areas can therefore be represented by individual model runs as you go deeper.

Acoustic propagation depends on slope, depth, seabed properties and water properties. If these are all the same then model results should be transferable, accounting for different source emission levels. Canyons and hills can disrupt normal propagation and thus must be considered individually.

Examples of the propagation up and down slopes are shown in **Figures 21, 22** and **23**, below.

Figure 21: Maximum-over-depth broadband (10 Hz to 2 kHz) sound pressure levels for a 3,300 in^3 airgun array, up to 75 km around the source. Bathymetry contours (m) are shown in blue (Zykov et al. 2012).

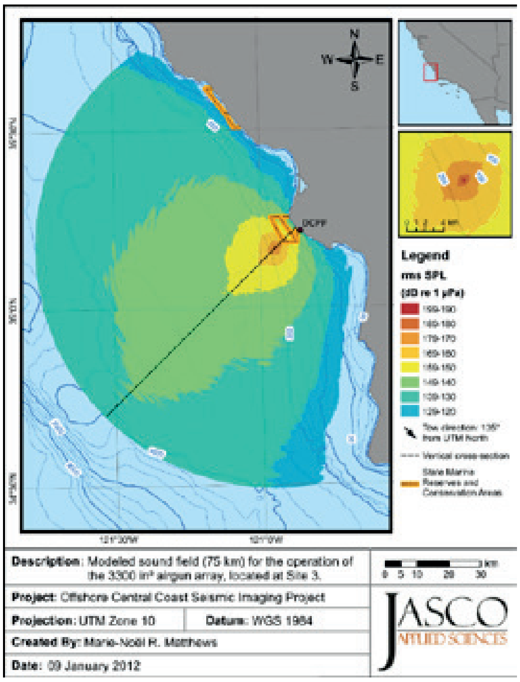


Figure 22: Vertical cross-section of the broadband (10 Hz to 2 kHz) sound pressure levels for a 3,300 in^3 airgun array, up to 75 km around the source (Zykov et al. 2012).

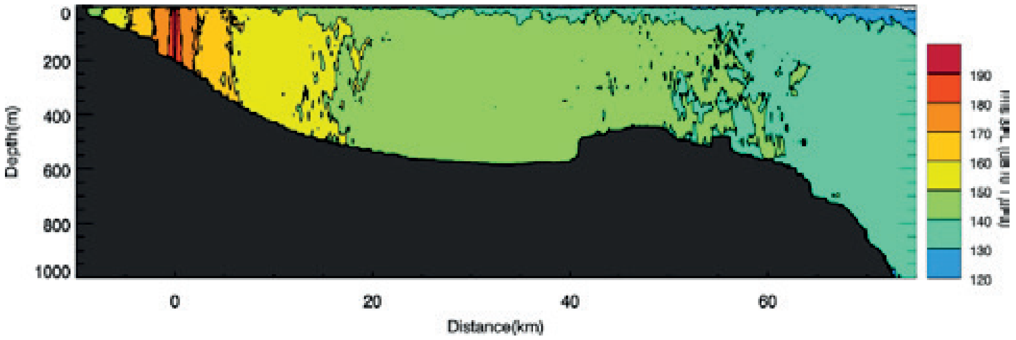


Figure 23: Upslope/downslope propagation example from the Australian GAB, 4,130 in^3 array, Maximum-over-depth broadband (8 Hz to 1 kHz) sound exposure levels (Maggi and Duncan 2011, Sound Exposure Level Modelling for the Ceduna 3D Seismic Survey).