Modelling the propagation of underwater sound from different seismic airgun configurations for the N4 area in the Dutch North Sea

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Title

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1 INTRODUCTION

ONE-Dyas is planning an exploratory seismic survey in license area N4, located on the Dutch continental shelf area (Figure 1.1). Seismic surveys are used as a method to map the geological characteristics of the subsoil. These surveys are conducted using a configuration of airguns as a sound source and arrays of hydrophones, i.e. streamers, as sound receptors. The reflected sound waves that are measured using the streamers give detailed information on the geology and sedimentology of the subsoil.

While only downward directed sound waves are needed to map the subsoil, part of the sound waves generated by the airgun configuration propagate in the horizontal plane. To reduce the environmental impact of sound sources in the North Sea, legislation in Germany includes a sound level that may not be exceeded at 750 m distance from a sound source. The block N04 exploration area is bordering the Dutch-German border and produced sound levels should, on the German side of the border, comply with the following requirements:

1. Sound Exposure Level (SEL) ≤ 160 dB re 1 µPa²s at 750 m from the border;
2. Peak Pressure Level (SPLzp) ≤ 190 dB re 1 µPa at 750 m from the border;
3. Sound Exposure Level (SEL) < 140 dB re 1 µPa²s in minimal 90% of Natura 2000 Borkum Riffgrund area.

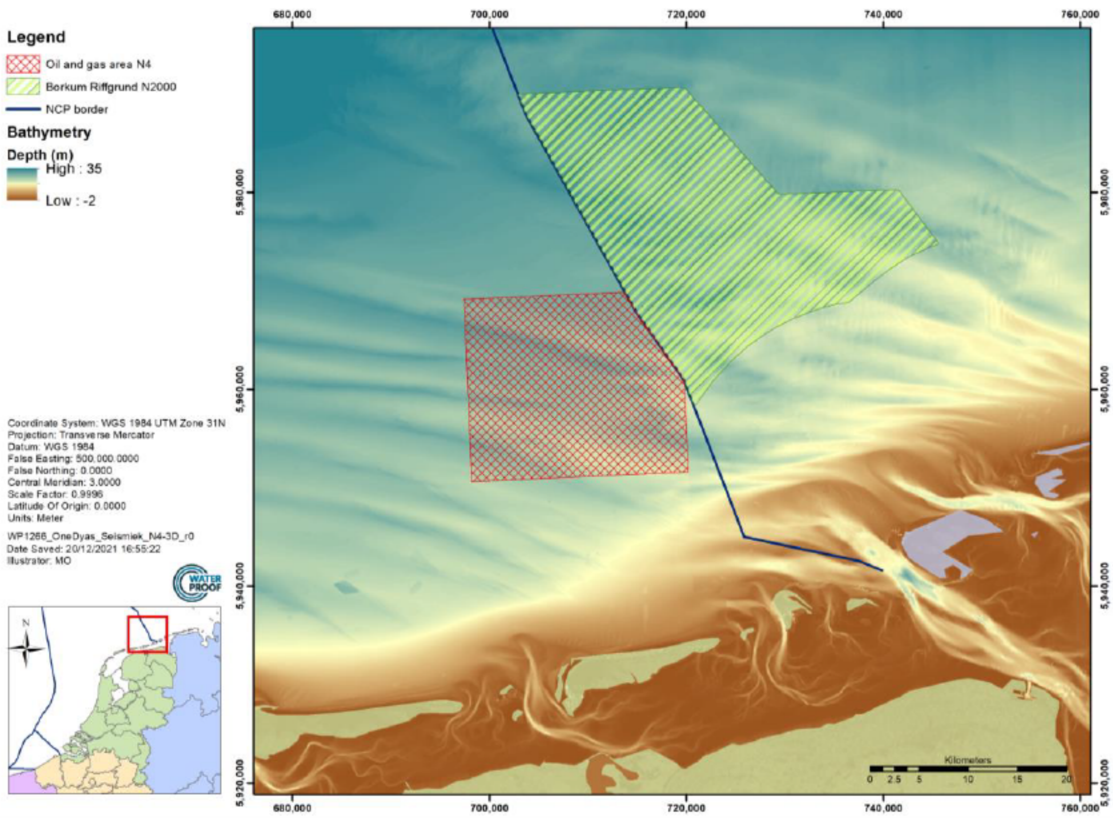

Figure 1.1 Location of the (red) N4 area in the Southeastern part of the Dutch North Sea and the (green) Natura 2000 Borkum Riffgrund area. The blue line represents the border between the Netherlands and Germany.

To ensure these thresholds are not exceeded, the environmental impact of different airgun configurations need to be known in advance for the design of the seismic survey. The allowed range between the survey vessel and the Dutch-German border have been estimated for different airgun configurations in two previous studies for this area. Simulations with the sound propagation model Aquarius 3.0 were conducted in 2018 (Te Raa et al., 2018) and resulted in ranges to the SEL-based threshold (SEL ≤ 160 dB re 1 μPa²s) between 280 and 1780 m for selected airgun configurations. This model, however, overpredicts propagation loss when compared with measurements that were conducted during the Hansa 4-quads seismic survey (Prior et al., 2015a, 2015b). A more measurement-based approach using the same measurement data, and using simple damped cylindrical spreading equations, indicated that the distance to the SEL-based threshold is more likely to be in the range between 1000 and 8000 m for the different airgun configurations (Brinkkemper and Snoek, 2019).

ONE-Dyas requested WaterProof to setup a well-calibrated and validated acoustic model to gain more insight in underwater sound levels and to determine what source configurations can be used in the project area, without exceeding the sound thresholds in Germany.

2 BACKGROUND

2.1 SEISMIC SURVEYS IN SHALLOW WATER

2.1.1 Seismic surveys using airguns

Seismic surveys are a non-intrusive and efficient method, in contrast to exploratory boreholes, to map geological layers in the seafloor. These surveys are based on the emission of low-frequency pressure waves, or sound waves, that penetrates the seafloor. The reflection of these waves are measured and provide information on the characteristics of the geological layers.

The sound source that is used in offshore seismic surveys is a cluster of airguns. These airguns produce sound by releasing compressed air, which cause the formation of an air bubble under water. This air bubble rapidly expands as the pressure within the bubble is larger than the hydrostatic pressure of the surrounding water, this generates a loud explosive sound. Due to the speed of the expansion, the pressure within the air bubble at the moment of maximal expansion is smaller than the hydrostatic pressure, and the air bubble thus collapses, down to nearly its original volume. This process repeats itself until the oscillation dissipates due to friction and/or the bubble reaches the water surface due to its buoyancy. The consecutive expansion and contraction of the air bubble generates low frequency seismic waves in the water column.

To get the needed output signal strength and sound directionality, individual airguns are combined in one or multiple strings that together form an array. The output strength of an airgun array is characterized in the total volume (in cubic inch) of all airguns combined and the used air pressure (in psi). These arrays are designed such that most of the seismic energy is directed vertically downward to penetrate the seabed. There are, however, also sound waves emitted in the horizontal plane, which can propagate over large distances in the water column. The directionality of the emitted sound in the horizontal plane depends on the array design.

Conventional airguns release the entire volume of compressed air at once and emit sound with a wide range in frequency, while only sound waves in the frequencies < 100 Hz are needed for seismic exploration. In particular the higher frequencies are audible to marine cetaceans and could disturb and potentially injure animals that are in the vicinity of a survey vessel. To address this issue, the eSource airgun was developed. These airguns have a redesigned air outlet and release the compressed air in a more controlled manner, this results in a significant reduction in emitted sound levels in the frequencies > 100 Hz and thus reduces the environmental impact.

The seismic reflections from the subsurface are measured using strings of hydrophones with a length in the order of a few kilometers. These strings are towed behind the seismic acquisition vessel. Measured sound reflections are used to construct a detailed image of the geological structure of the seafloor.

2.1.2 Propagation of sound in shallow water

The sound waves that are emitted from an airgun array in the horizontal plane will propagate in the water column and have an impact on the environment, e.g. can cause injury or disturb marine mammals. The received sound level (RL) at a certain distance from the sound source can be described by the classic sonar equation:

$$RL = SL - PL,$$

In which SL is the sound source level and PL is the propagation loss between the source and the receiver. The propagation loss represents the weakening of sound waves over the distance between a sound source and a receiver, the rate per unit distance depends on characteristics of the water column, seabed and sea surface.

In shallow water, propagating sound waves are trapped between the water surface and the seafloor, a feature that allows for the propagation of sound over long distances. Whether water is acoustically shallow depends on the sound frequency of interest, but is generally defined as the waters of the continental shelf, i.e. water depths less than 200 m. As the sound is trapped between the sea floor and the water surface, and sound waves are (partly) scattered, reflected or refracted at each interaction, the properties of these boundaries are relatively important for the propagation loss.

The earlier mention that shallow water acts as a waveguide for sound waves does not apply to low frequencies. Lower frequencies are not trapped between the seabed and sea surface, but dominantly propagate into the seabed. There is thus a critical frequency below which sound does not propagate over large distances in the water column. This cut-off frequency depends on the water depth and the ratio between the sound speed in water and in sediment, as:

$$f_c = \frac{c_w}{4h} / \sqrt{1 - {c_w}^2/{c_s}^2},$$

In which f_c is the critical frequency, c_w is the speed of sound in water, c_s is the speed of sound in the sediment and h is the water depth. The relation between the cut-off frequency with water depth is visualized for a seabed consisting of fine and coarse sand in Figure 2.1. For the water depths in this study, between 20 and 35 m, the cut-off frequency is between 43 (28) and 25 (16) Hz for fine sand (coarse sand).

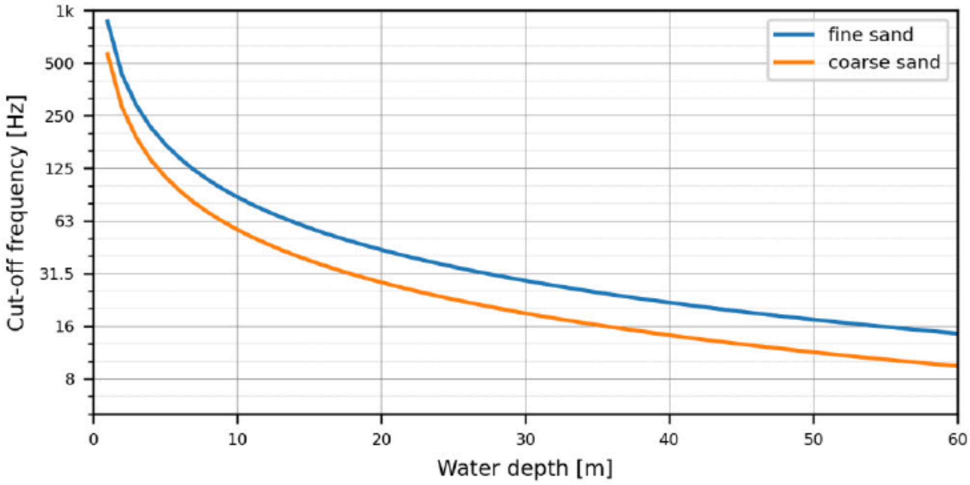

Figure 2.1 Cut-off frequency versus water depth for fine sand and coarse sand.

2.1.3 Sound level metrics

Sound is the result of pressure variations that propagate through a medium. At the location of a receiver in this medium, i.e. the ear of an animal, a microphone in air or a hydrophone in water, sound is received as pressure variations over time. The received sound pressure waves can be characterized by different sound level metrics.

The Sound Pressure Level (SPL) is defined as the mean square sound pressure in decibels (dB re 1 μPa) relative to a reference acoustic pressure:

$$SPL = 20log_{10}\left(\frac{p_{RMS}}{p_{ref}}\right),$$

in which pRMS is the root-mean-square of the acoustic pressure over a certain time period, and p_{ref} is the reference pressure, 1 μPa.

The broadband Sound Exposure Level for a single pulse (*SEL_{sp}*) in dB re 1 μPa²s is calculated for each sound pulse individually as:

$$SEL_{sp} = 10log_{10}\left(\frac{E}{E_{ref}}\right),$$

in which *E* is the sound exposure in μPa²s, integrated over the duration of a single pulse, and E_{ref} is 1 μPa²s. The single-pulse SEL is normally used to quantify the possible impact of impulsive sound on marine mammals and legal sound thresholds are thus often based on this parameter. In German legislation, the 95th percentile of all SEL_{sp} (or 5% exceendance level, SEL05) is used as the sound metric to define a threshold at 750 m from a sound source. The method to calculate the SEL05, i.e. over which period, is defined for offshore pile-driving, i.e. one foundation, but not for seismic surveys.

The zero-to-peak sound pressure level (SPL_{zp} or L_{peak} in dB re 1 μPa) is the maximum magnitude in sound pressure in the peak window:

$$L_{peak} = 20log_{10}(max|p(t)|).$$

The SPL en SEL values can also be calculated in one-third octave frequency bands to gain insight in the frequency content of the measured sound. Here, these bands are defined on the base-ten convention with centre frequencies between $10^{0.7}$ and $10^{4.2}$, corresponding to nominal frequencies 5 Hz and 16 kHz. Levels were calculated by a summation of the amplitude of the fourier transform for the frequencies that lie within these bands. In case the time signal is too short to attain sufficient resolution in the low frequency bands, this resolution can be enhanced by zero-padding the time series before performing the fourier transform.

3 METHODOLOGY

3.1 BATHYMETRY AND SEABED SEDIMENT

The bathymetry for the acoustic model was retrieved from the GEBCO (General Bathymetric Chart of the Oceans) database, with a resolution of 15 arc seconds (0.37 km, Figure 3.1). Median water depth for the calibration area is 33.7 m, for the area of interest 25.2 m (Figure 3.2). The area of interest is characterized by sand ridges with a WNW – ESE orientation and a height of 4-5 m. Range-dependent bathymetry is taken into account in the model approach and differences in the water depths between the calibration area and the area of interest are thus included.

The properties of the seabed sediments were attained from the Dutch atlas of seabed sediments, borehole surveys available in the Dutch DINO repository and from borehole surveys delivered by ONE-Dyas. Spatial data on the characteristics of seabed sediments show a high heterogeneity, with median grain sizes between 200 and 800 µm. The Dutch DINO repository as well as the data provided by ONE-Dyas, include boreholes in which the upper 2 m were characterized as fine sand, as well as boreholes in which the top soil consists of gravel. Borehole descriptions regularly indicate the presence of cobbles and boulders even when the general sediment is characterized as fine sand.

The median in the spatially variable grainsize is similar for the area of interest and the calibration area, the range in grainsizes present is slightly larger in the calibration area (Figure 3.2).

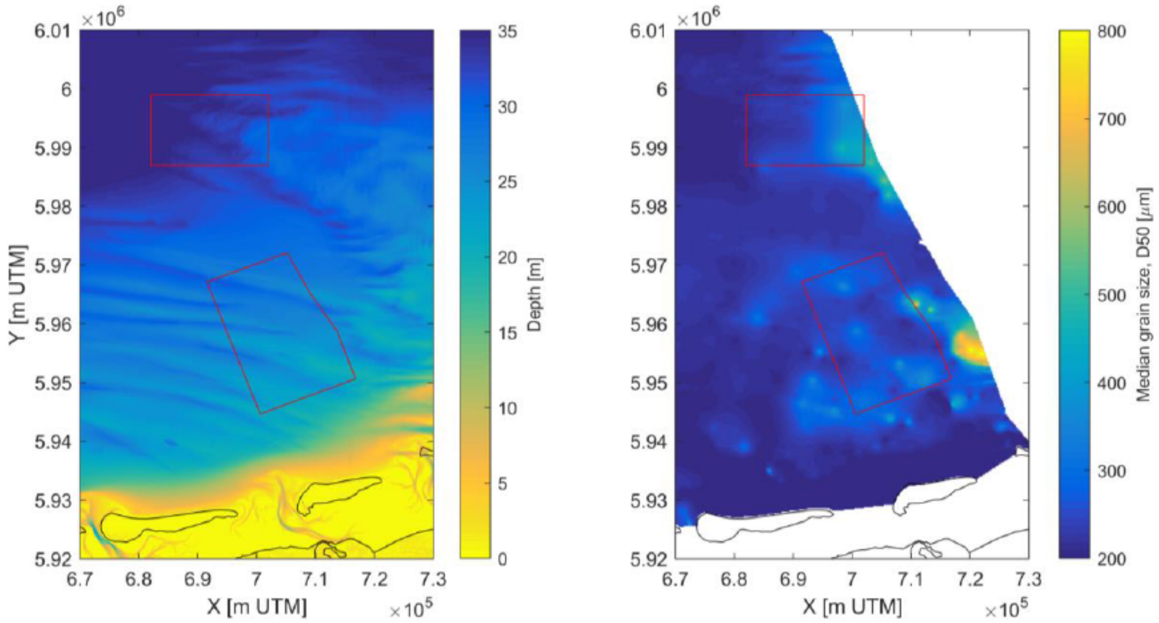

Figure 3.1 Bathymetry and d50 (median grain size) in the area of interest (Southern contour) and the calibration area (Northern contour).

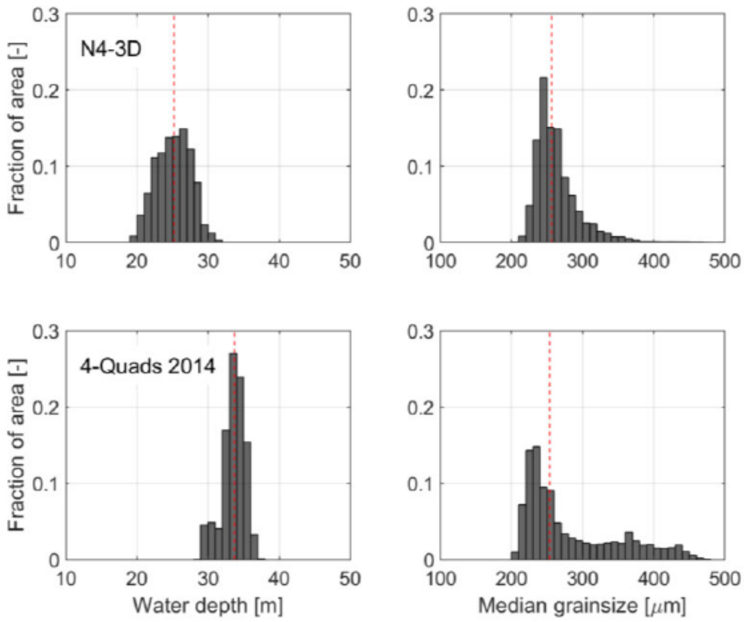

Figure 3.2 Water depth and medium grainsize at the seabed for the area of interest (N4-3D) and the calibration area (4-Quads 2014) as indicated in Figure 3.1. Red dashed lines indicate the median value.

3.2 MEASUREMENTS FOR MODEL CALIBRATION/VALIDATION

3.2.1 Available dataset

An extensive dataset on the propagation of underwater sound from different airgun configurations was collected by Hansa Hydrocarbons Ltd (Hansa hereafter) in the Dutch North Sea (Snoek et al., 2015a,b). These measurements were conducted approximately 40 km North of the N04 area, and the sites thus have comparable bathymetry and sedimentology.

In total four airgun configurations were used (Table 3.1) in two surveys, M1 and M2. The airgun configurations were towed approx. 200 m behind the seismic vessel at a water depth of 6 m. Survey M1 represents an entire seismic survey with the largest source array, survey M2 comprised of three tests with different airgun configurations.

Table 3.1 Overview of the four source configurations that were part of the 4-quads tests (Snoek et al., 2015b)

Seismic tests	Source configuration	Date and time (UTC)
M1	3147 cu. in. in 2000 psi, dual source mode	27 Jul. - 6 Sep. 2014
M2T2	1695 cu. in. in 2000 psi, dual source mode	06 Sept. 2014, 12:24 – 13:30
M2T3	1049 cu. in. in 1000 psi, single source mode	06 Sept. 2014, 18:03 – 19:26
M2T1	1049 cu. in. in 2000 psi, single source mode	06 Sept. 2014, 22:25 – 23:49

Underwater sound measurements were collected during these tests with four bottom-mounted and one vessel-mounted recorder, see Snoek et al. (2015b) for details. As the position of the seismic vessel changes during the tests, sound levels were measured at different distances and at different azimuths from the airgun array.

The collected sound measurements were used to calculated Sound Exposure Level (SEL), root-mean-square Sound Pressure Level (SPL), both broadband as well as in one-third octave frequency bands, and the zero-to-peak Sound Pressure Level (SPL_{zp}) and peak-to-peak Sound Pressure Level (SPL_{pp}) for each individual identified sound pulse that could be related to an airgun array shot.

To calculate these pulse characteristics, a time window needs to be defined around the identified pulses. An often-used practical approach, that provides accurate broadband values and limits contamination by background sound levels, is to define the time window from 5% to 95% of the cumulative energy of a sound pulse, including 90% of the total energy of the sound pulse (Figure 3.3). The downsides of this approach are that; (1) the window length is short (typically < 0.5 seconds) and low frequency content in the pulse signal can't be identified, and (2) when a low-frequency signal precedes (as in Figure 3.3) or succeeds the main sound pulse it is not included in the analyses window.

3.2.2 Re-analyses of measured data

To determine the difference between using a 90% and 100% time window on the calculated sound levels in one-third octave frequency bands, the dataset from Snoek et al. (2015a,b) was re-analyzed with a window of 2 seconds around each detected sound pulse. SEL values were calculated in deci-decade frequency bands with center frequencies between $10^{1.3}$ and $10^{4.2}$, corresponding to nominal frequencies 20 Hz and 16 kHz, for both the detected acoustic events and background sound periods in between. Sound exposure levels of the acoustic events were then compared per frequency band with the background sound, frequency bands for which the signal-to-noise ratio was < 6 dB were excluded from further analyses. Broadband SEL values were calculated by a summation over the frequency bands in which the sound levels were sufficiently elevated above the background signal.

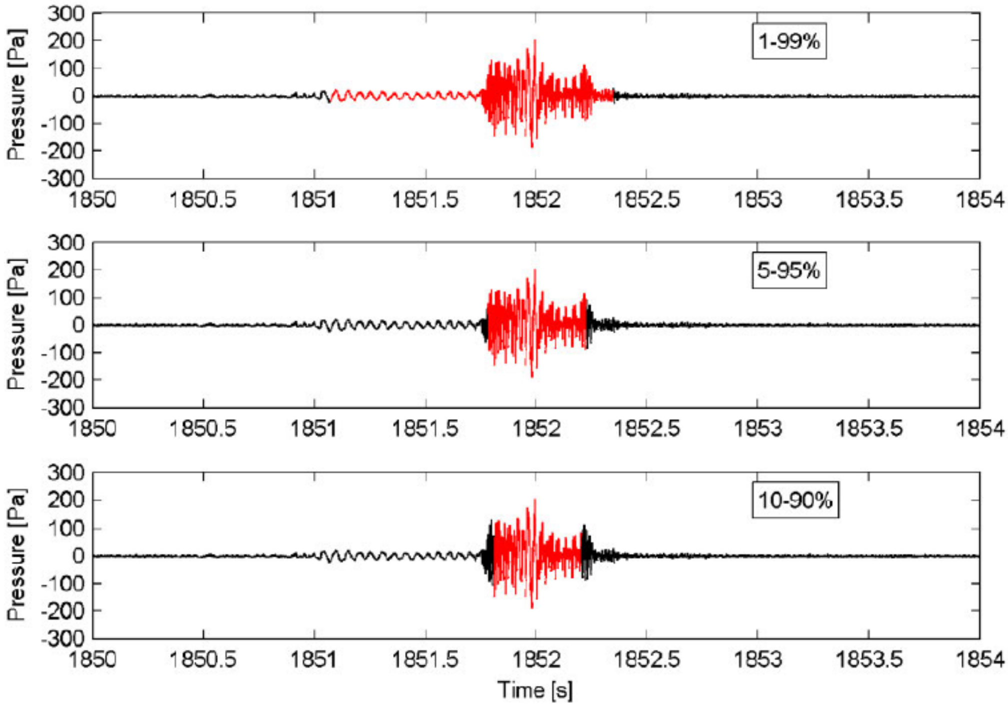

Figure 3.3 Example of a measured shot from an airgun array with emphasized different cumulative energy windows, from top to bottom; 98%, 90% and 80% (taken from Snoek et al., 2015a).

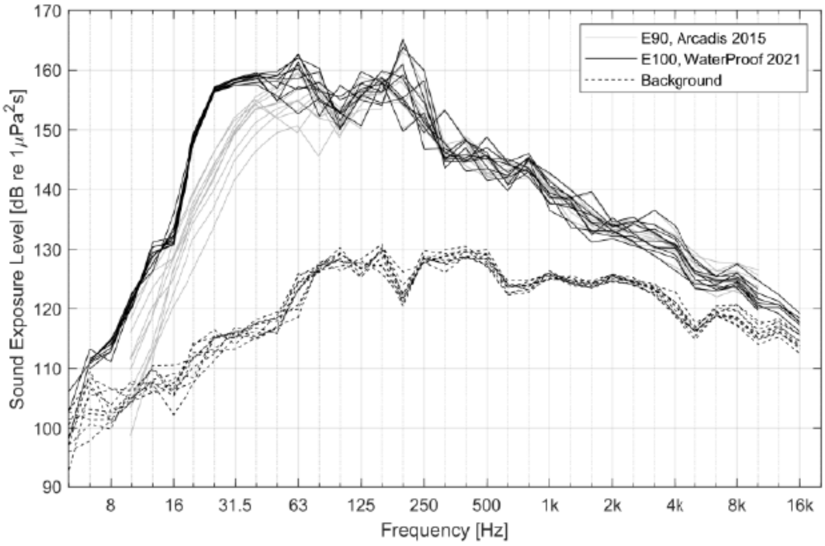

Figure 3.4 Comparison of calculated sound exposure levels calculated with the E90 window (solid grey) and the E100 window (solid black). Background sound levels are shown as dashed black lines.

The difference between the 90% and 100%-window approach is represented in the calculated sound levels in the frequency bands with center frequency < 63 Hz (Figure 3.4). The relative importance of the lower frequencies (depending on airgun configuration, distance, source azimuth) determines the difference in broadband SEL value due to the window length, but ranges between 0 and 5 dB.

Here, calculated values with the 100% energy window were used for model calibration, as these provide more accurate levels for the lower frequency bands.

3.2.3 Measured sound characteristics

Characteristics of the measured sound values were discussed in detail by Snoek et al. (2015a,b). Sound measurements confirm a directivity in emitted sound from an airgun array (Figure 3.5), and sound levels decrease with distance from the source. Highest sound levels were measured at azimuths around 90 degree from the seismic vessel.

Emitted sound energy consists dominantly of frequencies between 25 and 1000 Hz. The contribution of frequencies below 25 Hz to broadband SEL values is neglectable in measurements (99.9th percentile difference is 0.76 dB for all legacy sources combined). Overall, these measurements provide ample data on sound propagation over distance, sound directivity and source characteristics to be used as a detailed model calibration and validation set.

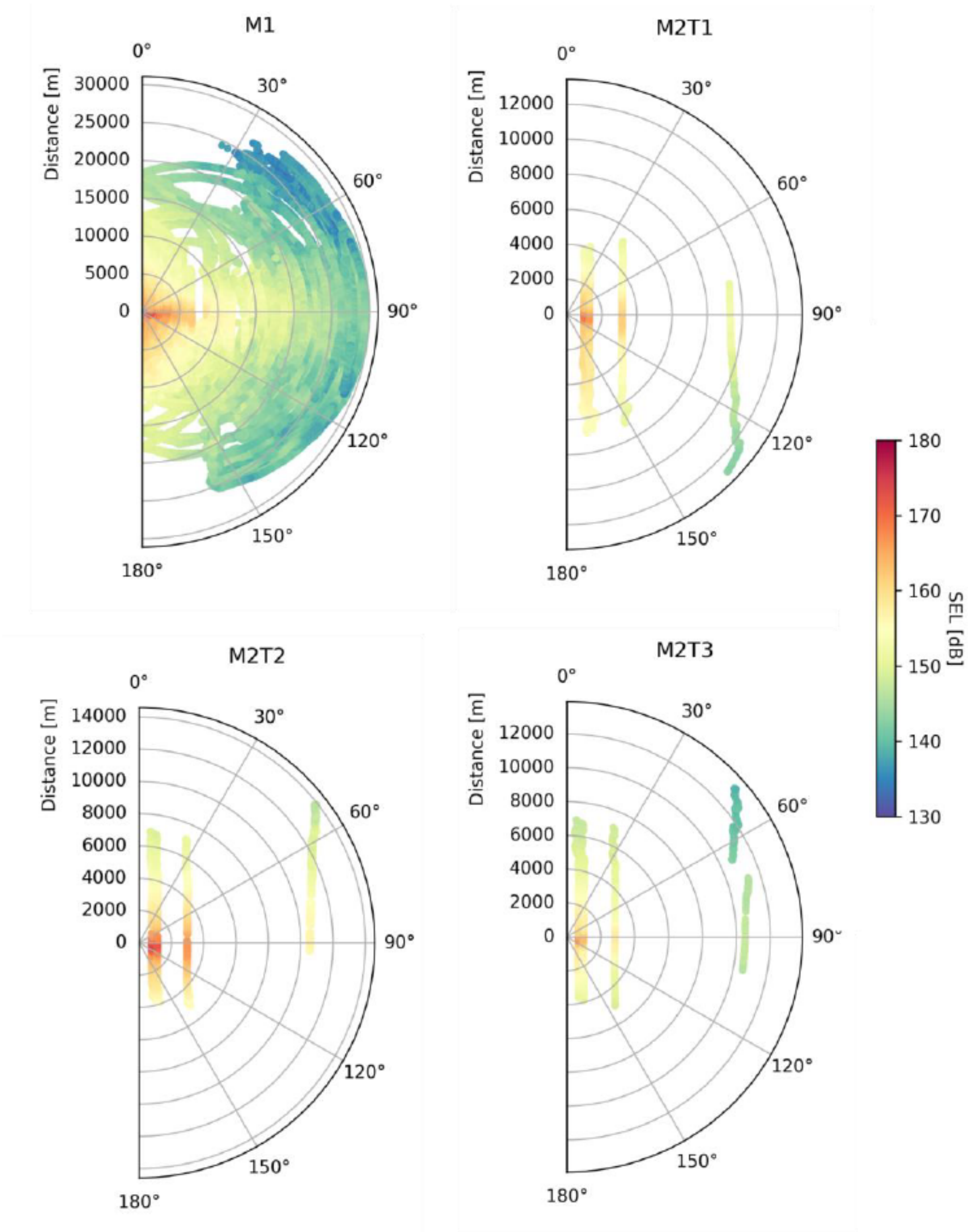

Figure 3.5 Measurements of the Sound Exposure Level collected during the Hansa 4quads survey for the four source configurations and for all azimuths. An azimuth of zero degrees is behind the vessel, and azimuth of 180 degrees is in front of the vessel.

3.2.4 Sound speed

The sound speed and sound speed vertical profile are important inputs to calculate sound transmission loss over distance, but also for the seismic acquisition itself. The vertical sound speed profile was regularly measured during the seismic tests (Figure 3.6). Days with higher sound velocity in the upper part of the water column are typical for the summer, when the surface of the sea is warmer. This strong stratification can result in the presence of a surface duct, a layer that can trap pressure waves, and for this reason no seismic tests were performed these days.

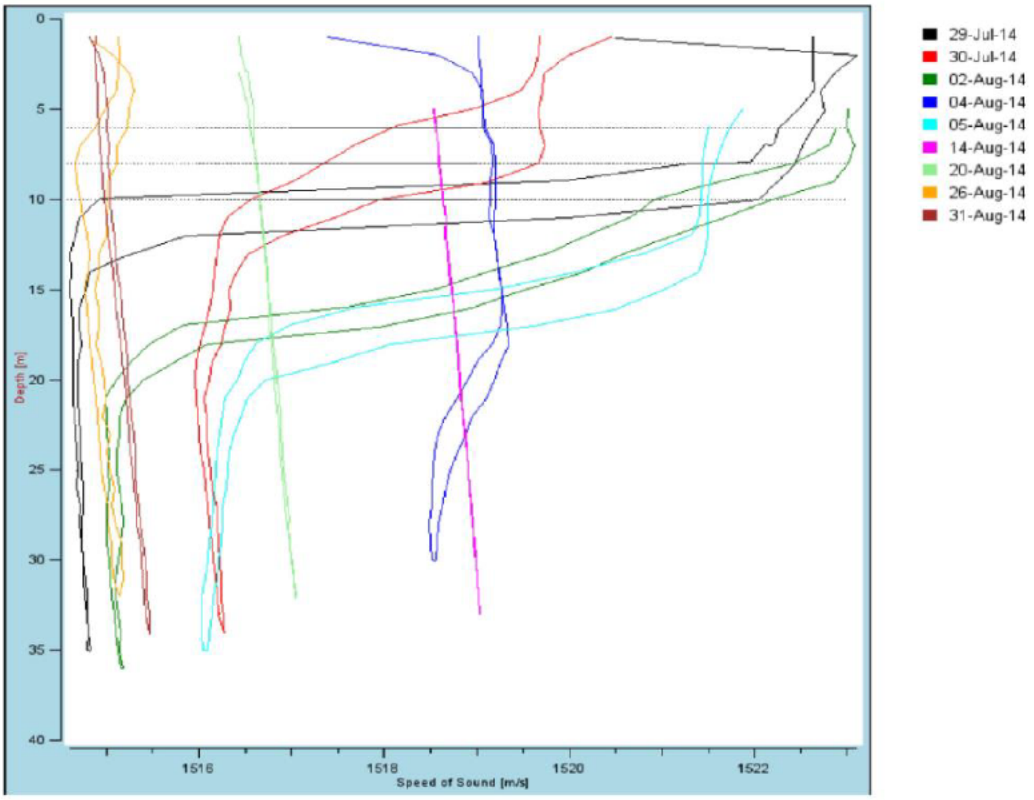

Figure 3.6 Sound speed profiles as measured before the Hansa measurements. (Provided by ONE-Dyas)

3.3 ACOUSTIC MODELING

3.3.1 Sound source levels

Sound source levels of the different airgun configurations were estimated by Shearwater using the Gundalf model (originally based on Laws et al., 1990). This model accurately calculates the pressure wave that is generate by single airguns and includes interactions between airgun outputs to calculate the output from clusters of airguns. The model has been calibrated against various datasets of near-field measurements.

The acoustic propagation model that is used requires a monopole source level, i.e. the source level in which interaction of the sound source with the sea surface is not included. The Gundalf models normally includes the effect of the sea surface ghost by setting a sea surface reflection coefficient to -1 (full reflection), this produces a reverse polarity copy of the source wavelet that is added to the primary wavelet with a time delay calculated from source depth, sound velocity and take-off angle. The reflection coefficient was here set to zero to exclude the sea surface ghost and thus calculate the monopole source level.

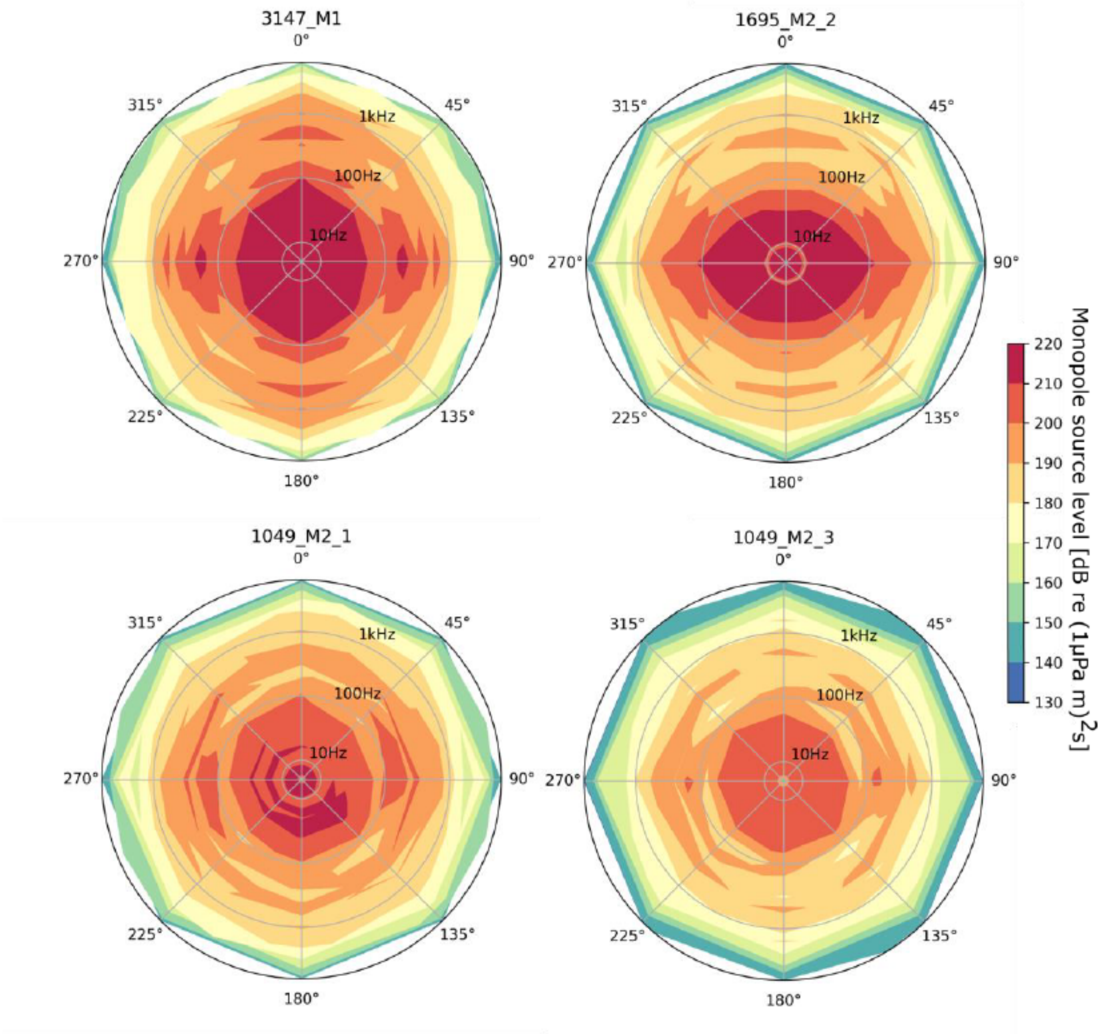

Figure 3.7 Monopole energy source level in one-third octave bands at 1 m distance as calculated from the Gundalf output for the source configurations used in the 4quads tests. Gundalf ouput was generated at azimuths with 15 degree increments, 180 degrees is in the vessel sailing direction.

Source levels were calculated at a take-off angle of 20 degrees from the horizontal, which is in the range of angles (0-30º) that is most important for the horizontal propagation of sound and for a range of azimuths (45º increments for calibration, 15º degree increments for application).

The pressure timeseries from Gundalf (in Bar at a distance of 9000 m) were converted to Pascal-metres by multiplying by 9000 and converting from bar to pascal for all azimuths. Source levels were subsequently calculated for each one-third octave band between 5 Hz and 6 kHz in dB re $1\mu Pa^2\ m^2s$. The source levels of the legacy sources as used in the 2014 tests (Snoek et al., 2015a,b), that are used to calibrate the acoustic model, are given for all azimuths in Figure 3.7.

3.3.2 Acoustic propagation

The Tritonic acoustic propagation model used is based on the acoustic model RAM (Range-dependent Acoustic Model). This model uses the U.S. Navy's Standard Split-Step Fourier Parabolic Equation (Collins, 1995) and is particularly suitable to calculate low-frequency sound transmission losses in environments with a range-dependent bathymetry.

The model estimates transmission losses per frequency in three dimensions by combining calculated transmission loss over the water column in evenly spaced radial transects over 360 degrees (an example for two frequencies is given in Figure 3.8). Environmental parameters that are included in the estimation of transmission losses include bathymetry, geo-acoustic properties of the seabed, and the vertical sound speed profile. Spatial variability in the sound speed profile and in the properties of the seabed sediments were not included. Horizontal and vertical resolution of the calculations were based on a sensitivity analyses and scale with the acoustic wavelength.

The seabed can be discretized in the acoustic model in different layers and using three parameters, or acoustical properties of the sediment. These parameters are the sound speed (c_s in m/s), the density (ρ_s in kg/m^3) and the acoustic attenuation (β_s in dB/λ) of the sediment. Typical values for these parameters for different sediment types were given by Ainslie (2010) for mid-frequencies (1 kHz – 10 kHz). The exact values for lower frequencies become dependent on the sound frequency, information on this is limited and this dependency is thus currently not taken into account.

The transmission losses calculated with the acoustic model Tritonic are combined with the sound source calculations per frequency band from Gundalf to attain sound exposure levels (SEL in dB re 1 μPa^{2}s) with range. The maximum sound level in the lower half of the water column and at least 1 m above the seabed was taken as a conservative estimate and as most representative for a comparison with measurements. Broadband SEL values were calculated by a summation over sound levels in the individual one-third octave frequency bands.

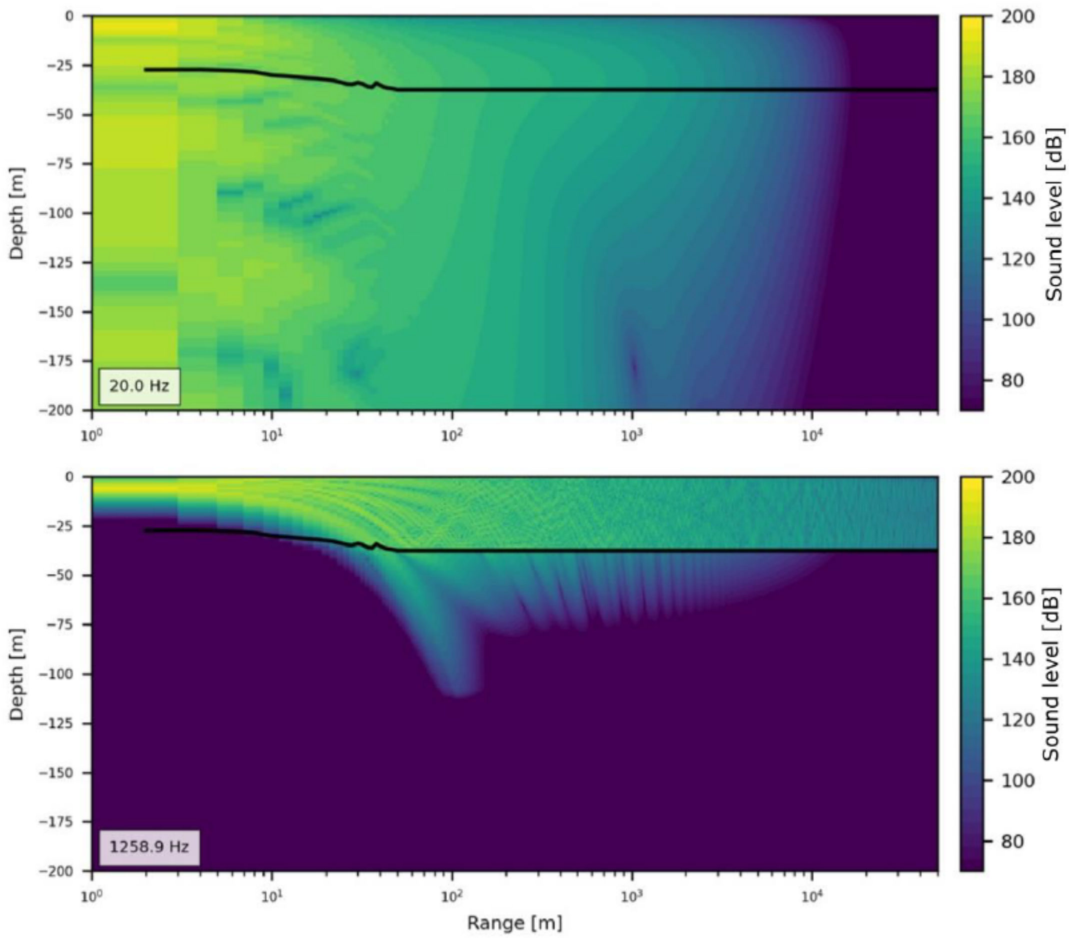

Figure 3.8 Examples of calculated sound levels at one azimuth for 20 Hz (top) and 1250 Hz (bottom), as calculated with the acoustic model from a point source at a depth of 6 m. The black line represents the seabed.

3.4 MODEL CALIBRATION

To attain realistic predictions for the sound levels in the N04 area, the model was calibrated and validated using the collected data described earlier. The monopole energy source levels of the airgun arrays used during these tests were provided by Shearwater and are characterized in Section 3.3.1.

Calibration of the model focused on the largest source array, M1 with a total volume of 3147 cubic inch, at an azimuth of 90º. This is the azimuth for the 3147 cubic inch array with the highest sound source levels, this combination was selected for the abundance of measurements available (Figure 3.5). Measured pulses used for the calibration were recorded at azimuths between 85º and 95º. The sound speed profile as measured during the seismic tests was directly used in the model.

Most uncertainty in underwater acoustic modeling in shallow water originates from the lack of detailed information on the seabed sedimentology. While there is a large amount of data on the area of interest, the data also shows a high level of heterogeneity in sediment characteristics and it is not clear from the data how this level of heterogeneity can be captured spatially. The encountered range in sediment characteristics is here used to calibrate the acoustic model and determine the values for the sediment parameters that are most representative for the entire area.

The sound frequencies taken into account for the calibration are in the range 25 – 800 Hz as the contribution to the broadband SEL value of frequencies outside this range is neglectable. As mentioned earlier, the difference in the 99.9th percentile of the broadband SEL is 0.76 dB, for all legacy sources combined, when frequencies < 25 Hz are included. The limited importance of these lower frequencies in the water column is also not surprising, as these are close to or below the cut-off frequency for these water depths (Figure 2.1). Including these frequencies in the acoustic model is possible, but as these lower frequencies penetrate the seabed further, it becomes important to include deeper sediment layers. Average values found through calibration are given in Table 3.2.

Table 3.2 Characteristics of the sediment properties, relative to values for sea water, based on calibration.

Property	Value
Sound velocity c_s	1.4 c_w [m/s]
Density ρ_s	2.4 ρ_w [kg/m^3]
Attenuation β_s	0.7 [dB/λ]

Calibration results show that for the 3147 cubic inch source at an azimuth of around (+/- 5º) 90º and 270º, broadband SEL values are within 5 dB of the highest measurements in the entire range between 650 and 30000 m (Figure 3.9). This difference between the model and measurements is decreasing with distance from the airgun array. Individual frequency bands show for low frequencies (Figure 3.9 and Figure 3.10) that both the source level as well as the propagation loss are overpredicted in the model. The difference between model and measurements is within 5 dB in the range of interest. Propagation loss in the higher frequencies (f>500Hz) is underpredicted by the model (Figure 3.10). The frequencies that dominate far-field sound propagation in these measurements (63 < f < 400 Hz) are reproduced accurately.

The same model settings were used to validate the model against the measurements for different azimuths from the M1 source configuration, and for different azimuths for the M2T1, M2T2 and M2T3 source configurations. The results of the validation simulations are provided in Appendix A. The model approach, combining Gundalf with an acoustic propagation model, can reproduce sound levels sufficiently accurate for the difference airgun configurations at different azimuths.

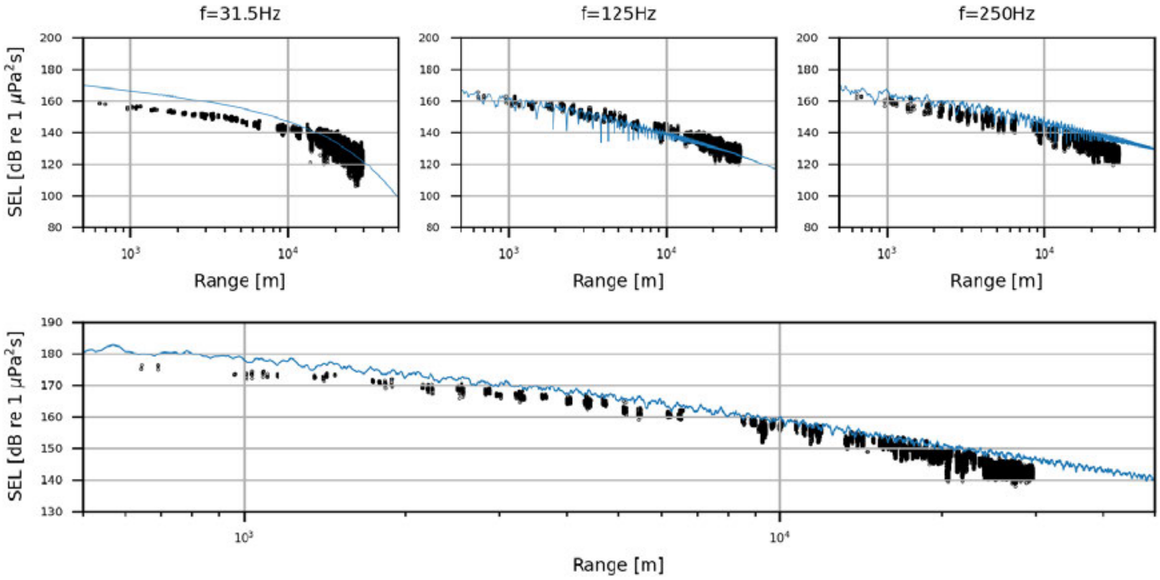

Figure 3.9 Calibrated model results (blue) in comparison with measurements (black dots) for 31.5 Hz, 125 Hz, 250 Hz and broadband SEL values. Results are shown for the 3147 cubic inch source (M1) at an azimuth of 90 (+/- 5) degrees.

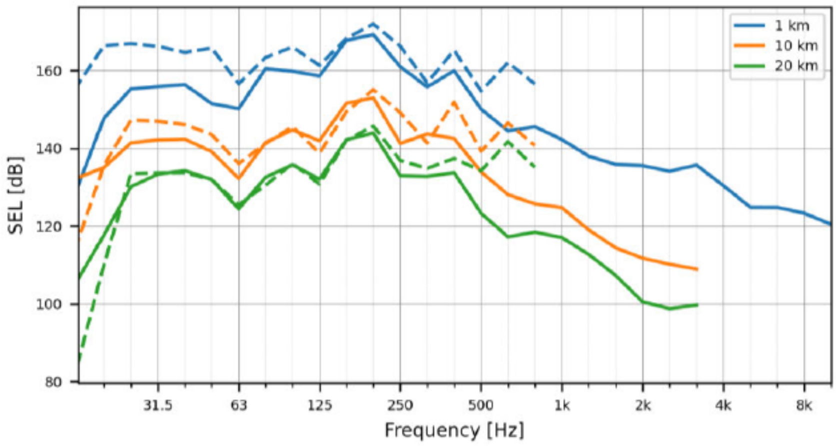

Figure 3.10 Measured (50th percentile, solid lines) and modelled (dashed lines) Sound Exposure Levels per one-third octave frequency band at 1 km, 10 km, and 20 km distance at an azimuth at 90 (+/- 5) degrees.

Simulated distances from the airgun array to the SEL<140 dB contour are provided in Table 3.3 for the different source configurations and can be used as a reference. Distances to the 140 dB contour are highest at 90º (and thus at 270º), are lower and similar for other azimuths (M2 sources), or (M1 source) decrease toward 45 º (135 º) and then increase toward 0 º (180 º).

Table 3.3 Distances from the airgun array to the 140 dB contour based on the calibrated model for the four legacy source configurations at azimuths 0, 45, 90, 135 and 180º.

Azimuth	M1 (3147 cu in)	M2T2 (1695 cu in)	M2T1 (1049 cu in)	M2T3 (1049 cu in)
0º	47.8 km	19.1 km	20.3 km	13.6 km
45º	24.6 km	19.2 km	20.3 km	13.5 km
90º	>50.0 km	38.6 km	29.3 km	17.7 km
135º	25.3 km	21.0 km	21.1 km	14.2 km
180º	46.4 km	20.3 km	20.3 km	13.7 km