Environment plan Appendix 6-1 Underwater sound modelling report

Stromlo-1 exploration drilling program

Equinor Australia B.V.
Level 15
123 St Georges Terrace
PERTH WA 6000
Australia

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APPENDIX 1 dBSea benchmark test

1.0 Abbreviations, units and acronyms

Abbreviation / acronym	Description
dB	decibels
DP-AT	Dynamic positioning-system acoustic transmitters
in^3	Cubic inches
MODU	Mobile offshore drilling unit (drilling rig)
m/s	Milliseconds
PTS	Permanent threshold shift
SEL	Sound exposure level
SELcum1	Cumulative sound exposure level over one pulse
SELcum5	Cumulative sound exposure level over five pulses
SELcum24h	Cumulative sound exposure level over 24 hours
SPL	Sound pressure level
SPLpeak	Peak sound pressure level
SPLpeak-peak	Peak to peak sound pressure level
SPLrms	Root mean square sound pressure level
TTS	Temporary threshold shift
VSP	Vertical seismic profiling
µPa	Micropascals (unit of pressure)

2.0 Background

Equinor Australia B.V. (Equinor) is planning to undertake exploration drilling in the offshore Commonwealth marine waters of the Great Australian Bight (GAB), within exploration lease area EPP 39. The Stromlo-1 exploration well will be drilled using a dynamically positioned mobile offshore drilling unit (MODU) and on completion, well evaluation will be carried out using vertical seismic profiling (VSP). Sound emitted by the MODU's thrusters while maintaining station during drilling, VSP and use of dynamic positioning-system acoustic transmitters (DP-AT) was identified as an unavoidable environmental impact of the activity. It was necessary to quantify underwater sound levels being emitted such that environmental impacts on sound-sensitive receptors could be assessed appropriately. Modelling was undertaken to quantify underwater sound levels received at various distances from the sound. This report presents underwater sound propagation modelling for drilling (MODU operation including DP-AT) and VSP activities associated with the Stromlo-1 drilling program.

2.1 Purpose

The purpose of the underwater sound modelling was to predict the propagation of sound emitted from the MODU and DP-AT during drilling and from VSP operations, to assist with the assessment of environmental impacts associated with the drilling.

3.0 Design input and requirements

3.1 Underwater sound generation

3.1.1 Low frequency sound sources

Throughout the drilling of the Stromlo-1 exploration well, low-frequency sound (main energy below 1 kHz) will be generated continuously by the thruster propellers on the MODU and support vessels. The mechanical operation of the drill string and other machinery on the MODU and support vessels will also generate sound underwater. VSP will create high levels of impulsive sound during the short test periods at the end of drilling. Helicopters will generate airborne and underwater noise periodically throughout the program.

3.1.2 High frequency sound sources

The dynamic positioning system of the MODU uses acoustic signals at high frequencies (main energy above 20 kHz); throughout the operation. This is similar to the sound emitted routinely by commercial vessel echosounders but higher in energy due to the deeper water it operates in. Energy is emitted from a ship mounted transducer and from transceivers at the sea floor. The sound generating equipment is referred to as dynamic-positioning-acoustic-transducers (DP-AT) in this report.

3.1.3 Underwater sound level ranges

Sound (measured at source) from these activities is generally in the ranges shown in Table 1.

Table 1 Indicative underwater sound levels during drilling

Source	Sound level (re 1 µPa at 1m SPLrms)
MODU thrusters	190–195 dB (omnidirectional, major energy <1 kHz)
Drilling	157–162 dB (omnidirectional, major energy <1 kHz)
Support vessels	108–182 dB (omnidirectional, major energy <1 kHz)
VSP	>200 dB (downwards, major energy <1 kHz)
DP-AT	>200 dB (downwards, only energy in 21 to 31 kHz band)

Sound generated by the MODU thrusters, the DP-AT and by VSP will be the dominant sound sources during the drilling of Stromlo-1. These sound sources were therefore the focus of the sound modelling. Sound emissions from helicopters, the drill string, machinery and other vessels are lower in magnitude and duration compared to the dominant sources identified and were not modelled.

3.2 Underwater sound metrics

Given the multiple metrics commonly used to express sound levels and assess potential impacts to marine fauna, it is important to ensure any comparisons between specific sound level values are made using the same metrics (e.g. SPL or SEL). Care must also be taken when comparing decibel (dB) sound levels in air with sound levels underwater.

The decibel scale is a logarithmic scale that expresses the ratio of two values of a physical quantity. It is used to measure the amplitude or “loudness” of a sound. As the dB scale is a ratio, it is denoted relative to some reference level, which must be included with dB values if they are to be meaningful. The reference pressure level in underwater acoustics is one micropascal (µPa) whereas the reference pressure level used in air is 20 µPa, which was selected to match human hearing sensitivity. The result is that sound waves with the same intensities in water and air have dB values that differ, dB in water cannot easily be compared with dB in air.

As a result of these differences in reference standards, sound levels in air are not equal to underwater levels. To compare sound levels in water to sound levels in air, it is necessary to subtract 62 dB from the sound level in water to account for the difference in reference levels and absorption characteristics of the two mediums.

Underwater sound is typically measured in terms of sound pressure level (SPL), in dB re 1 µPa (Richardson et al. 2005). SPL for an impulsive sound is typically expressed in terms of SPL peak, SPL peak-to-peak or SPLrms (root mean square), which is an average pressure over a period of time. This measure is commonly associated with continuous sounds but is also used to characterise pulse sounds where the time duration is related to pulse duration or a percentage of energy of the pulse signal.

Source level is a measure of sound properties at a nominal distance of 1 m from the source and is denoted in dB re 1 µPa at 1 m.

SPLrms has historically been used to assess potential impacts to marine life but SEL and SPLpeak are increasingly used instead. SEL accounts for the duration of a sound exposure and enables comparison between sound from different sound signals (and therefore sound sources) with different characteristics.

SEL is a metric used to describe the amount of acoustic energy that may be received by a receptor (such as a marine animal) from an event. SEL is the dB level of the time-integrated, squared sound pressure, normalised to a one second period, and is expressed as dB re 1 μPa^2 s.

3.3 Sound propagation modelling

With knowledge of the strength of the sound at the source and the specific properties of the water and seabed, the propagation of sound can be modelled. A commercial modelling package dBSea (dBSea v2.1.2 build 281, Marshall Day Acoustics) was used. The specific parameters used in the modelling are described in the following sections.

3.3.1 Input data

3.3.1.1 Position of drill site

The position of the drill site (Figure 1) in the Great Australian Bight is longitude 130.662106° E and latitude 34.925354° S (UTM zone 53 easting 651815; northing 6132427).

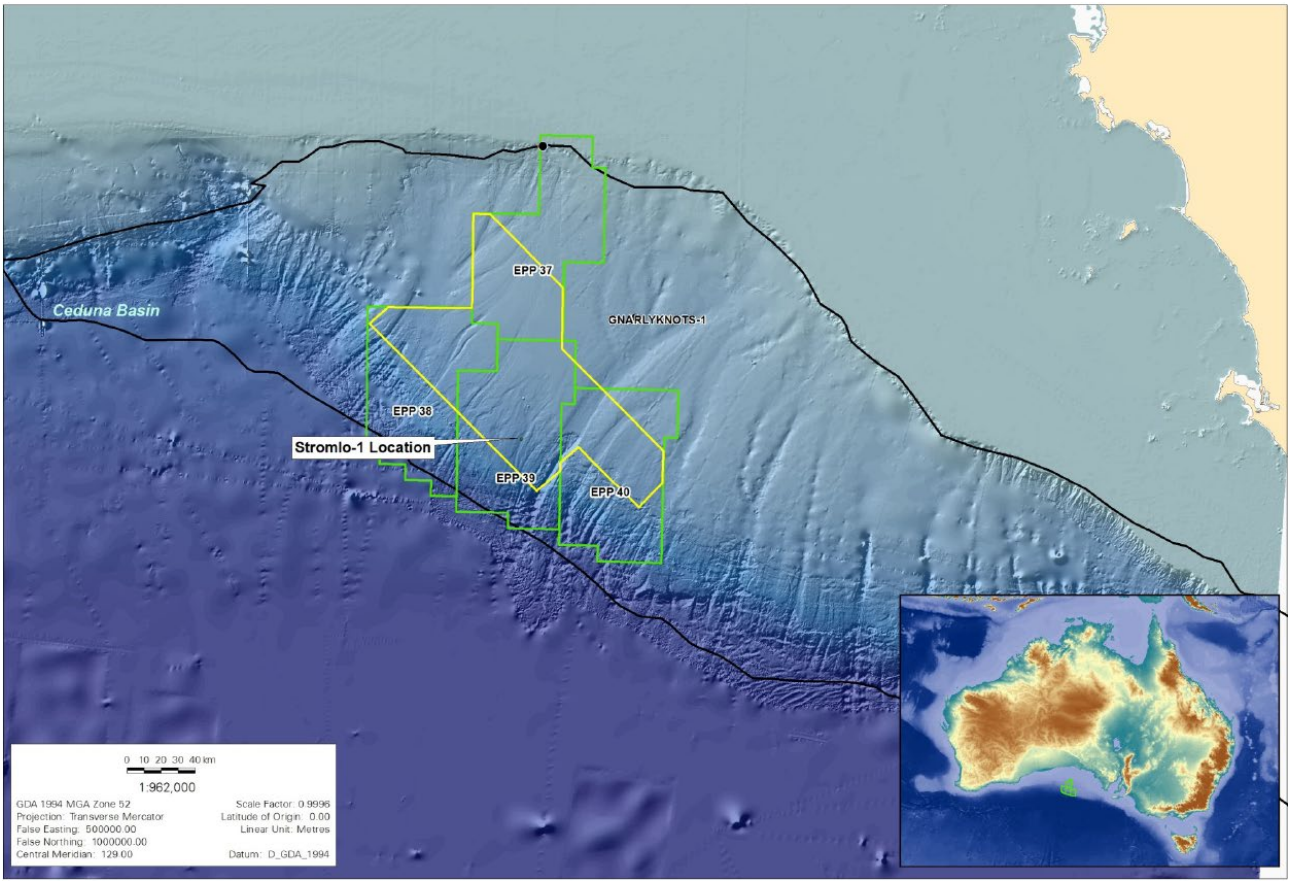


Figure 1 Location of Stromlo-1 exploration well in the Great Australian Bight

3.3.1.2 Source strength of MODU

No decision has been made on the type of MODU that will be used, meaning that the sound emitted can only be assumed based on data available for similar drilling units. Good data are available for a semi-submersible drill ship, Seadrill Limited's West Sirius (Figure 2), which was subject of sound modelling conducted by JASCO (Zykov 2016). Modelled sound source data for the West Sirius MODU were used as input data for Stromlo-1 sound propagation modelling, as a typical MODU. This is at the high end of the range of MODU sizes (and sound emissions) that may be used.

Figure 2 Typical MODU, Seadrill Limited's West Sirius

Seadrill's West Sirius is equipped with eight Rolls Royce UUC 355 thrusters, which have a fixed-pitch propeller in a PV-nozzle. The UUC 355 thrusters have a 3.5 m propeller diameter, 177 rpm nominal propeller speed, and 3800 kW maximum continuous power input. They each operate at variable power as required to keep the MODU on station.

For modelling, all eight thrusters were assumed to operate constantly at full speed which conservatively estimates the maximum sound output from the MODU. The vertical position of the thrusters was 18 m below the sea surface. Source spectrum information was used as input data into the sound propagation software, using data in the JASCO report. The total sound pressure level is given as 196.7 dB re 1 µPa at 1 m SPLrms.

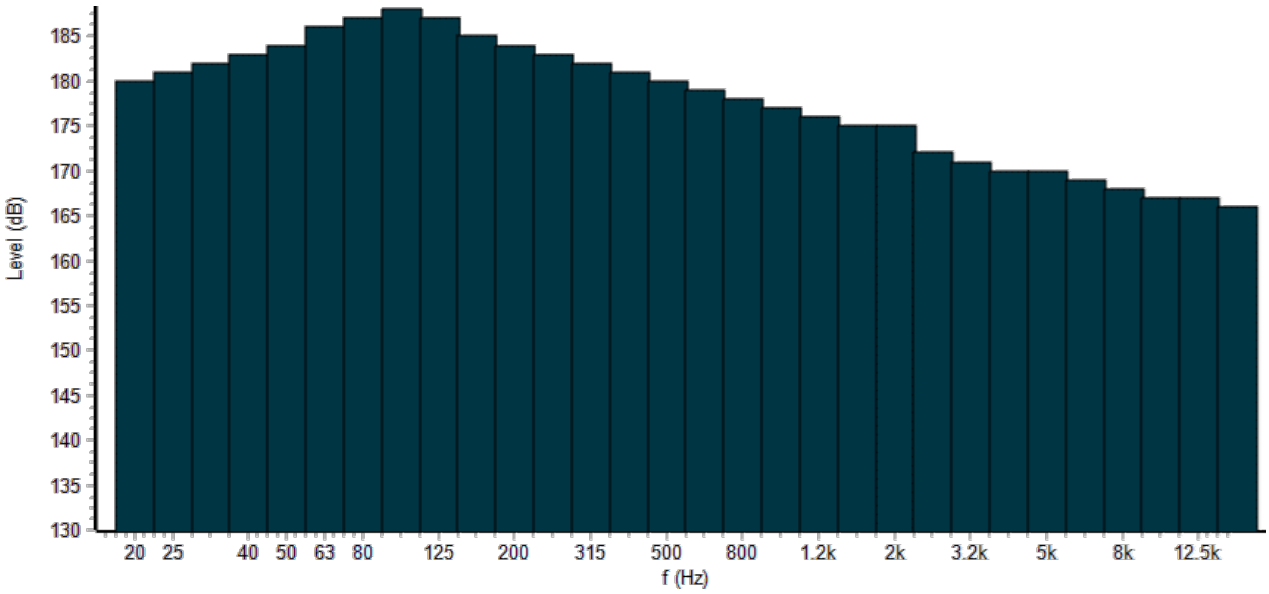


Figure 3 Spectral content of signal from MODU thruster source, dB levels given in dB re 1 µPa m for 1/3 octave frequency bands

The sound level (in dB) (Figure 3) contributes to the total sound energy propagated in the water column in a logarithmic manner, such that levels more than 20 dB below the peak level, contribute less than 5% to the total energy of the sound source. This means that <5% of the energy is in the frequencies above 1 kHz.

3.3.1.3 Source strength of dynamic positioning acoustic transducers

The MODU is held in position with help of an acoustic transducer on the MODU and transponders (or transceivers) on the sea floor. The exact system that will be used is not known yet because it will be equipment associated with the selected MODU, Consequently, we have used information from a typical system; the Kongsberg Maritime HiPAP system. The Kongsberg system consists of an acoustic transducer on the MODU and several acoustic transponders on the sea floor. The acoustic transducer emits a series of short high-frequency pulses, these are received by the transponders and similar, lower energy, pulses are returned to the transducer. The MODU's position is calculated from the properties of the return signals. The pulse from the MODU-based transducer (the strongest signal) is considered in the sound propagation modelling. The transducer creates sound in the frequency range from 21 kHz to 31 kHz, at a source level of 206 dB re 1 µPa. The pulse length is 30 m/s and it is repeated every five seconds. The answering transponders on the sea floor will return a signal with a source level of SPL 200 dB re 1 µPa.

3.3.1.4 Source strength of VSP

A 3 × 150 in^3 array is likely to be used during VSP but as a conservative measure, the estimated source volume of a 3 × 250 in^3 array was used, delivering a sound pressure of approximately 238 dB re 1 µPa at 1 m zero to peak SPL. In order to get spectral values for this, a sound file of an idealised acoustic signal (Figure 4) was used to get spectral values (Figure 5), adding up to the respective SPL (build in feature in dBSea). The assumed depth of the acoustic source was 8 m below the sea surface.

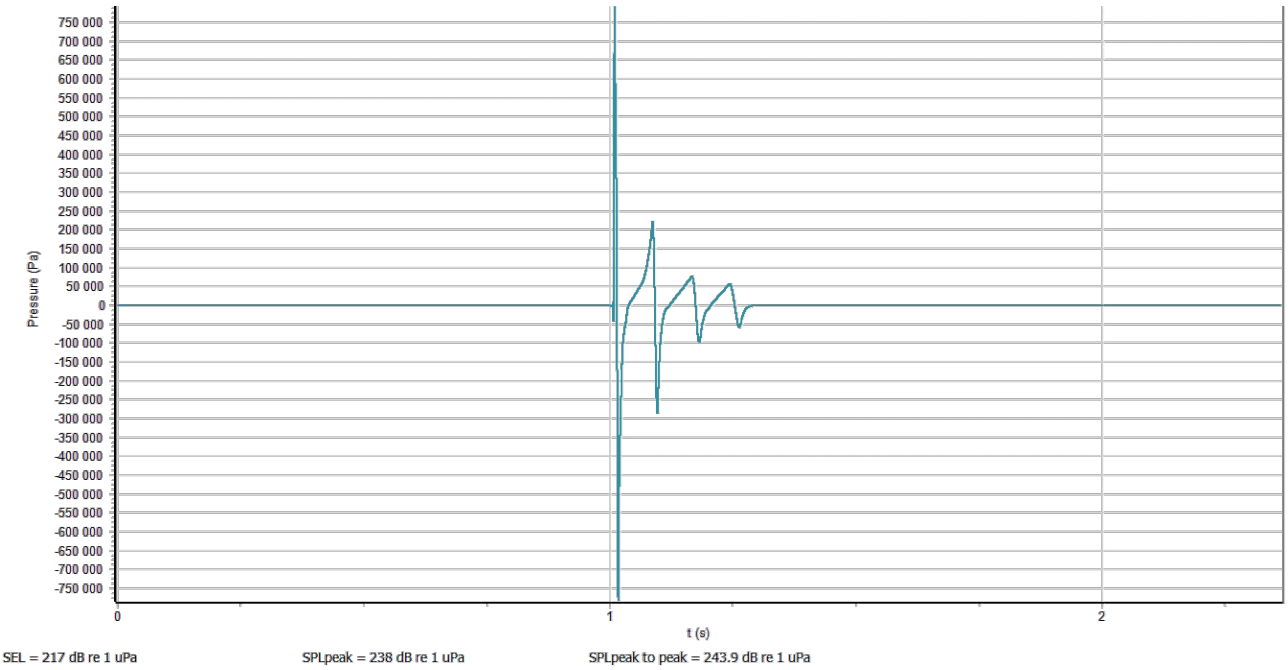


Figure 4 Time series display of idealised VSP source output scaled up to an SPL of 238 dB re 1 µPa

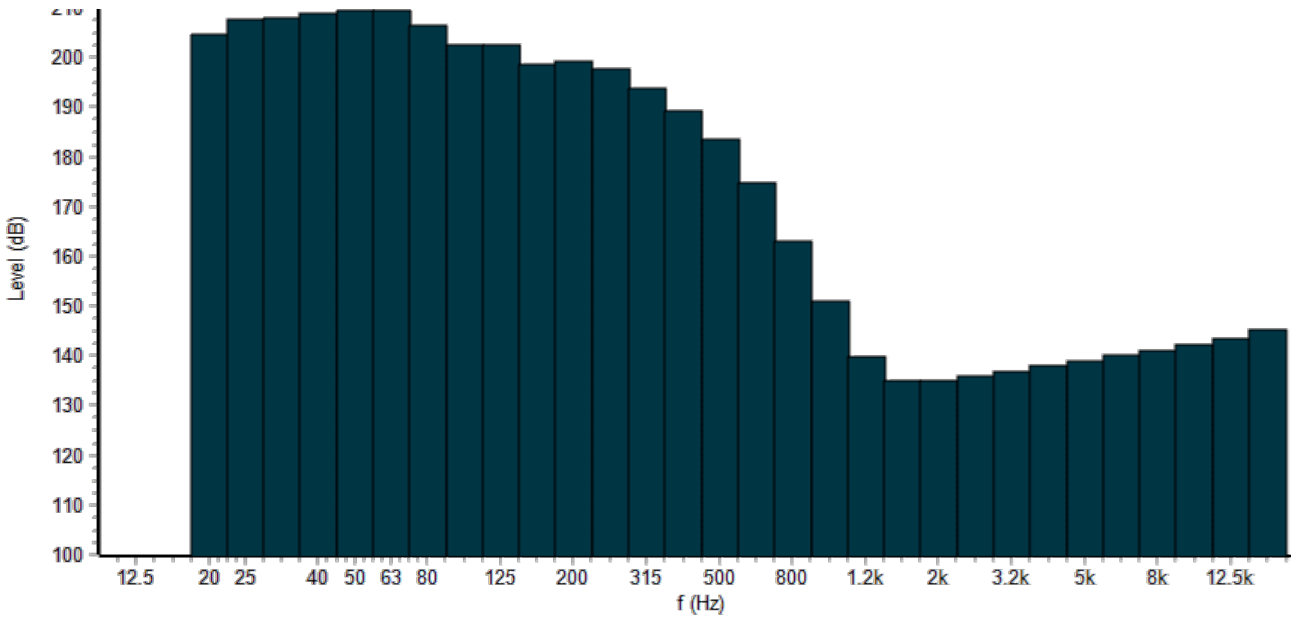


Figure 5 Spectral content of signal from VSP source, dB levels given in dB re 1 µPa m for 1/3 octave frequency bands

The sound level (in dB) (Figure 5) contributes to the total sound energy propagated in the water column in a logarithmic manner, such that levels more than 20 dB below the peak level, contribute less than 5% to the total energy of the sound source. This means that <5% of the energy is in the frequencies above 1 kHz.

3.3.1.5 Sound speed profile

A sound speed profile for the Ceduna 3D seismic survey described by Maggi and Duncan (2011) was used in this modelling and is considered appropriate because it was from the same area and was derived from oceanographic data from a regional dataset which encompasses the Stromlo location and the assumptions of seabed type are consistent with the benthic descriptions from the GABRP around Stromlo. Using the sound profile presented by Maggi and Duncan (2011), the values for continental shelf for the upper 150 m were combined with the values for deep ocean from 150 m down to the sea floor (Figure 6).

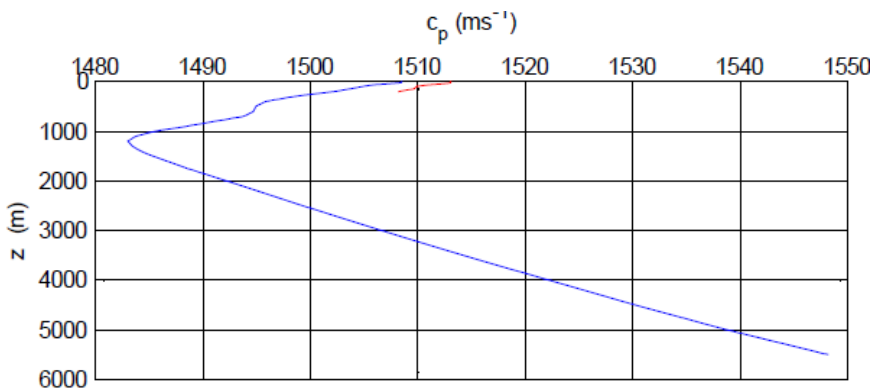


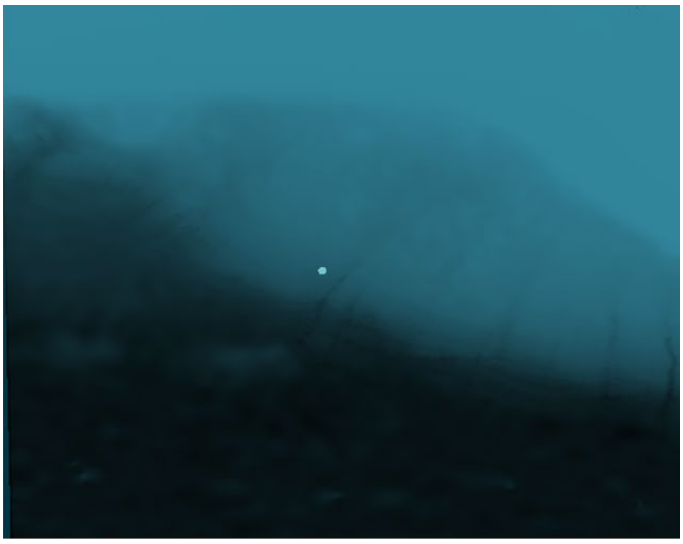
Figure 6 Sound speed profile used in modelling

3.3.1.6 Seabed properties

The modelling report for the Ceduna 3D seismic survey gives seabed properties for the area and investigated the influence of different sediment materials (Maggi and Duncan 2011). For the deep-water environment, “silt-sand” sediments were considered representative of the area (Maggi and Duncan 2011) and this assumption has been applied to the Stromlo-1 modelling. The properties of silt-sand given by Maggi and Duncan (2011) and used herein are a sound velocity of 1,612.5 m/s, a density of 1800 kg/m^3 and an attenuation of 0.9 dB/ wavelength throughout the modelling area.

3.3.1.7 Bathymetry

Bathymetry data from the GEBCO2014 database with 30” resolution was used, corresponding to about 500 to 700 m in the GAB region. For a wide area view, an area of 446 km (east–west) by 552 km (south–north) over the source was used (Figure 7). For a narrow area view, an area 30 km (east–west) and 64 km (north–south) inside this area was used. Note that in the wide area view the drill site appears to be on a steep slope setting (Figure 7 B) whereas the narrow view shows the seabed to be relatively flat in the vicinity of the Stromlo-1 well (Figure 8).



A) 3D view from above

B) 3D view from west

Figure 7 Three-dimensional view from above (A) and from the west (B) of the bathymetry used in the modelling, with the light blue dot indicating the position of the MODU

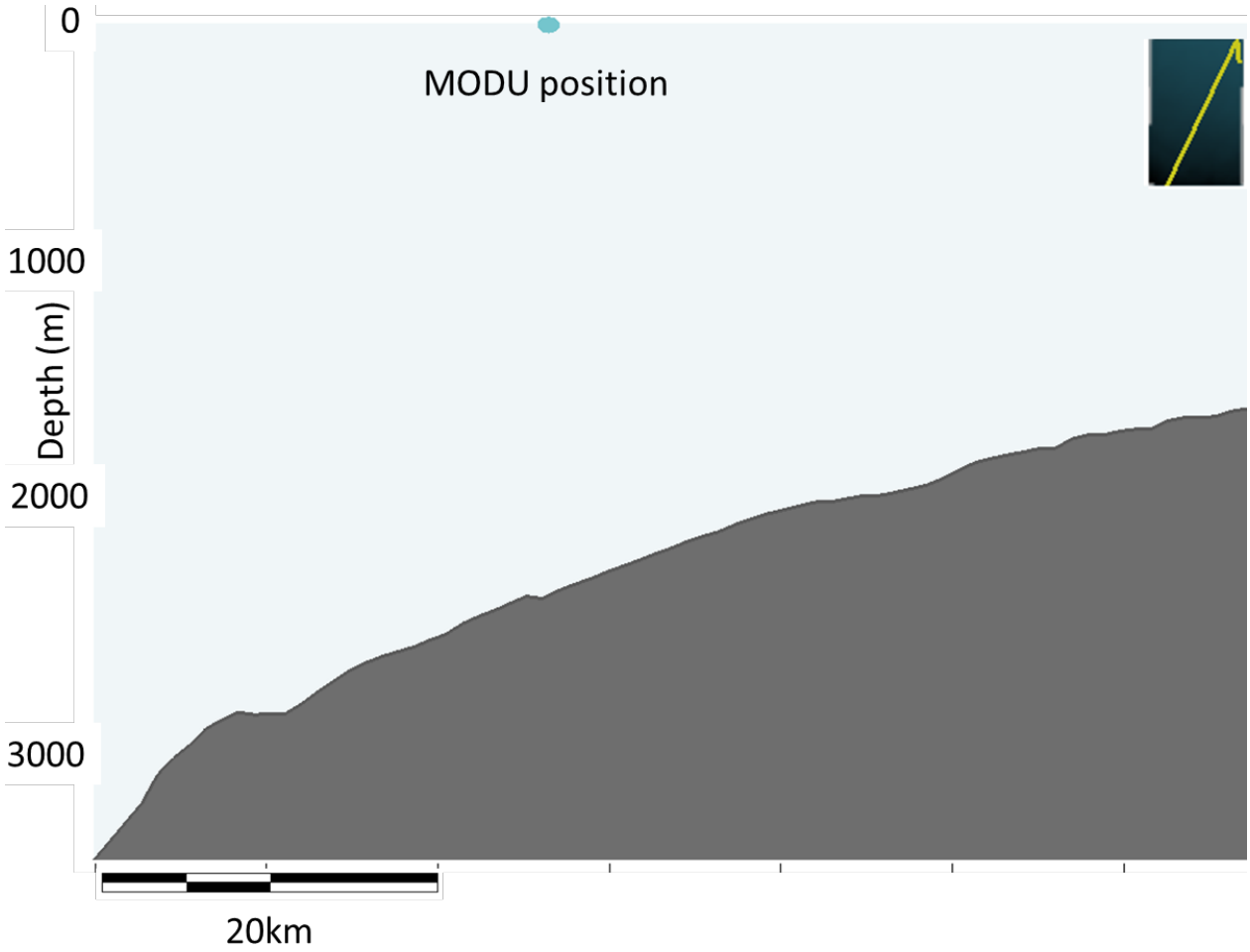


Figure 8 Depth profile over the narrow area, with light blue dot indicating the position of the MODU/ VSP sound source, orientation of transect shown in insert

3.4 Modelling software

The dBSea V.2.1 model was selected as the sound propagation simulation software. A frequency band of 12.5 Hz to 16 kHz was used to simulate the MODU thrusters Sound propagation modelling for sound pressure levels was done using a parabolic wave equation solver for frequencies from 12.5 Hz to 250 Hz and a normal mode solver for higher frequencies. Both solvers use bathymetry, sea floor and water properties in their range-dependent calculations.

SEL values for the MODU were simulated over a 24-hour assessment period. Sound propagation was simulated with the same split solver as used for SPL calculation described above.

For modelling the high frequency signal from the MODU DP-AT, ray-trace theory was used in the frequency band 16 kHz to 32 kHz. The directivity of the signal was introduced by full signal strength (206 dB) in near-vertical direction (15 deg from vertical) and -7 dB for all other directions up to horizontal and no upward sound. DP-AT was assumed to be active all the time emitting a 30 m/s sound pulse every five seconds.

For the VSP, a split solver as described above was used to calculate the SPL levels based on the spectral input of the acoustic source (small air gun array).

For the simulation of SEL and the calculation of cumulative SEL values, a ray trace solver based on the time series was used. Due to high demand for computing power, this simulation was done with a reduced frequency band from 12.5 Hz to 5 kHz, which encompasses nearly all of the sound energy.

For both simulations, on both the wide area view and the narrow area view, a grid with 100 points in x and y direction, and 50 points in z direction was used (Figure 9). Values in the grid were extrapolated between the 100 points. Sound propagation was simulated along 100 radial slices with 100 range points each for the calculations.

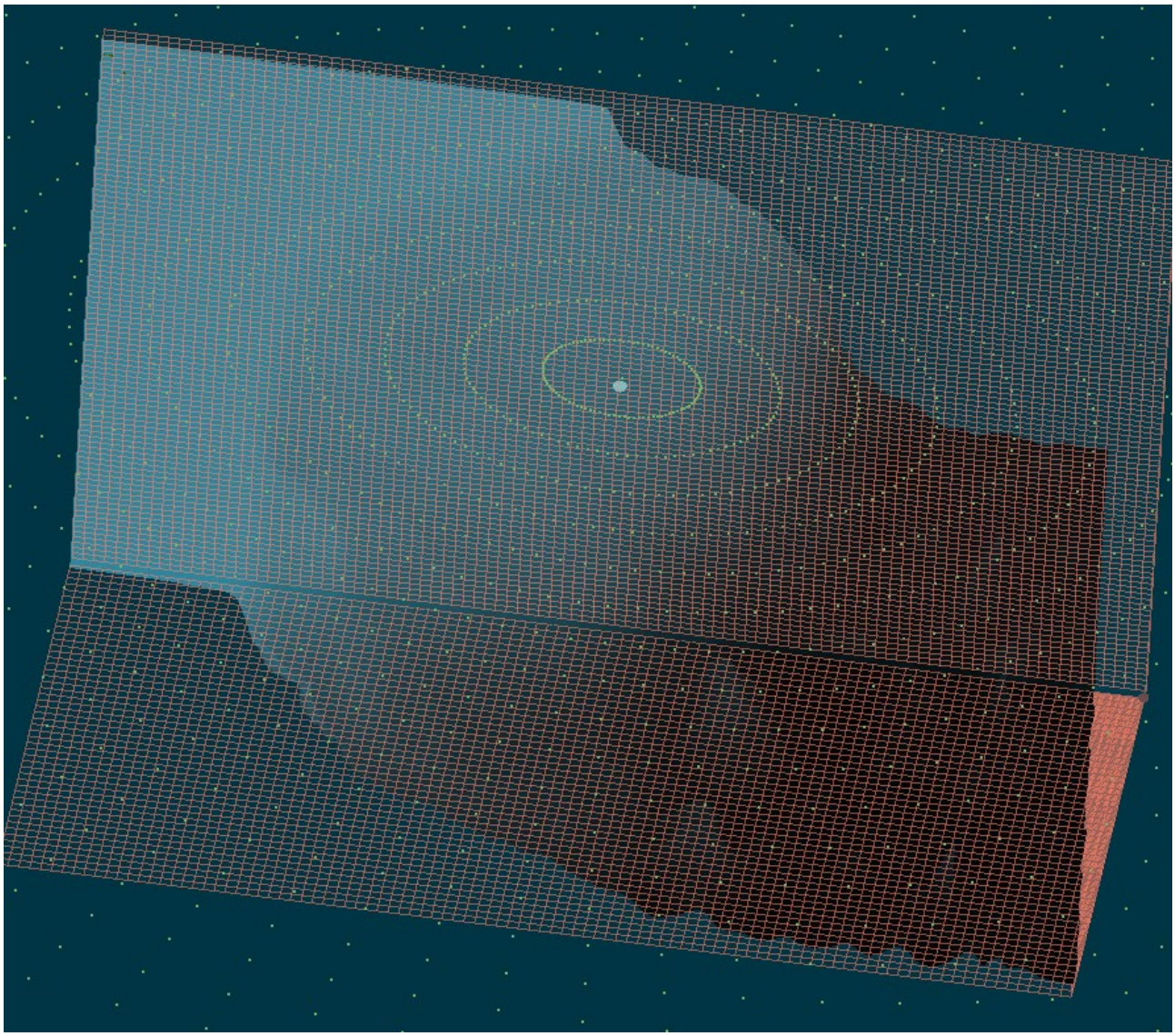


Figure 9 Graphic display of the grid (red lines) used for sound propagation modelling and positions of discrete sound propagation calculations (light green points)

4.0 Sound simulation for MODU

4.1 Sound pressure levels from MODU thrusters

All simulations were done over both a wide area coverage and a narrow area coverage.

4.1.1 Wide area simulation

The wide area simulations were used to assess sound pressure values far away from the source. Figure 10 shows 2D sound level "slices", which represent sound levels along transects running from the sound source outward towards deep water, towards the shore and parallel to the slope. Critical values for SPL are not exceeded at greater distances from the MODU source. Higher values closer to the source (e.g. the source level at 1 m) cannot be accurately modelled and are not displayed in the figure. The spread of values in the different slices is due to variation in bathymetry over the wide area model domain.

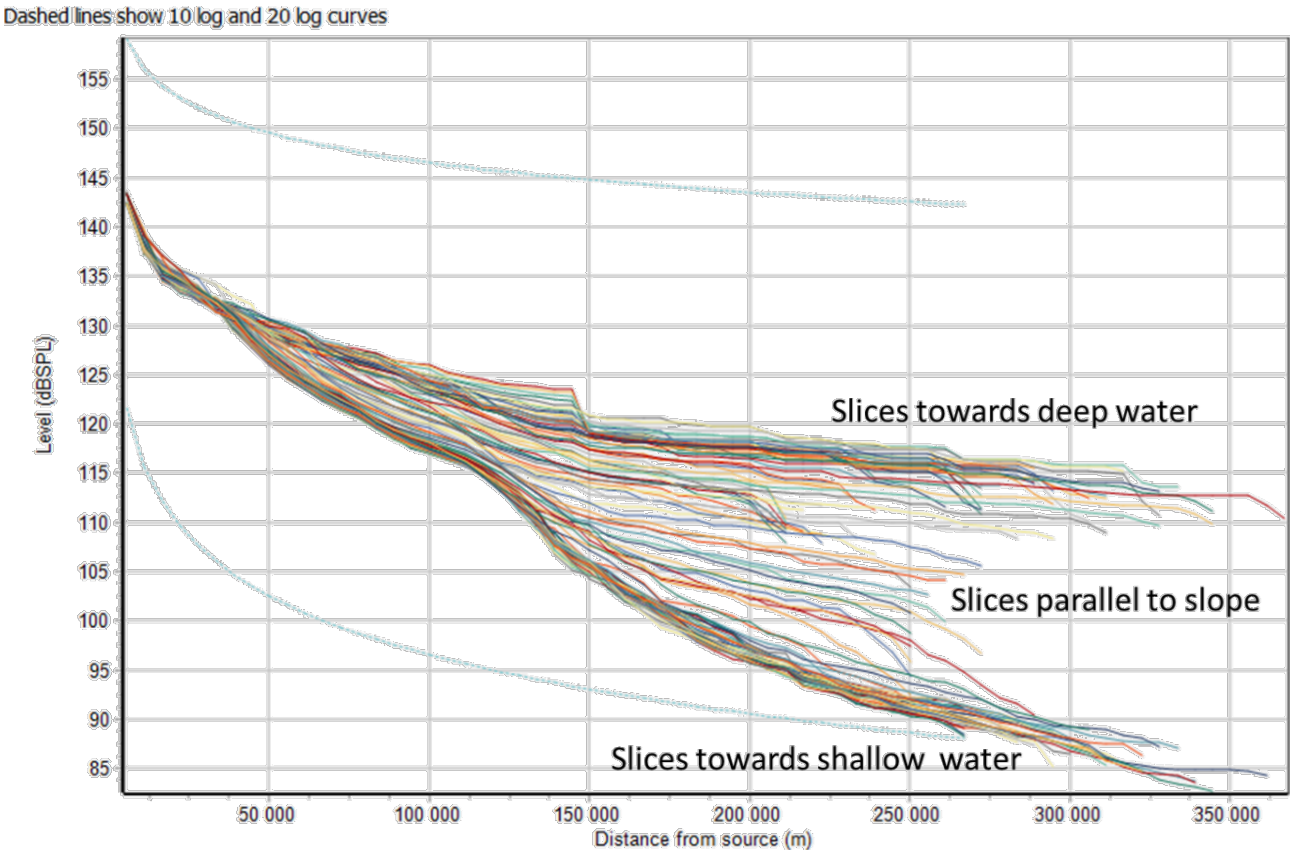


Figure 10 SPL levels from MODU thrusters in dB re 1 µPa peak for all slices in the wide area simulation

4.1.1.1 Narrow area simulation

The narrow area simulations were used to assess sound pressure values close to the source. Figure 11 shows 2D sound level around the MODU position where the highest sound level, even if it is at greater depth, is projected to the surface. Figure 12 shows a vertical profile of the sound pressure levels propagating through the water column from the MODU on the sea surface. Note that the area with relatively high sound pressure levels (red–orange) is smaller at the surface than in the deeper layers.

Figure 13 shows the maximum extent of sound pressure levels in all directions around the sound source, using the highest value in the vertical plane. The lack of spread in the data at distance is due to relatively uniform bathymetry over the narrow area model domain.

Using Figure 13 results for assessing effect threshold ranges is conservative because most of the sensitive marine fauna (cetaceans and fish in particular) spend most of their time in the top 200 m of the water column. At 0–200 m water depth the range of underwater sound effects is significantly less; the area of ensonification above effects thresholds is approximately 25% of that at 1000 m depth; however, we have projected the maximum ranges upwards into the biotic zone.

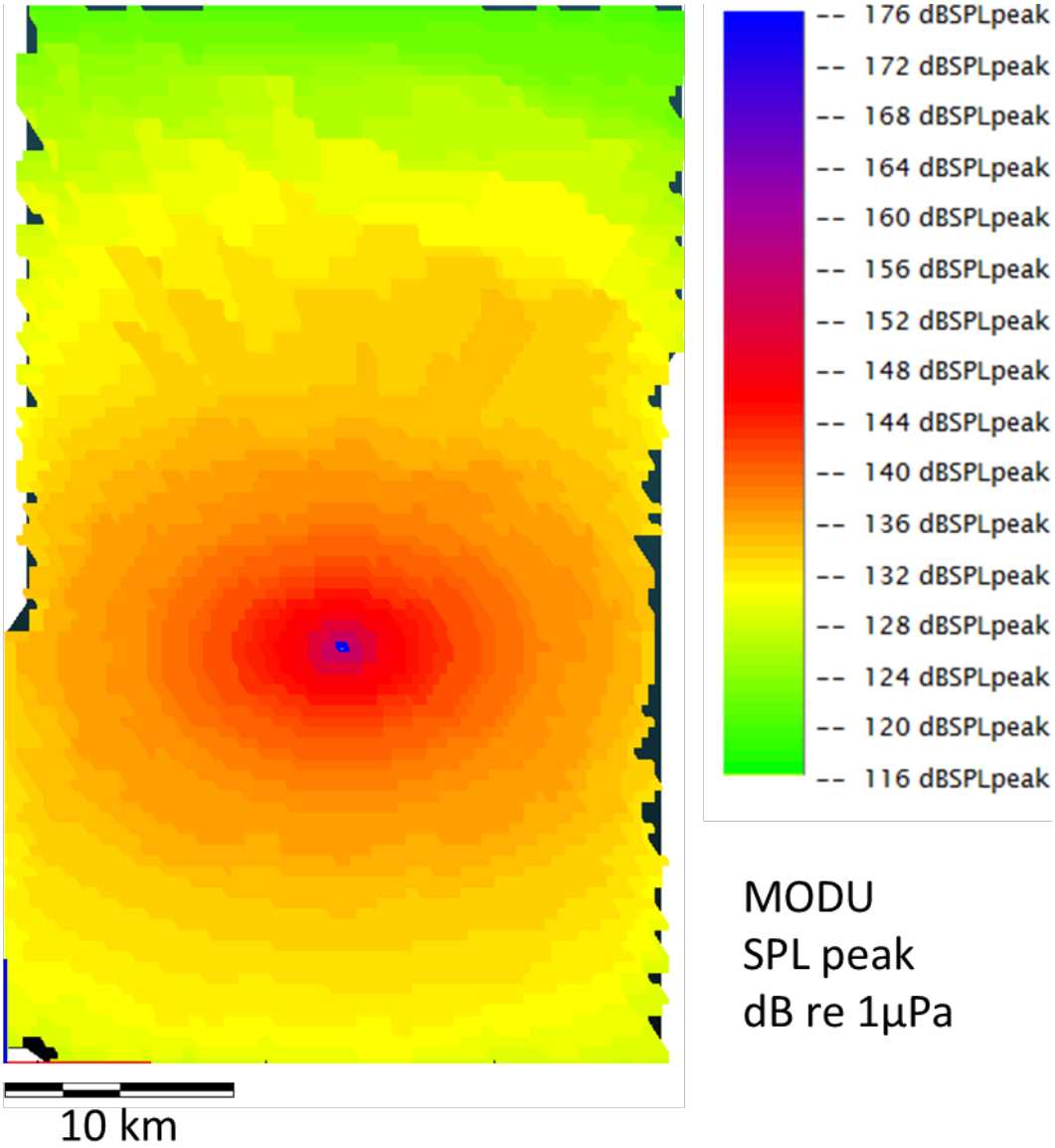


Figure 11 SPL in dB re 1 µPa peak for MODU sound source in the narrow area simulation (highest values projected to surface)

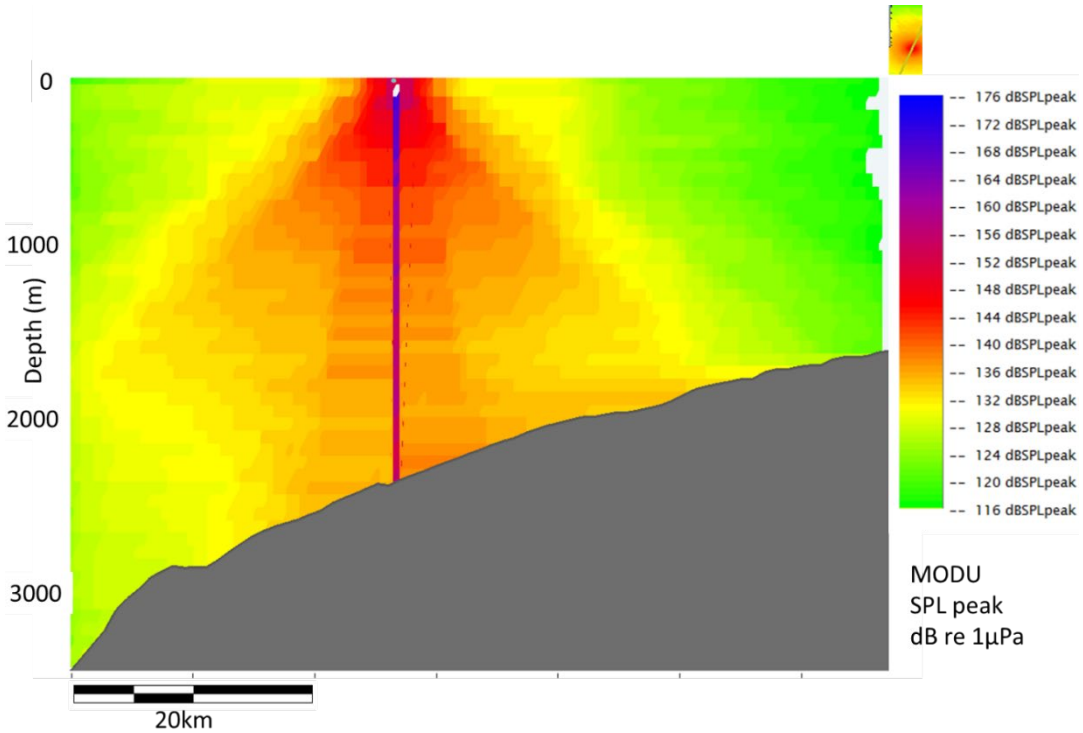


Figure 12 SPL in dB re 1 µPa peak for MODU sound source in the narrow area simulation, with cross-section from deep water to shallow water shown in insert

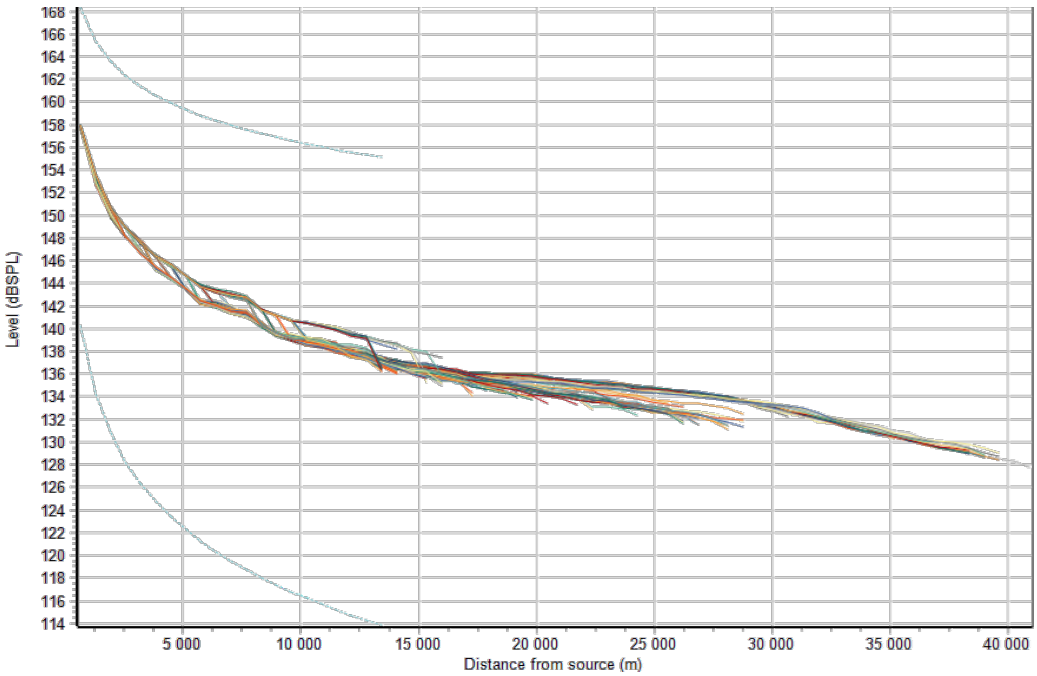


Figure 13 SPL levels in dB re 1 µPa peak for MODU sound source for all slices in the narrow area simulation

The sound exposure level (SEL) at the source for the MODU is 196.4 dB re 1µPa^2 s at 1 m and the SELcum 24 h is 245.8 dB re 1µPa^2 s at 1 m. These are theoretical values which will not be reached as it impossible to be 1 m from all components of the source at once (the thrusters are more than 2 m apart); it is however necessary to calculate for the propagation modelling. Figure 14 shows sound exposure level over distance and depth in one cross section. Figure 15 shows the SEL (1 s) and Figure 16 the SELcum24h at the various directions from the source.

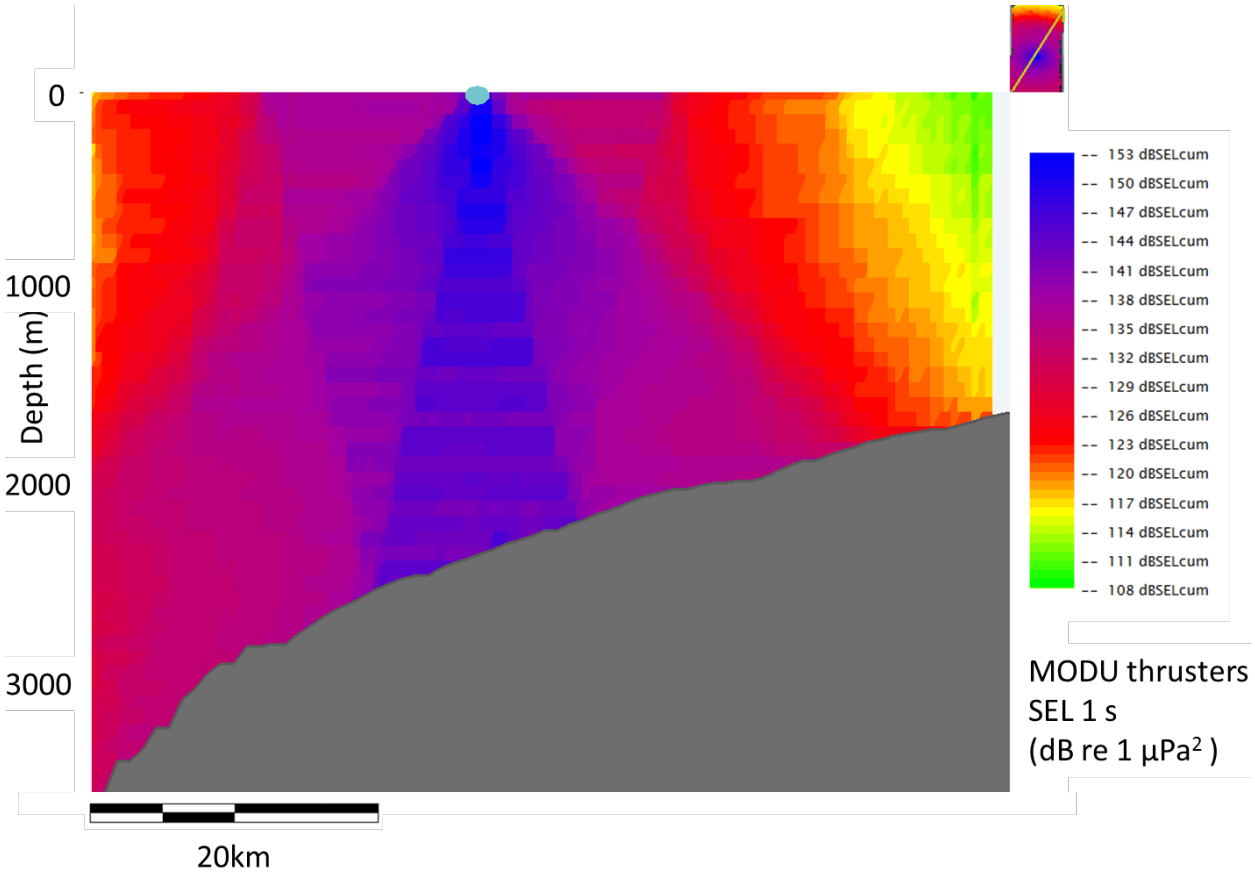


Figure 14 Cross-section of unweighted SEL for the MODU

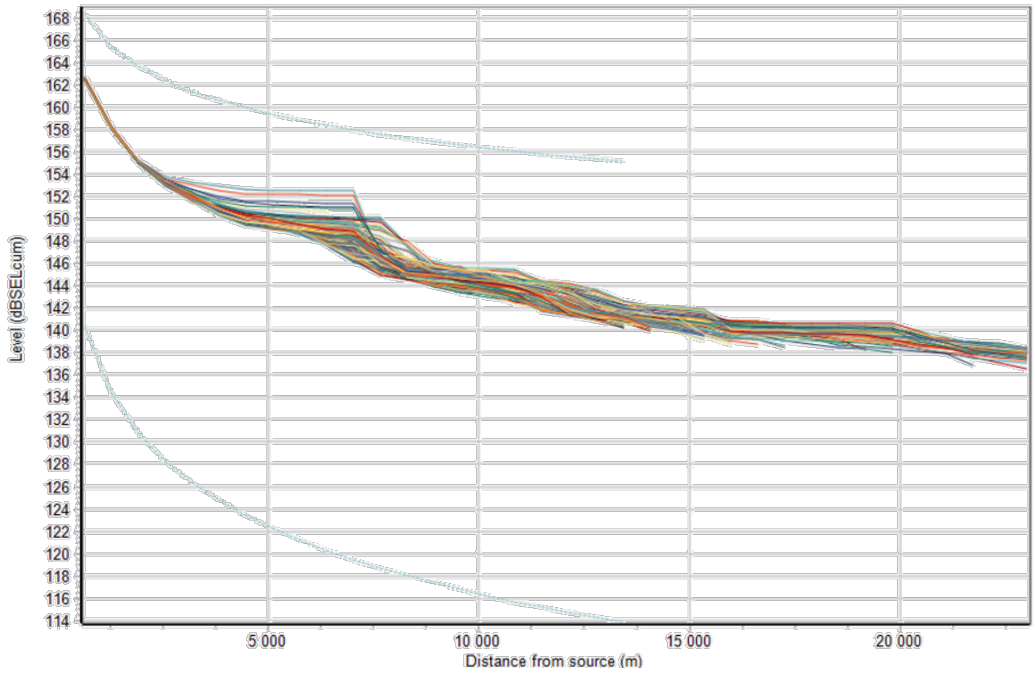


Figure 15 SEL values for the MODU with distance from the sound source (solid blue line)

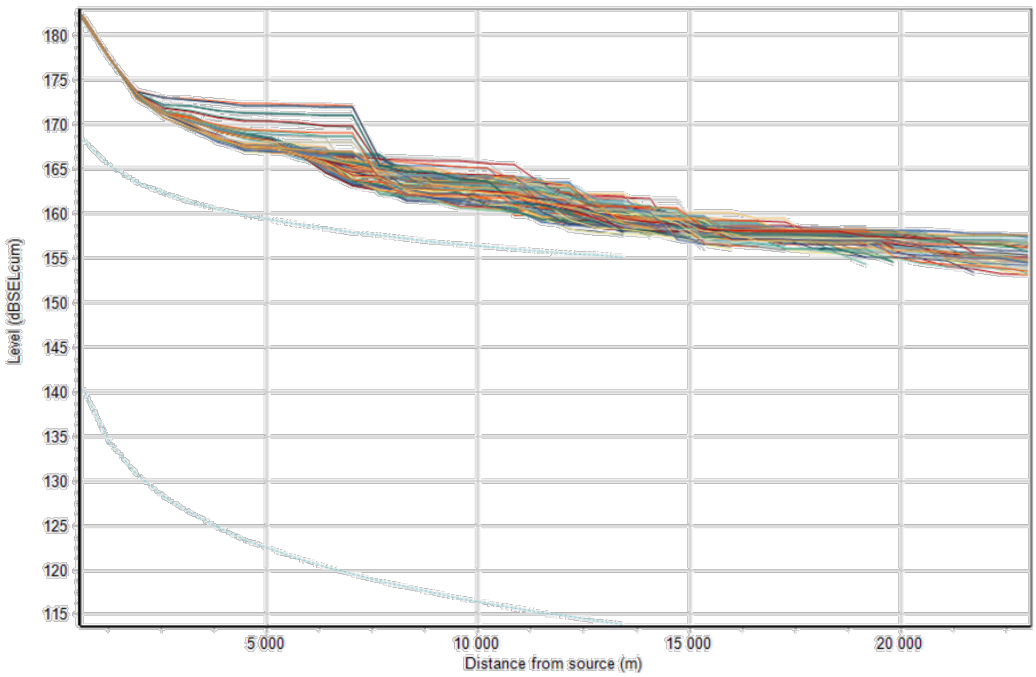


Figure 16 SELcum 24 h for the MODU thrusters with distance from the sound source

SELcum 24 h was calculated as unweighted and weighted values Figure 17. Weighting takes the hearing abilities of different animal groups into account. Figure 17A shows the unweighted SEL cum 24 h whilst Figures 17B to 17F show the weighted SEL for different groups of animals. Figure 17D for example, shows that high-frequency cetaceans do not hear the mostly low frequency noise from the MODU thrusters very well, which is indicated by the lighter colours.

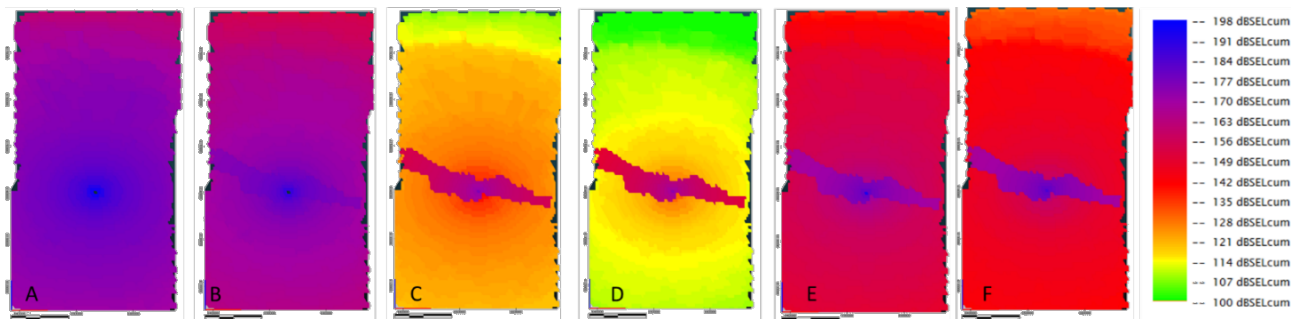


Figure 17 SELcum 24 h for the MODU in dB re 1 µPa^2 s unweighted (A), weighted for low-frequency cetaceans (B), mid-frequency cetaceans (C), high-frequency cetaceans (D), phocid pinnipeds (E) and otariid pinnipeds (F)

4.1.2 Sound pressure levels from MODU DP-AT

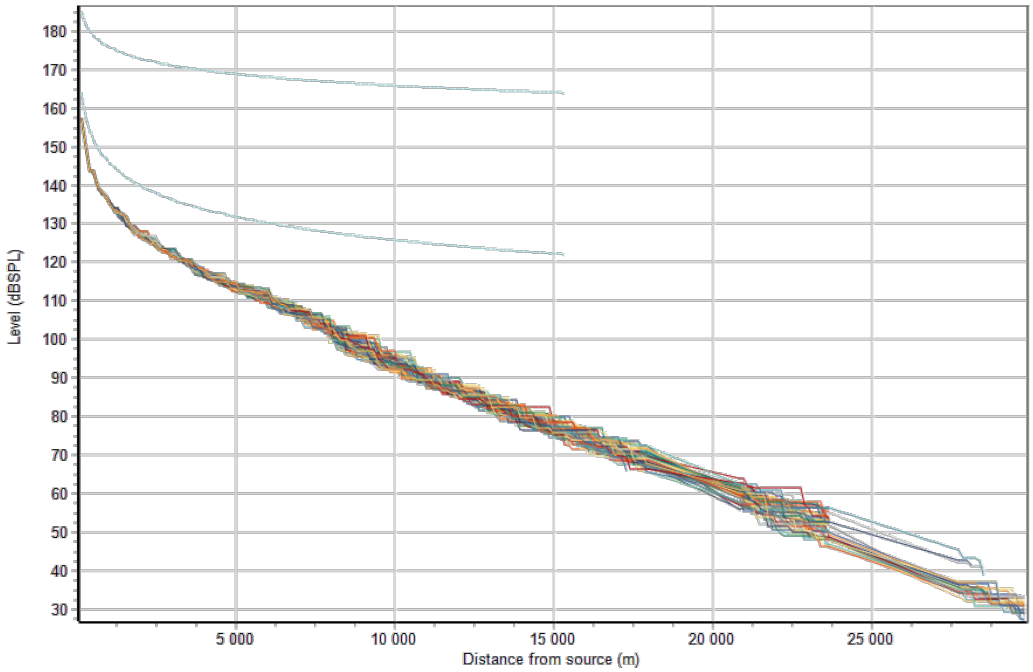


Figure 18 SPL from DP-AT at distances from MODU position

Sound pressure levels from the DP-AT, despite a higher dB value at the source, attenuate rapidly due to the greater absorption of high frequency sound (Figure 18). Propagation is relatively uniform in all directions, with little influence of bathymetry over these distances.

4.1.3 Sound exposure levels from MODU DP-AT

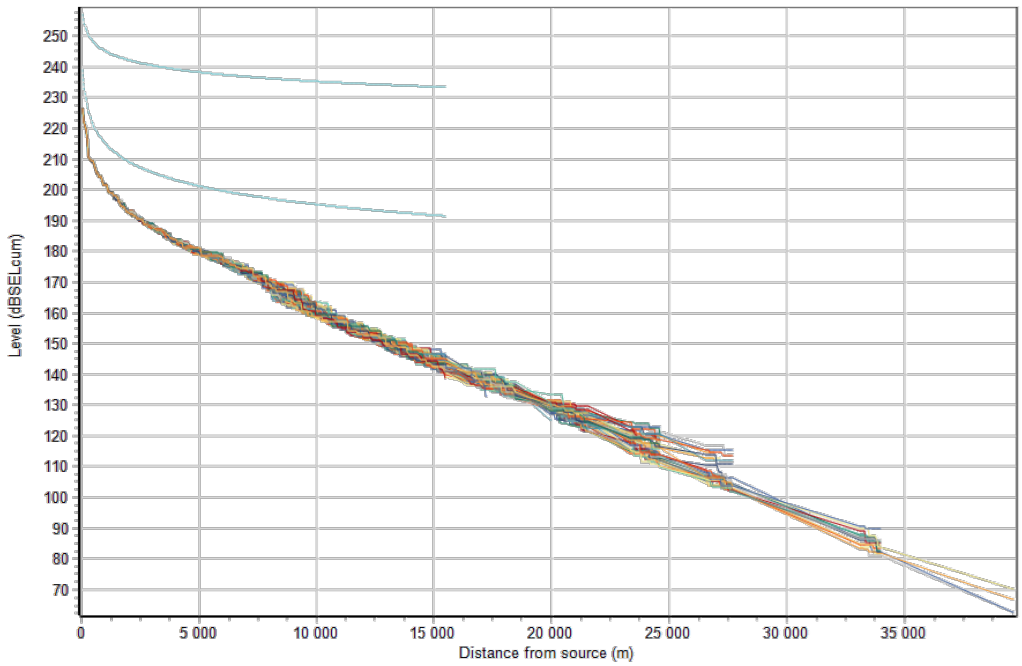


Figure 19 SEL cum 24 h from DP-AT at distances from MODU position

SEL values from the MODU DP-AT show a comparable even propagation in all directions from the MODU source (Figure 19).

5.0 Sound simulation for VSP

5.1 Sound pressure level from VSP

The propagation of sound pressure levels from the VSP over the narrow area simulated is shown in Figures 20–22.

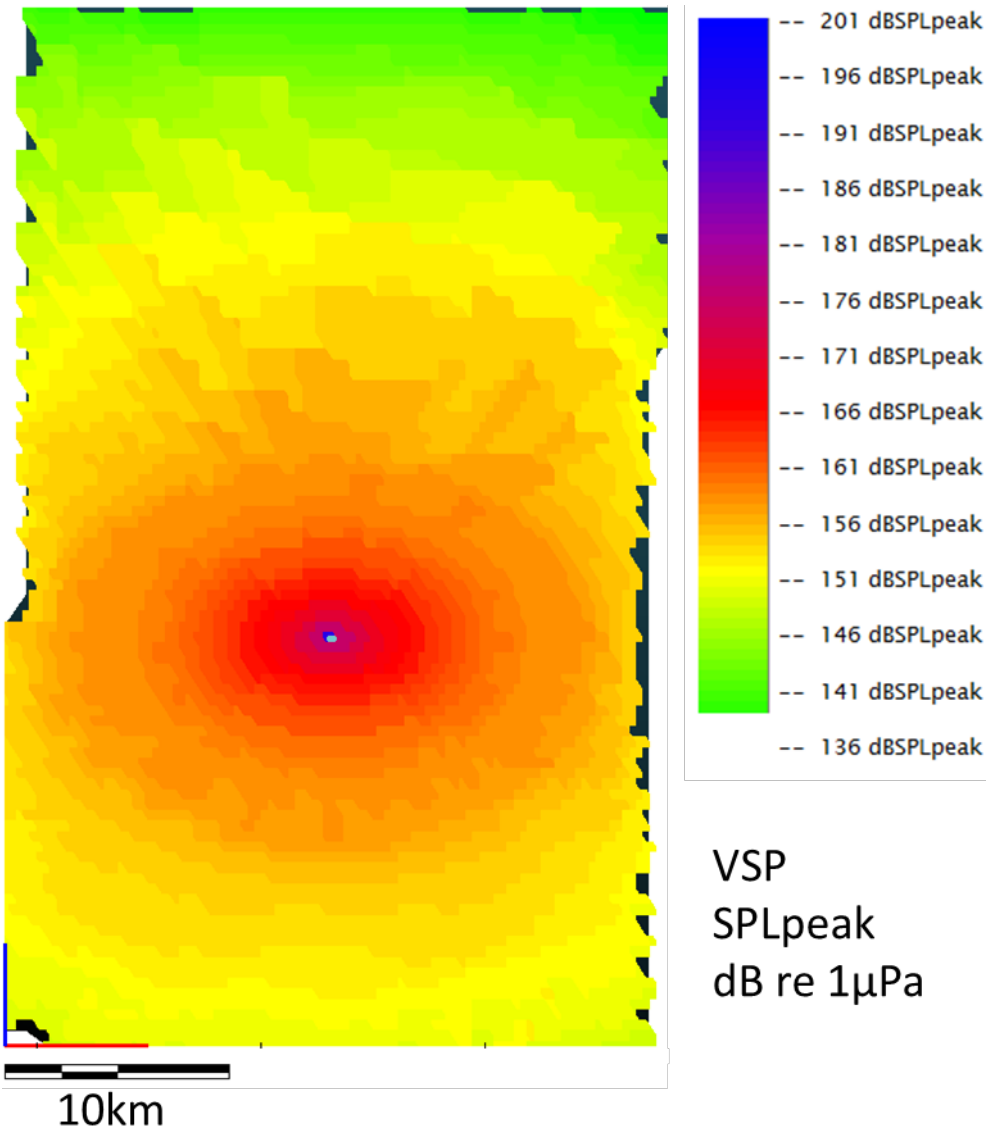


Figure 20 SPL in dB re 1 µPa peak for VSP sound source in the narrow area simulation

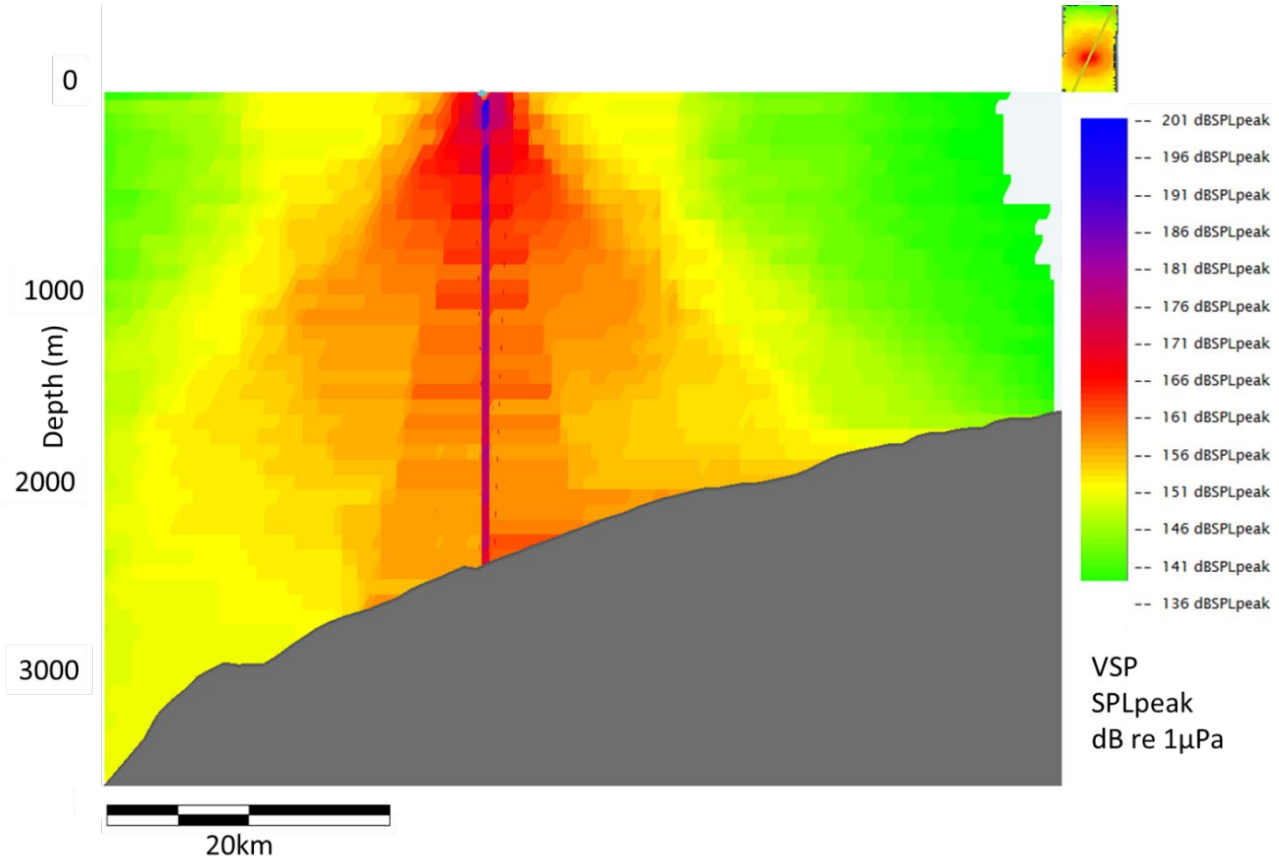


Figure 21 SPL in dB re 1 µPa for VSP sound source in the narrow area simulation, with cross-section from deep water to shallow water shown in insert

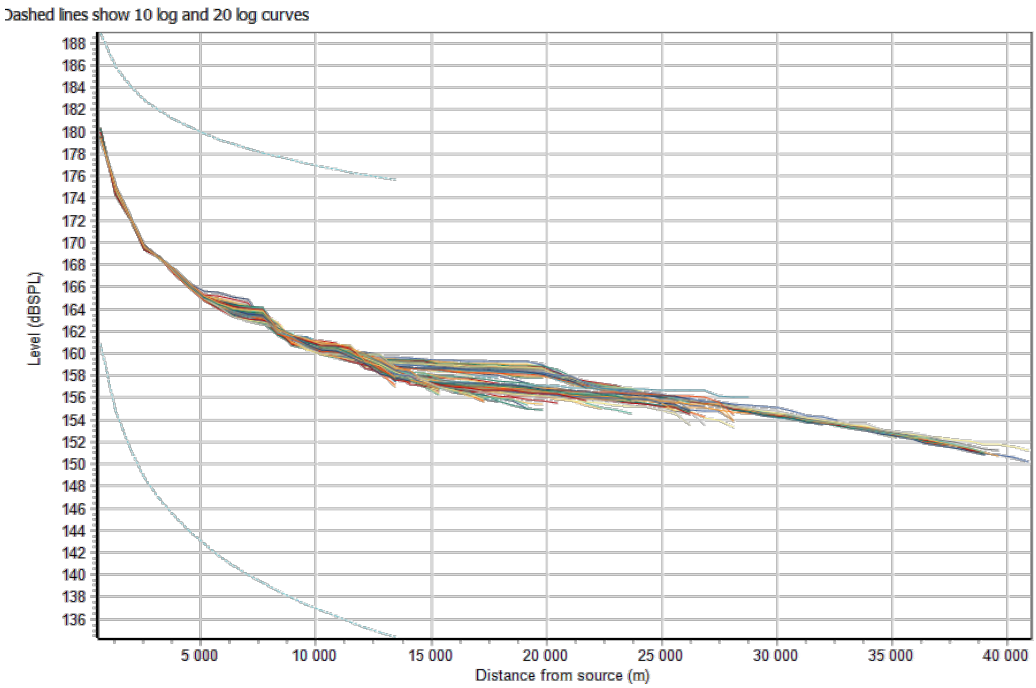


Figure 22 SPL levels in dB re 1 µPa peak for all slices in the narrow area simulation. Lack of spread in the data is due to relatively uniform bathymetry over the narrow area model domain

5.2 Sound exposure level from VSP

The SEL values vary depending on the integration time used to calculate the SEL. As standard, a one-second integration time for SELcum 1 s and 24-hour integration time for SELcum 24 h were used. There are, however, other recommendations for appropriate integration times, such as those from Popper et al. (2005) who suggest calculating SEL over five shots. The number of shots used in VSP may vary, but the seismic source will not be continuous over any 24-hour period; the VSP planned for Stromlo-1 will likely involve 450 shots over a period of four to eight hours and occasional test shots (approximately 10 in total). We used integration over 460 shots for calculation of SELcum 24h in relation to exposure criteria.

To compare SELcum values, SELcum was calculated for numbers of shots (Table 3).

Table 2 Sound exposure levels for VSP sound source

	SELcum 1 (single shot)	SELcum 5 (5 shots)	SELcum 24 h (460 shots over 24 hours)
dB re 1 µPa2 s	217	224	238

5.2.1 Wide area simulation

Modelled SEL values from wide area simulation are shown in horizontal projection in Figure 23 and in cross-section in Figure 24.

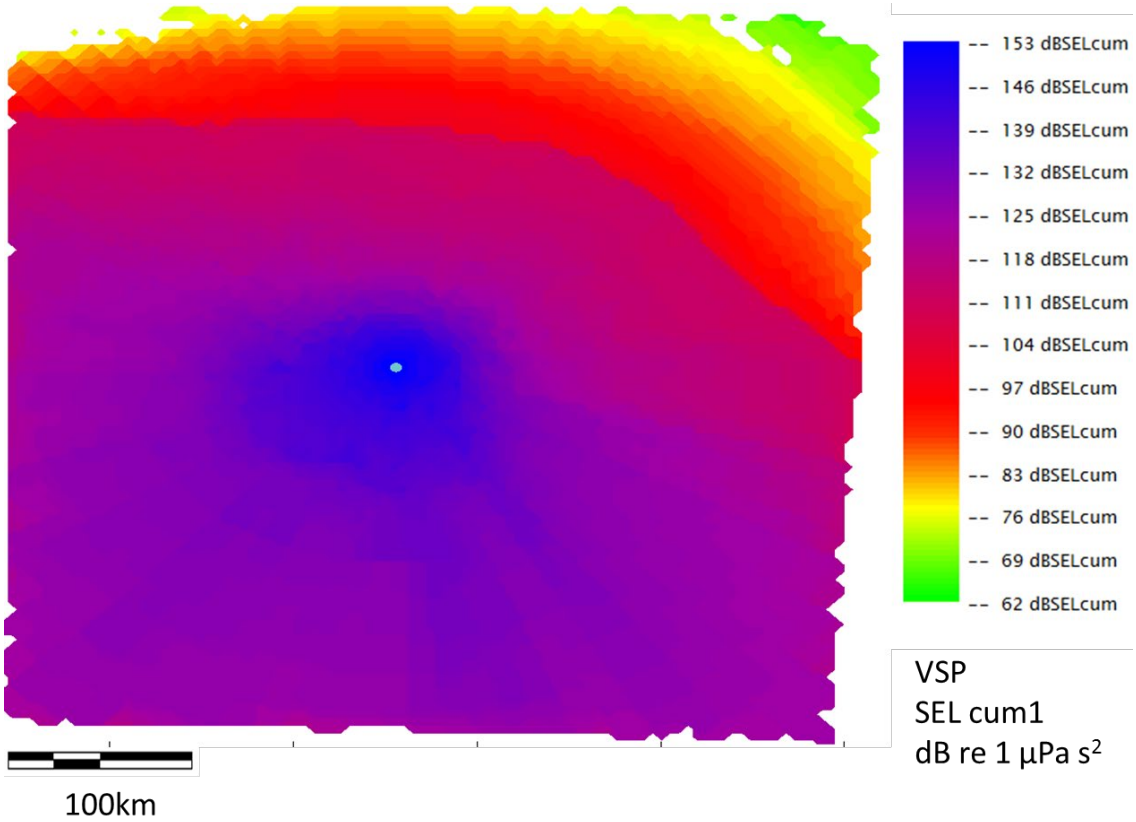


Figure 23 SELcum 1 from VSP in relation to distance from source, where maximum SEL from all depths is projected on to the sea surface

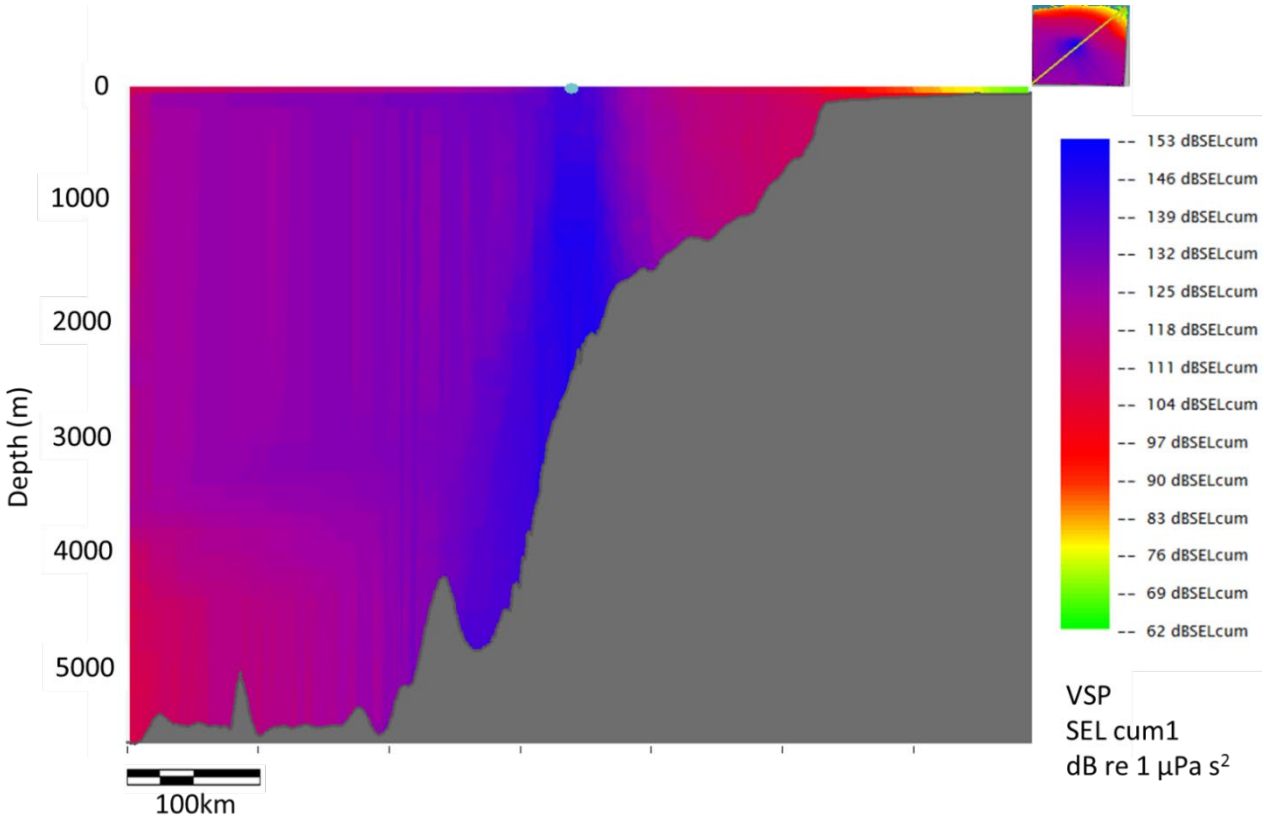


Figure 24 SELcum 1 from VSP sound source in cross-section from deep water to shallow water (with orientation shown in insert; direction was roughly perpendicular to seabed slope)

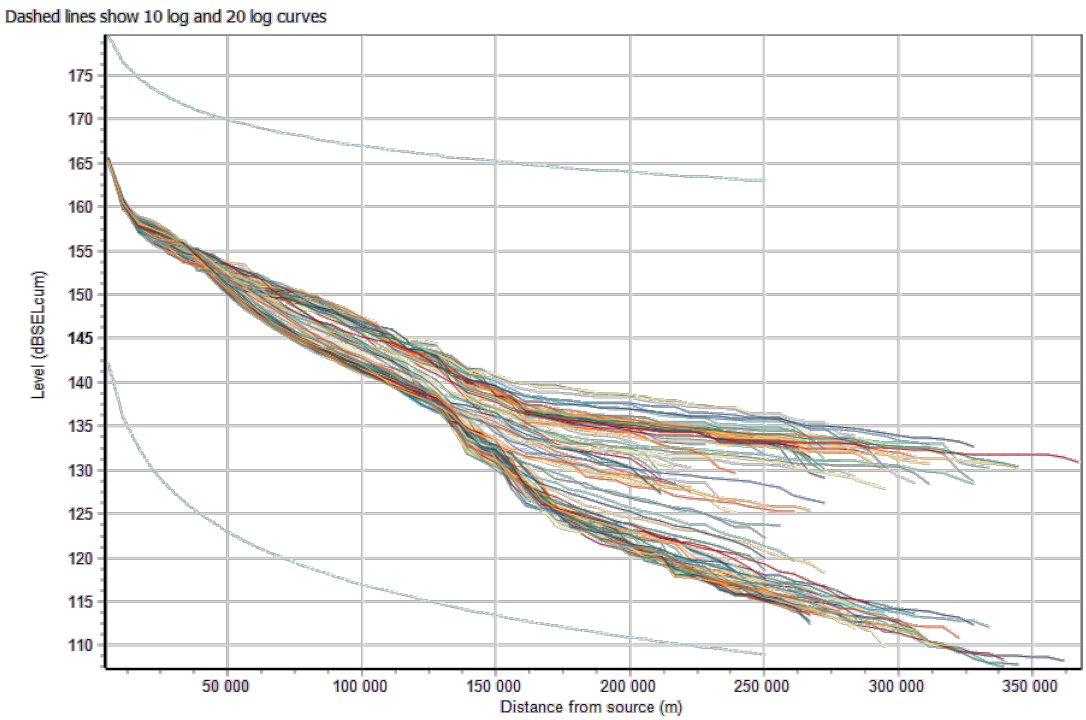


Figure 25 SELcum 1 from VSP in relation to distance from source as maximum value for each depth

The spread of data at distances in Figure 25 is due to bathymetry where higher values are towards deep water and lower values are towards shore. The graph is not precise close to source due to the resolution chosen for the model calculations and the near field effects close to the array.

5.2.2 Narrow area simulation

Figure 26, Figure 27 and Figure 28 show the modelled sound exposure levels accumulated over 24 hours (SELcum 24 h) from the narrow area simulations. There are no big differences in the different directions (Figure 26). The slight spread of data with distance from the VSP source in Figure 28 is due to changes in bathymetry, with higher energy propagating further into deep water away from shore.

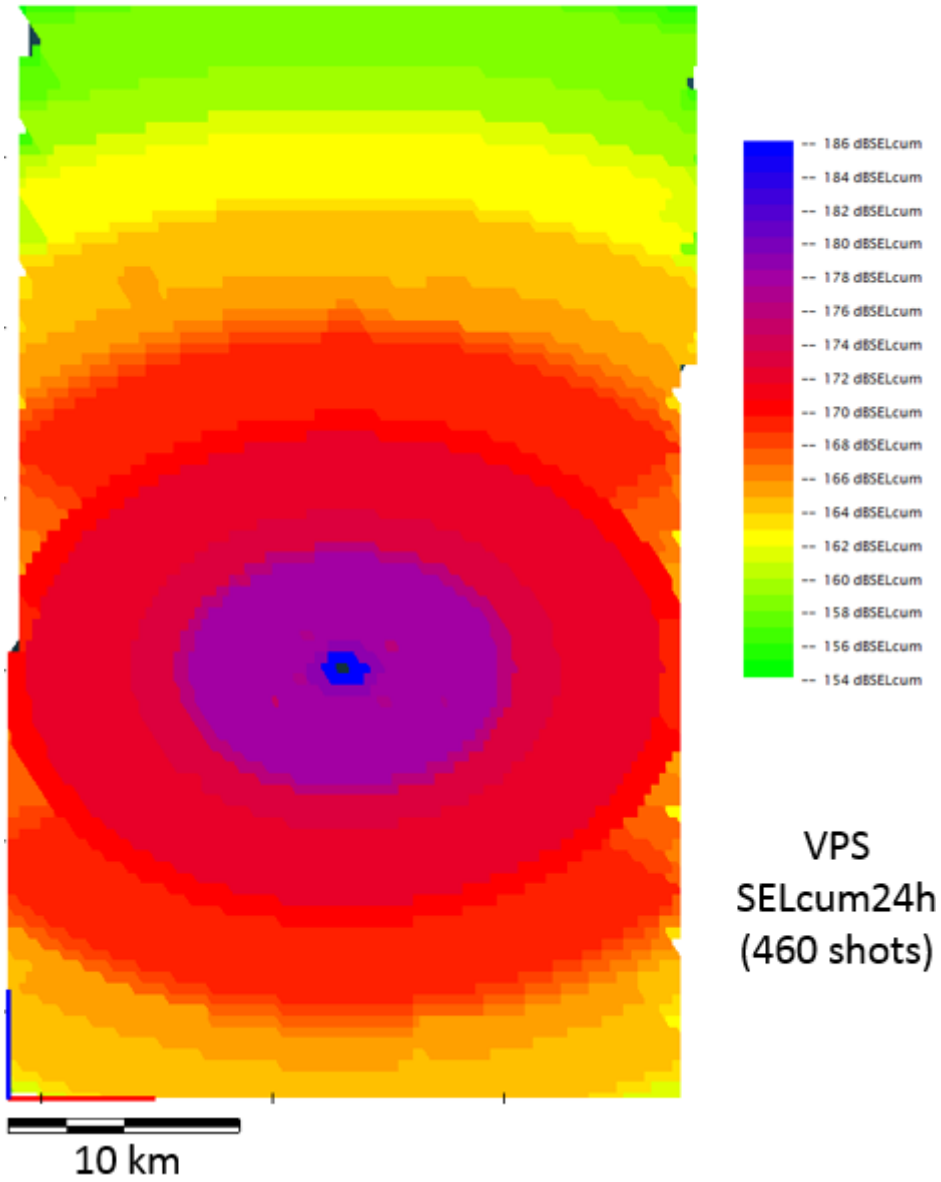


Figure 26 SELcum 24 h in the narrow area simulation

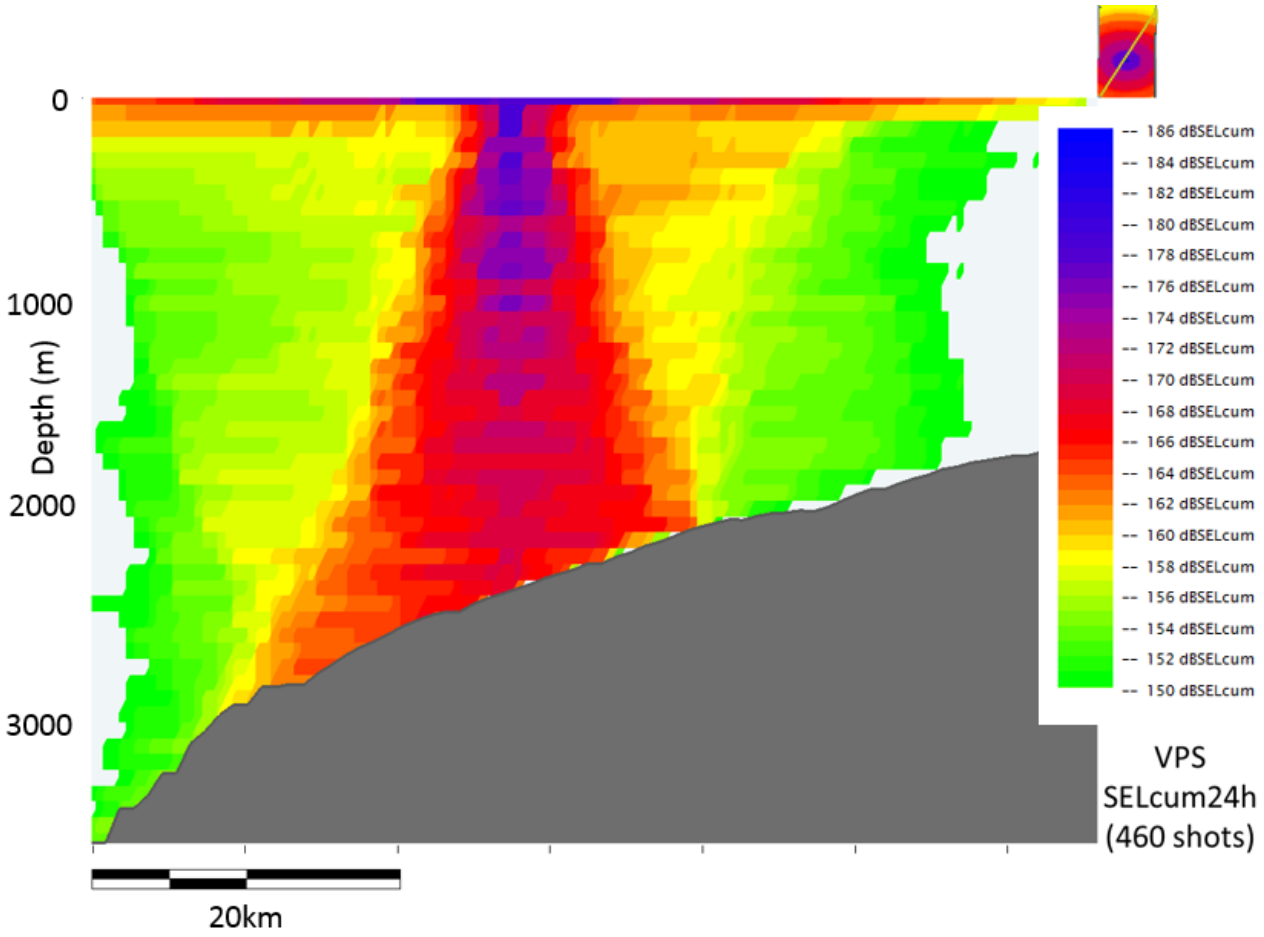


Figure 27 **Cross-section of SELcum 24 h in the narrow area simulation, cross-section from deep water to shallow water (with orientation shown in insert; direction was roughly perpendicular to seabed slope)**

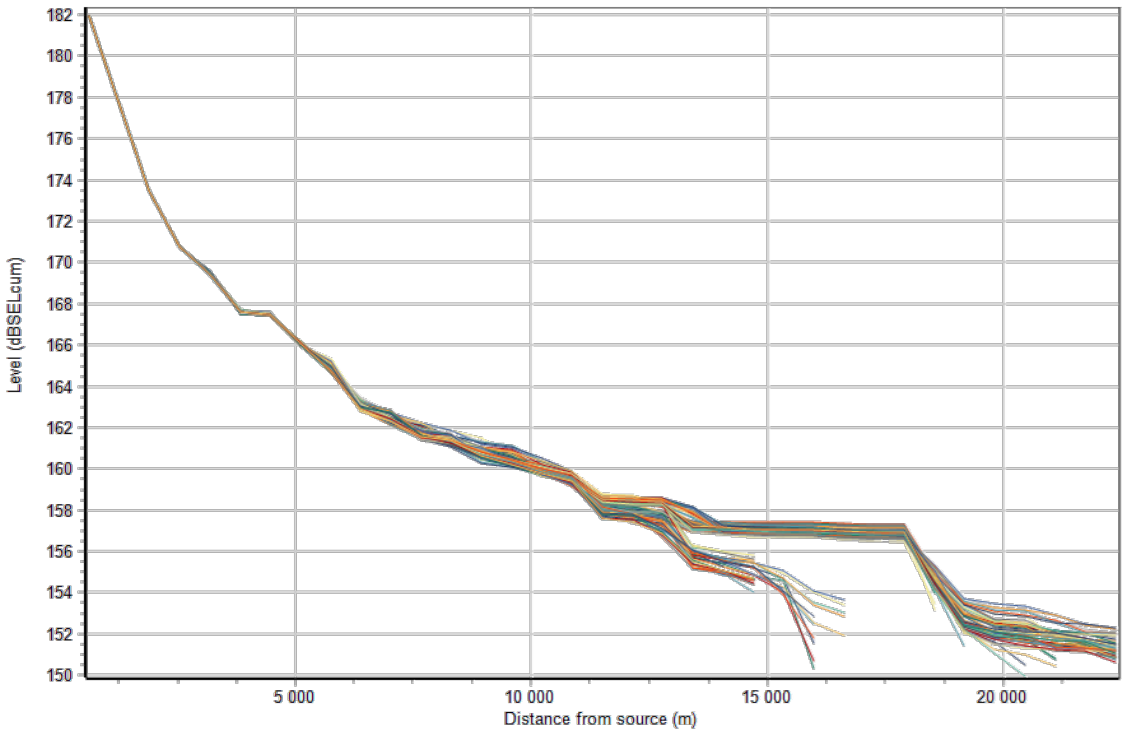


Figure 28 **SELcum 24 h from VSP in the narrow area simulation**

6.0 Predicted impact ranges for marine fauna

In accordance with NMFS (2018) guidelines, SPL threshold criteria on unweighted SPL simulations and SEL criteria on weighted SELcum simulation data were used. A recent peer-reviewed scientific publication by Southall et al. (2019) has confirmed the threshold values in NMFS (2018). For fish, SELcum criteria were used with SEL integration for five shots (denoted as SELcum5). The values of the respective criteria are shown in Table 3 and Table 4. Threshold criteria may have been exceeded at a few metres from the source in cases where the source strength in SPL or SEL values exceeds the respective threshold value but were not resolved with the current setting of the model horizontal resolution.

6.1 MODU operations

For onset of behavioural reactions SPL values above 140 dB re 1 µPa are also discussed (Southall 2007). For the MODU DP-AT this range was about at 600 m. For the MODU thruster this low level had to be interrogated with wide area simulations. The 140 dB re 1 µPa SPL would reach to a maximum of 17 km (at 90 deg = east) with an average of 9 km in all directions.

Table 3 Marine mammals – Received sound levels from MODU thruster operations compared with thresholds

Hearing group	NMFS (2018) – (SELcum24h)			
	Permanent threshold shift (PTS - Injury)		Temporary threshold shift (TTS)	
	Weighted SELcum24h	Distances (km)	Weighted SELcum24h	Distances (km)
Low-frequency cetaceans	199	1.6 (max 1.9)	179	20 (max 25)
Mid-frequency cetaceans	198	NE	178	4.072 (max 9.8)
High-frequency cetaceans	173	0.2 (max 0.3)	153	0.9 (max 1.9)
Phocid pinnipeds in water (elephant seal)	201	0.5 (max 0.9)	181	1.9 (max 2.2)
Otariid pinnipeds in water (fur seal, sea lion)	219	NE	199	NE

NE – no exceedance, threshold not reached

Table 4 Fish, fish eggs/larvae and turtles – Received sound levels from MODU thruster operations compared with thresholds

Type of animal	Popper et al. 2014			
	Recoverable injury	Distances (km)	TTS	Distances (km)
Fish: Swim bladder involved in hearing (primarily pressure detection)	170 dB SPLrms	0.6 (average) 1.0 (max)	158 dB SPLrms	1.0 (average) 1.9 (max)

Table 5 shows the respective distances or PTS and TTS thresholds for impulsive sound. The distances to the respective thresholds for SEL are the one with the longest distance from source, therefore we only show the SEL threshold values and not the SPLpeak values.

Table 5 Marine mammals – received sound levels from MODU DP-AT operations (impulsive source) compared with thresholds

Hearing group	NMFS (2018) – (SELcum24 h)			
	Permanent threshold shift (PTS - Injury)		Temporary threshold shift (TTS)	
	Weighted SEL 24 h (cumulative)	Distances (km)	Weighted SEL 24 h (cumulative)	Distances (km)
Low-frequency cetaceans	183	3.5 (max 3.6)	168	6.5 (max 6.7)
Mid-frequency cetaceans	185	4.7 (max 4.9)	170	7.9 (max 8.1)
High-frequency cetaceans	155	11.3 (max 11.6)	140	14.8 (max 15.2)
Phocid pinnipeds in water (elephant seal)	185	4.0 (max 4.1)	170	7.0 (max 7.2)
Otariid pinnipeds in water (fur seal, sea lion)	203	1.3 (max 1.4)	188	3.3 (max 3.4)

Table 6 Fish, fish eggs/larvae and turtles – received sound levels from MODU DP-AT operations (impulsive source) compared with thresholds

Type of animal	Popper et al. 2014			
	Mortality / potential mortal injury / recoverable injury SPLpeak dB re 1 µPa	Distances (km)	TTS SELcum 24 h dB re 1µPa^2 s	Distances (km)
Fish: No swim bladder (particle motion detection) Fish: Swim bladder not involved in hearing (particle motion detection) Fish: Swim bladder involved in hearing (primarily pressure detection) Turtles Fish eggs and fish larvae	207 to 213	<0.075	186	4.6

6.2 VSP operations

The modelling results were used to derive the maximum distance over which behavioural responses to the MODU VSP could be expected; based on the NMFS cetacean behavioural threshold level of 160 dB SPLrms (unweighted). The modelling showed that the sound level from the VSP could cause avoidance behaviour in all cetacean groups, to a maximum distance of 16 km from the source (Figure 29).

The modelling results were also interrogated for the EPBC Policy Statement 2.1 guideline threshold level of 160 dB SEL (SELcum over one second, unweighted) and showed that the sound level from the VSP exceeded the 160 dB SEL threshold out to 9 km from the source (Figure 30).

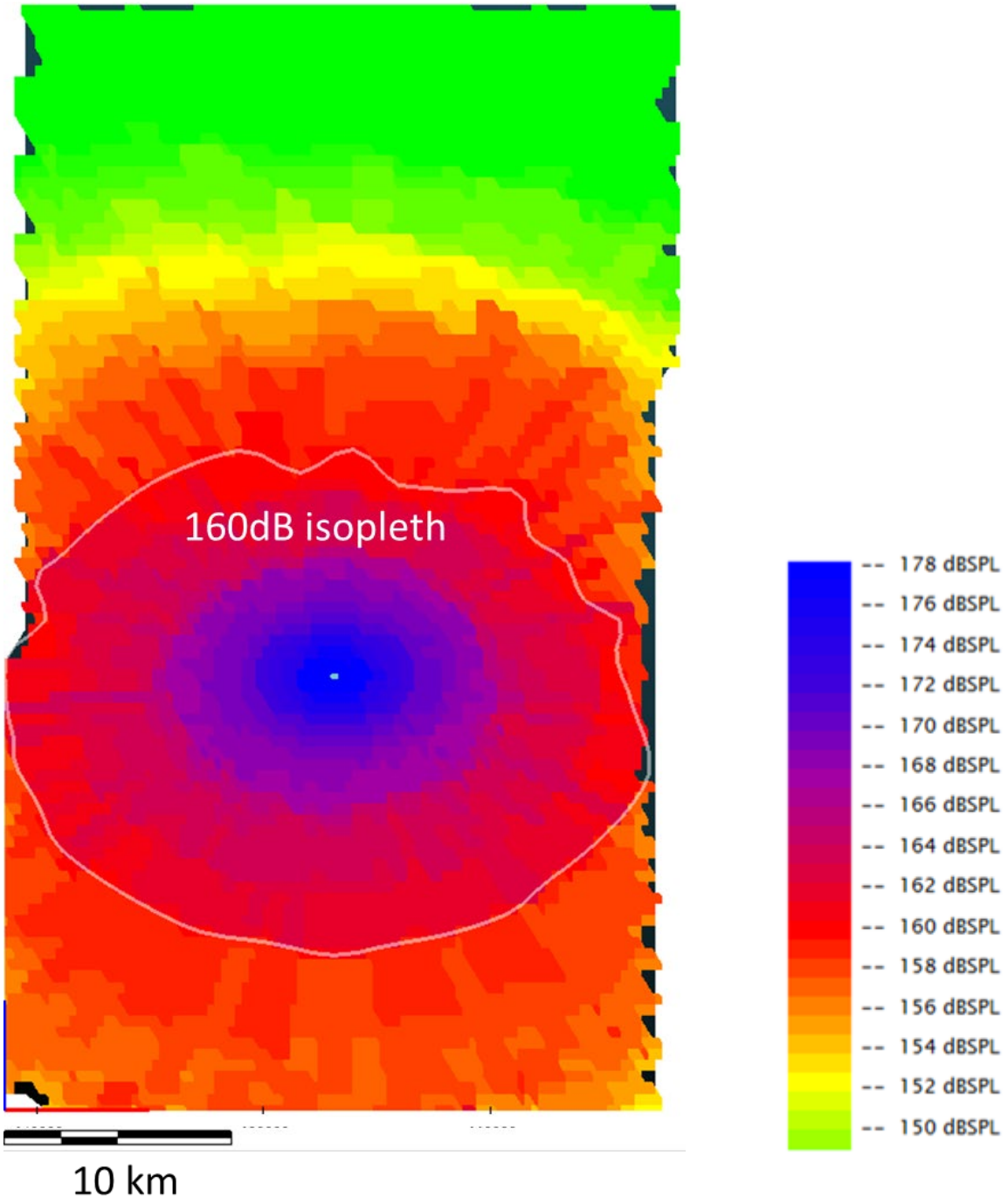


Figure 29 Isopleth of marine mammal behavioural threshold (160 dB SPLrms) showing almost equal propagation in all direction in the deep waters of the Stromlo-1 well location

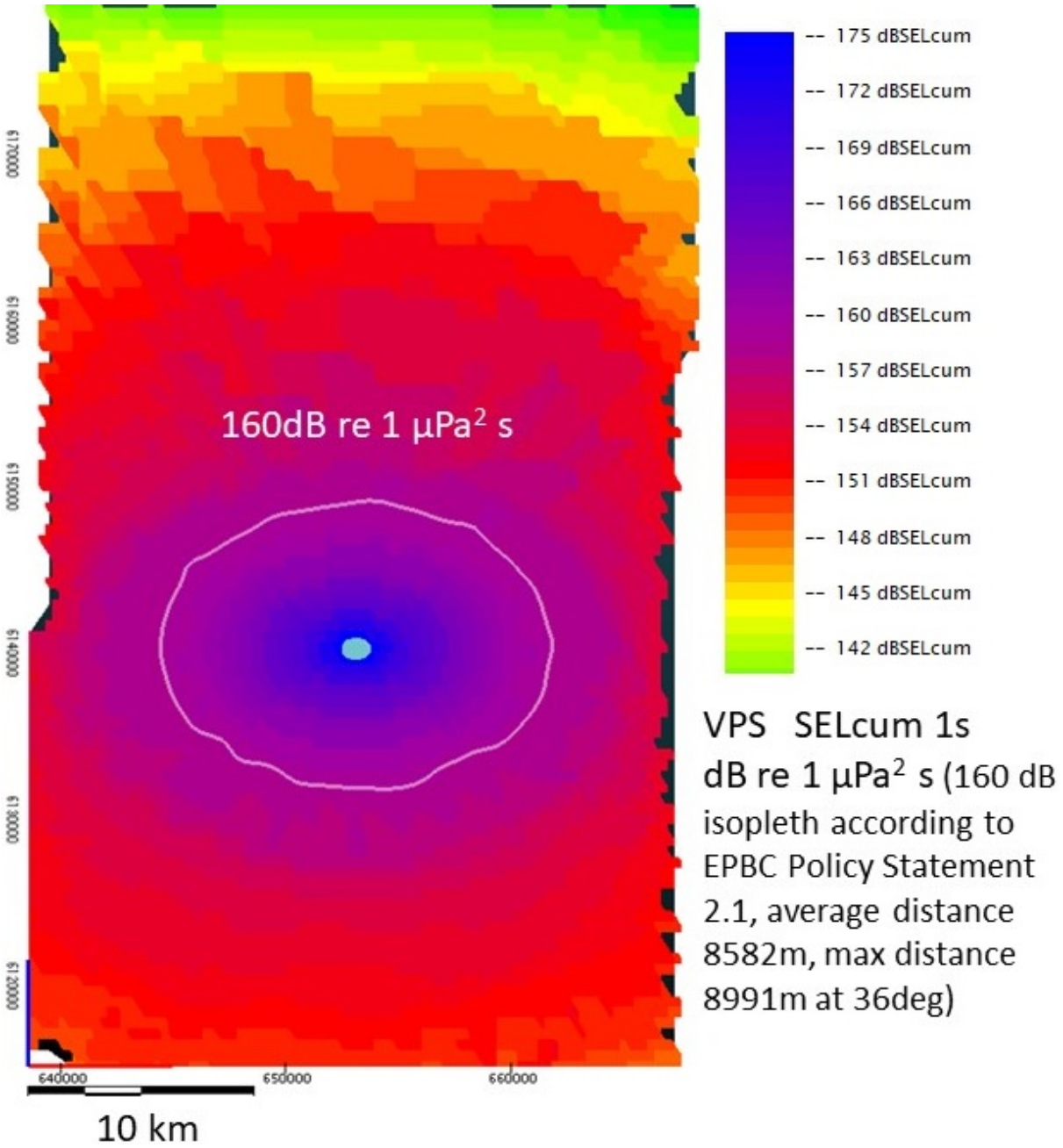


Figure 30 Isopleth of EPBC PS2.1 marine mammal management threshold (160 dB SEL) showing almost equal propagation in all direction in the deep waters of the Stromlo-1 well location

Table 7 Marine mammals – received sound levels from VSP operations compared with thresholds

Hearing group	NMFS (2013)	NMFS (2018) – Dual metric criteria (PK and SEL24h)							
	Behaviour	Injury (PTS)				TTS			
	160 SPLrms (dB re 1 µPa)	Weighted SEL24h (cumulative)	Distances (km)	PK (dB re 1 µPa)	Distances (km)	Weighted SEL 24 h (cumulative)	Distances (km)	PK (dB re 1 µPa)	Distances (km)
Low-frequency cetaceans	14 km (average) 16 km (max)	183	NE	219	NE	168	3.3 (average) 3.5 (max)	213	NE
Mid-frequency cetaceans		185	NE	230	NE	170	NE	224	NE
High-frequency cetaceans		155	NE	202	0.2 (average) 0.3 (max)	140	1.4 (average) 1.6 (max)	196	0.58 (average) 1.0 (max)
Phocid pinnipeds in water (elephant seal)		185	NE	218	NE	170	1.4 (average) 2.2 (max)	212	NE
Otariid pinnipeds in water (fur seal, sea lion)		203	NE	232	NE	188	NE	226	NE

NE – no exceedance, threshold not reached

Table 8 Fish, fish eggs/larvae and turtles – received sound levels from VSP operations compared with thresholds

Type of animal	Popper et al. (2014)			
	Mortality / potential mortal injury / recoverable injury (PK dB re 1 µPa)	Distances (km)	TTS SEL24h (cumulative)	Distances (km)
Fish: No swim bladder (particle motion detection)	213	NE	186	NE
Fish: Swim bladder not involved in hearing (particle motion detection)	207	NE		
Fish: Swim bladder involved in hearing (primarily pressure detection)				
Turtles	207	NE	No relevant guideline	
Fish eggs and fish larvae	210	NE		

NE – no exceedance, threshold not reached

Table 9 Invertebrates – received sound levels from VSP operations compared with published values

Type of animal	Day et al. 2016	Distances (km)
Invertebrates (scallops/bivalves)	191 dB SPLpk-pk (peak to peak)	0.8 (average) 1.5 (max)
Invertebrates (lobster/crustaceans)	209 dB Lpk-pk (peak to peak)	NE

NE – no exceedance, threshold not reached

7.0 Summary

The modelling of underwater sound propagation from the loudest sources of sound associated with the drilling activity (VSP and MODU thrusters) showed a range of maximum distances at which the various biological effects levels are predicted to be exceeded. The greatest of these was the maximum distance over which the NMFS (2018) guideline for TTS effects on low-frequency cetaceans was exceeded at a maximum of 25 km from the MODU, due to the continuous emission of sound over 24 hours (Table 3). The propagation distances for sound from the acoustic positioning system on the MODU (DP-AT) were much lower; potentially affecting high-frequency cetaceans out to ~15 km from the MODU.

Recognising there is uncertainty in the sensitivity of marine fauna, a conservative buffer is recommended and the maximum extent of underwater noise effects on marine fauna should be set at 40 km from the well location.

8.0 References

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APPENDIX 1

dBSea benchmark test

dBSea Benchmark Testing

Testing dBSea's solvers in multiple comparisons with well-known benchmark problems.

We here present solutions to a range of well-defined underwater sound propagation calculation problems for the comparison of dBSea's algorithms to the open source method based on the same modelling approach.

Many of the examples will link to "UWA" files. These are dBSea scenario files that can be viewed in dBSea BASIC (freely available from: http://www.dbsea.co.uk/media/30273/dBSea-Basic-220.zip).

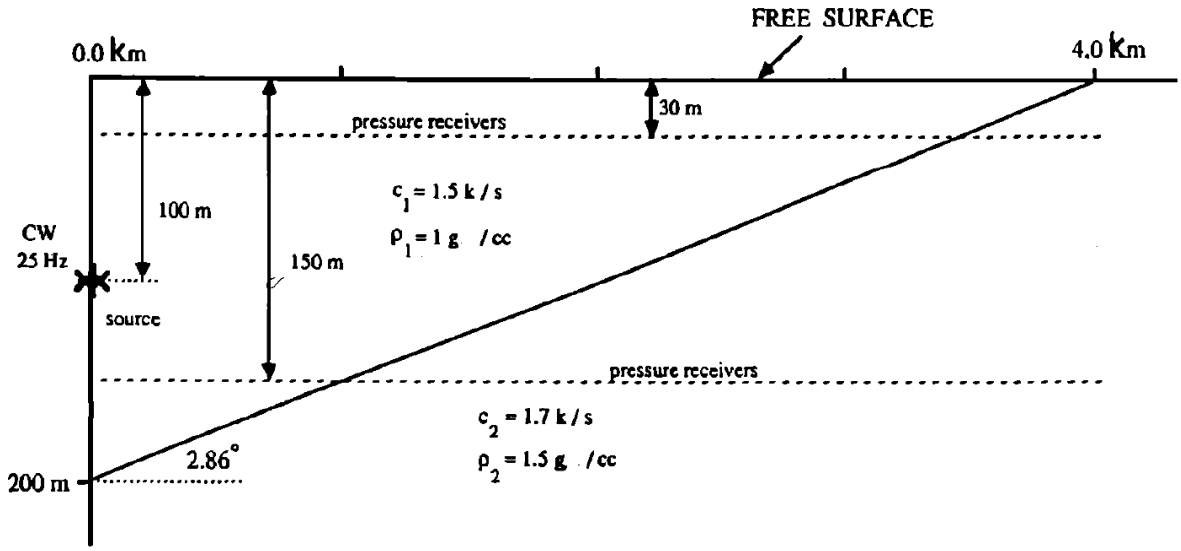
Please not that while raytracing methods have been included in this document for the sake of completeness, they are generally not suitable for low frequency problems (wavelength > 1-3 % of depth).

1 Upslope Wedge

1.1 ASA Benchmark

The ASA Benchmark problems (Jensen & Ferla, 1989) represent a classic base for comparison of propagation modelling.
The UWA file for this scenario is available from:
https://drive.google.com/open?id=0B7cNj3oy6fp0TFg0ZXhrMTZucEU

Figure 1. Schematic of scenario for wedge problem



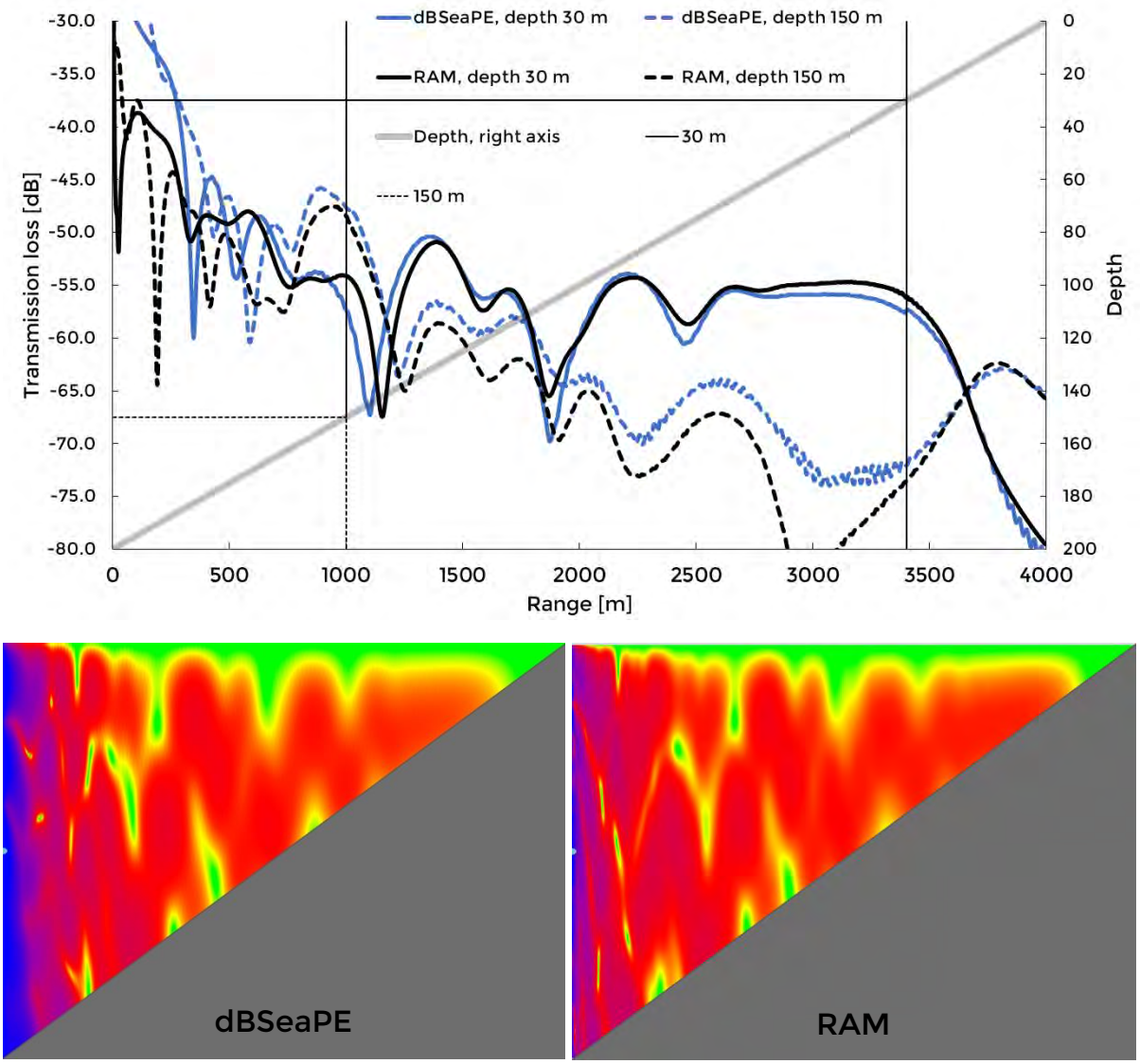
The following results are based on a comparison of dBSea's solvers with solvers from the AcTUP tool-box[1], covering the three most popular methods of calculating the sound field, namely:

- Parabolic equation method - dBSeaPE & RAM
- Normal modes method - dBSeaModes & Kraken
- Ray tracing method - dBSeaRay & Bellhop

Note that the scenario is modelled for 25 Hz. At this frequency we do not expect the two raytracing methods to work well.

1.1.1 Parabolic Equation method

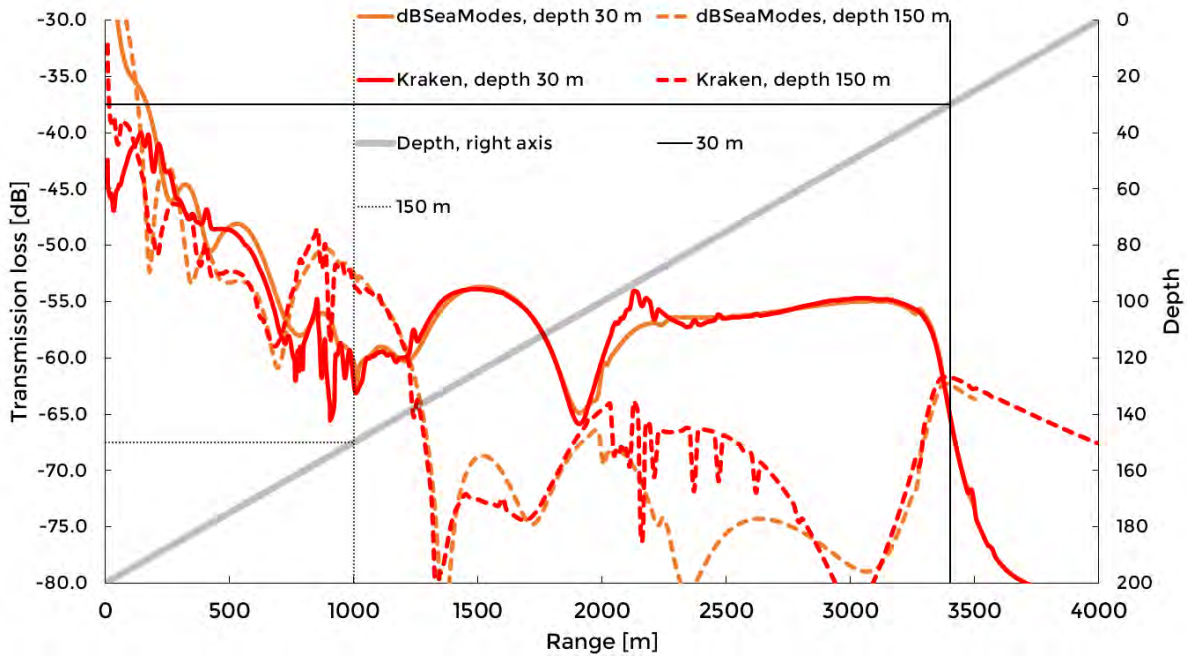
Figure 2. Transmission losses for dBSeaPE and RAM. Depths 30 m and 150 m are shown in chart, while full transects in colour are presented below.

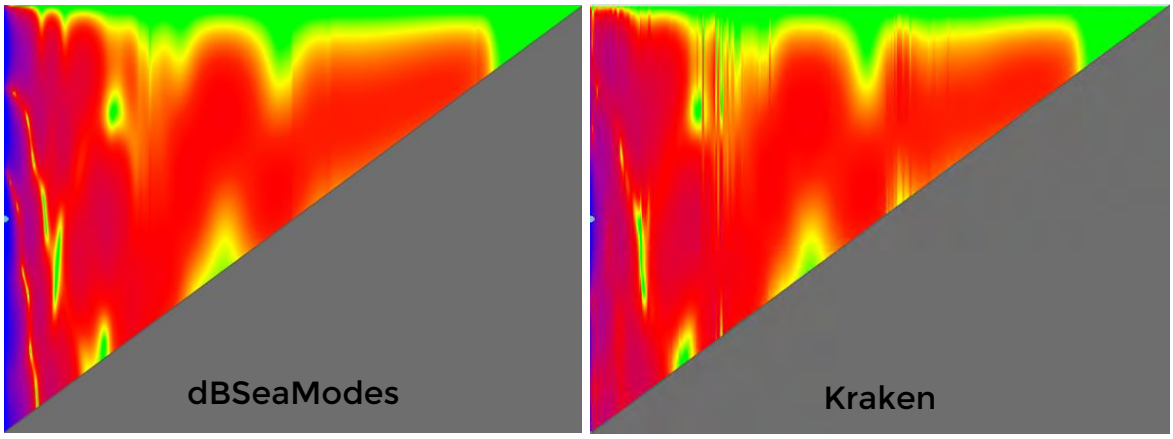


[1] http://cmst.curtin.edu.au/products/underwater/

1.1.2 Normal Modes Method

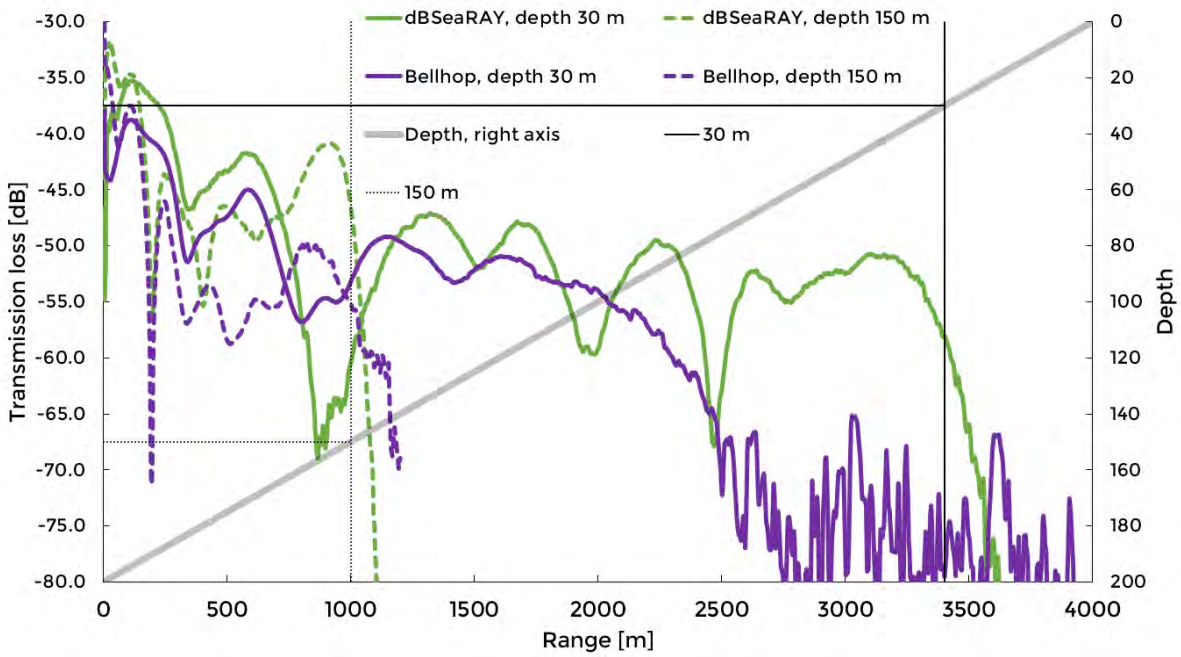
Figure 3. Transmission losses for dBSeaModes and Kraken. Depths 30 m and 150 m are shown in chart, while full transects in colour are presented below.

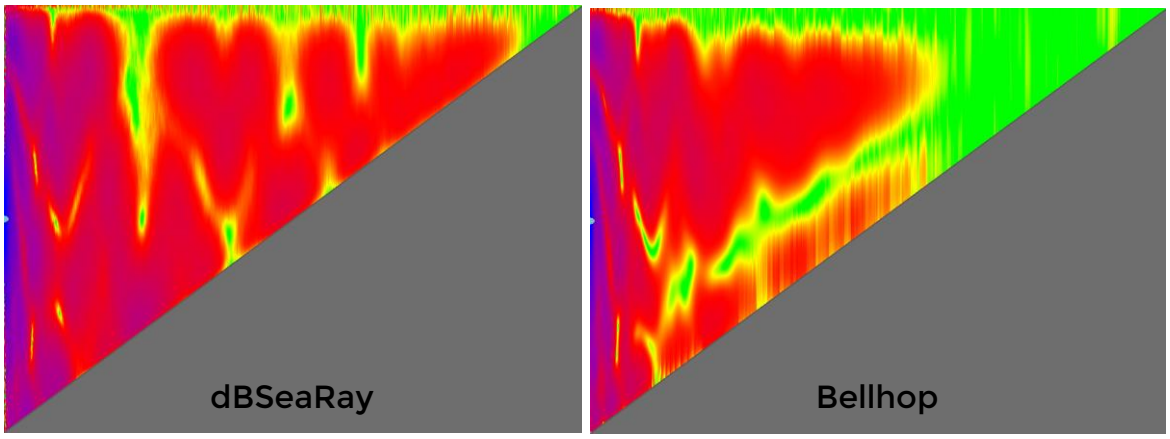




1.1.3 Ray Tracing Method

Figure 4. Transmission losses for dBSeaRay and Bellhop. Depths 30 m and 150 m are shown in chart, while full transects in colour (-20 dB to -70 dB) are presented below.





Note that neither of the ray tracing methods penetrate the sediment, and so the receiver depth at 150 m terminates shortly after a range of 1000 m. Notice that dBSeaRay reproduces the results well from both the parabolic equation method and the normal modes method, despite being unsuitable for the chosen frequency (25 Hz).

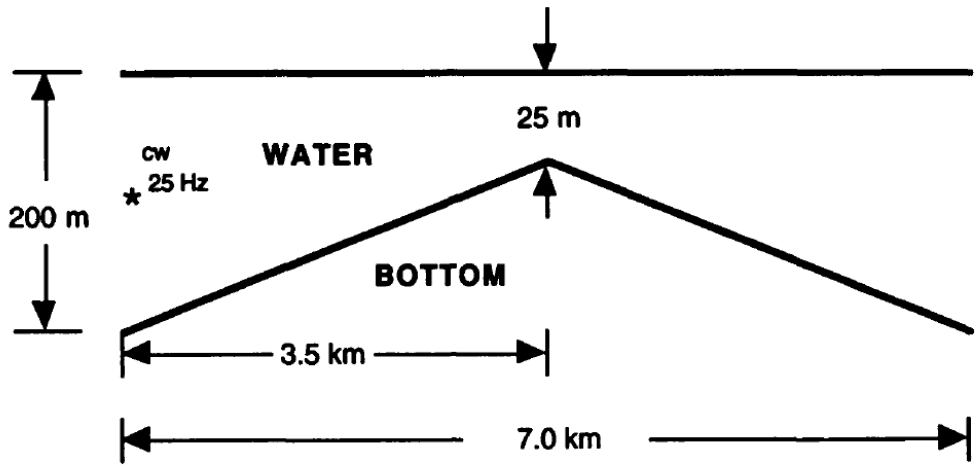
2 Up-Down Energy Conservation problem

2.1 Parabolic Equation Workshop II 1993 – Case II

An upslope-downslope problem formulated to test the energy conservation in strongly range-dependent environments was formulated in (Chin-Bing, et al., 1993).

The UWA file for this scenario is available at:
https://drive.google.com/open?id=0B7cNj3oy6fp0Wi1SdGJGWmhDSHc

Figure 5. Schematic outlining upslope-downslope problem.

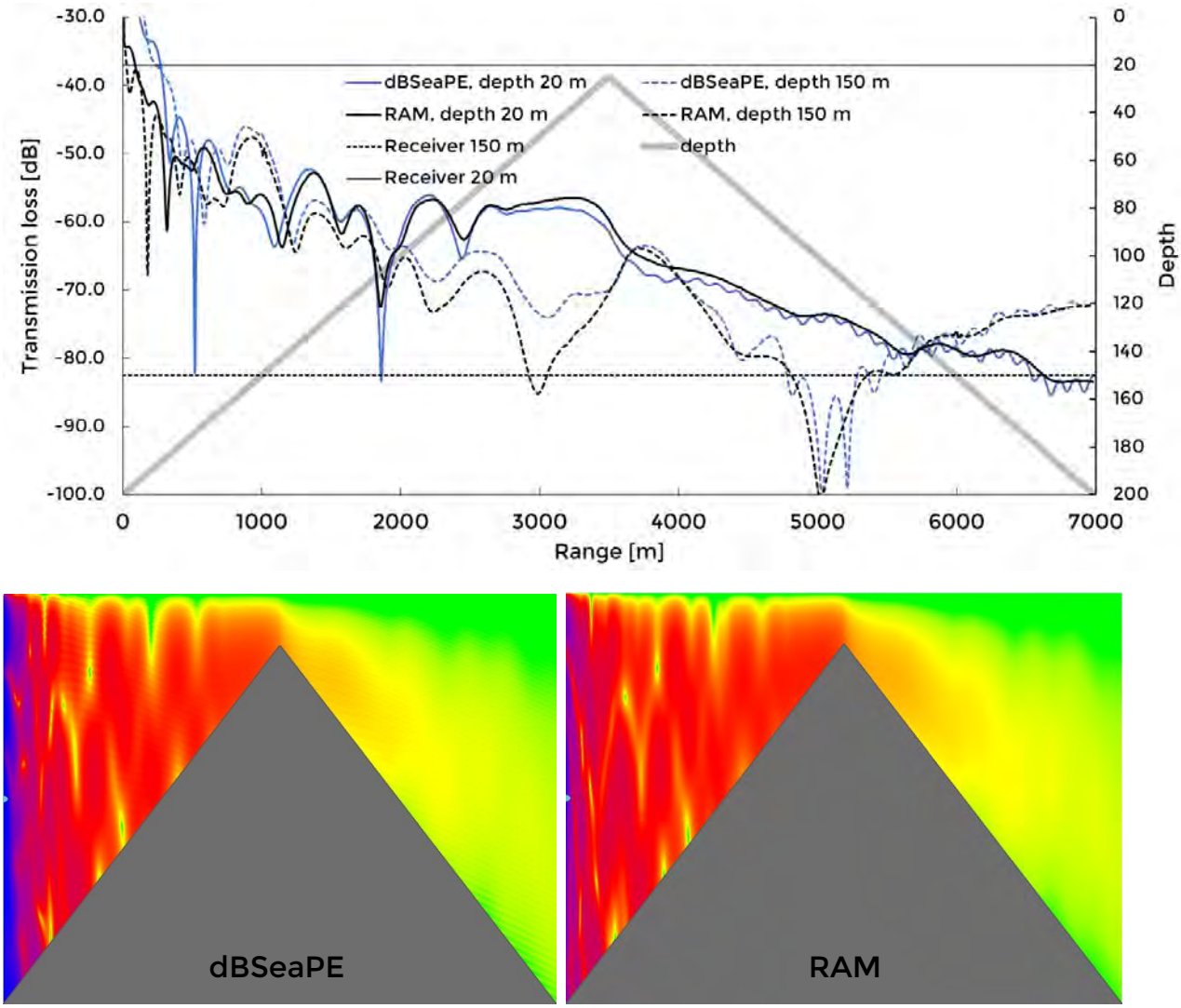


Environmental parameters for Test Case 2.

In the water the sound speed is 1500 m/s, the density is 1 g/cm^3, and there is no attenuation. In the fluid bottom the sound speed is 1700 m/s, the density is 1.5 g/cm^3, and there is an attenuation of 0.5 dB/λ. The frequency is 25 Hz, the fixed point depth (source depth) is 100 m, and the moving point depths (receiver depths) are 20 m and 150 m.

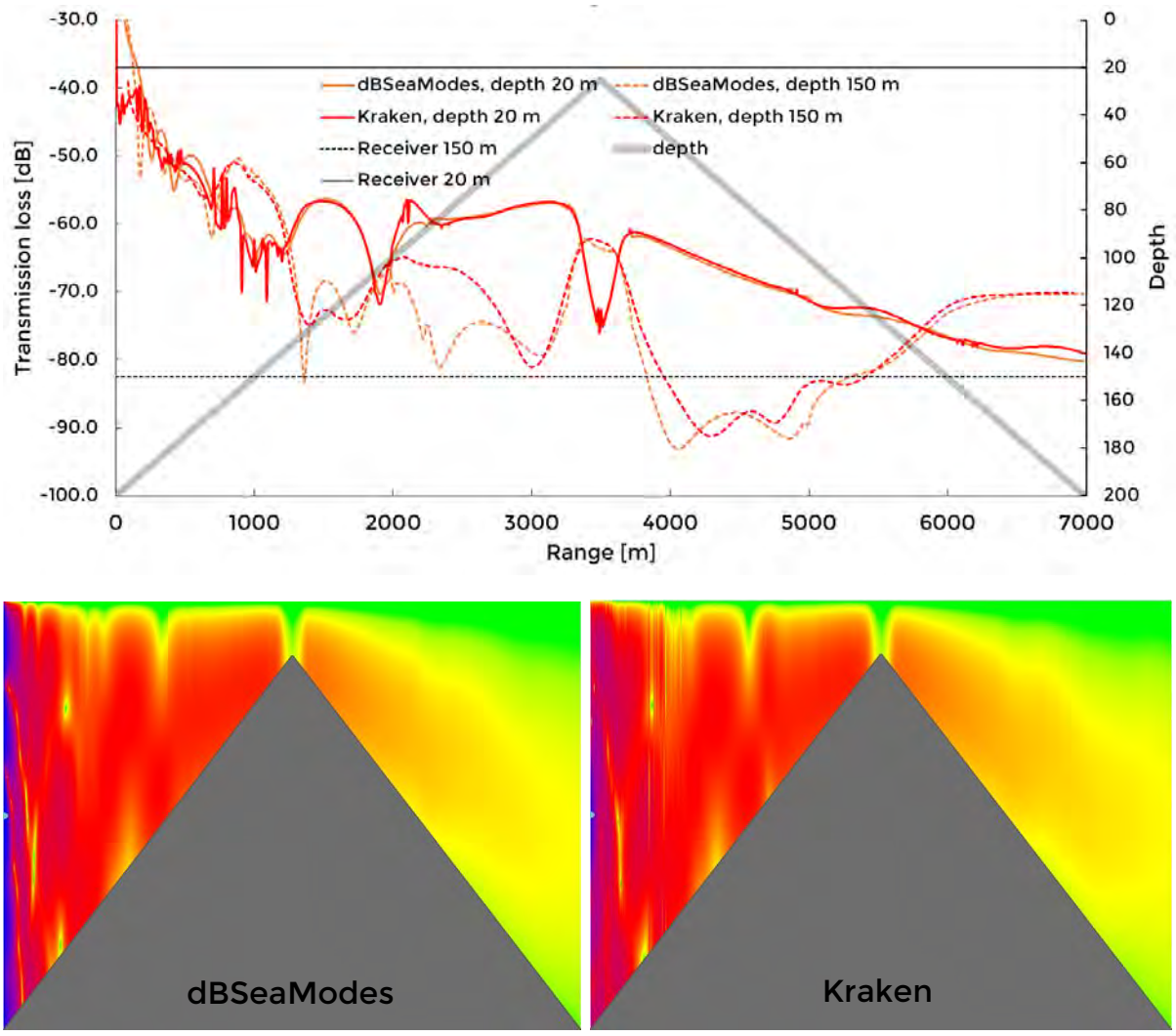
2.1.1 Parabolic Equation Method

Figure 6. Transmission losses for dBSeaPE and RAM. Depths 20 m and 150 m are shown in chart, while full transects in colour are presented below.



2.1.2 Normal Modes Method

Figure 7. Transmission losses for dBSeaModes and Kraken. Depths 20 m and 150 m are shown in chart, while full transects in colour are presented below.

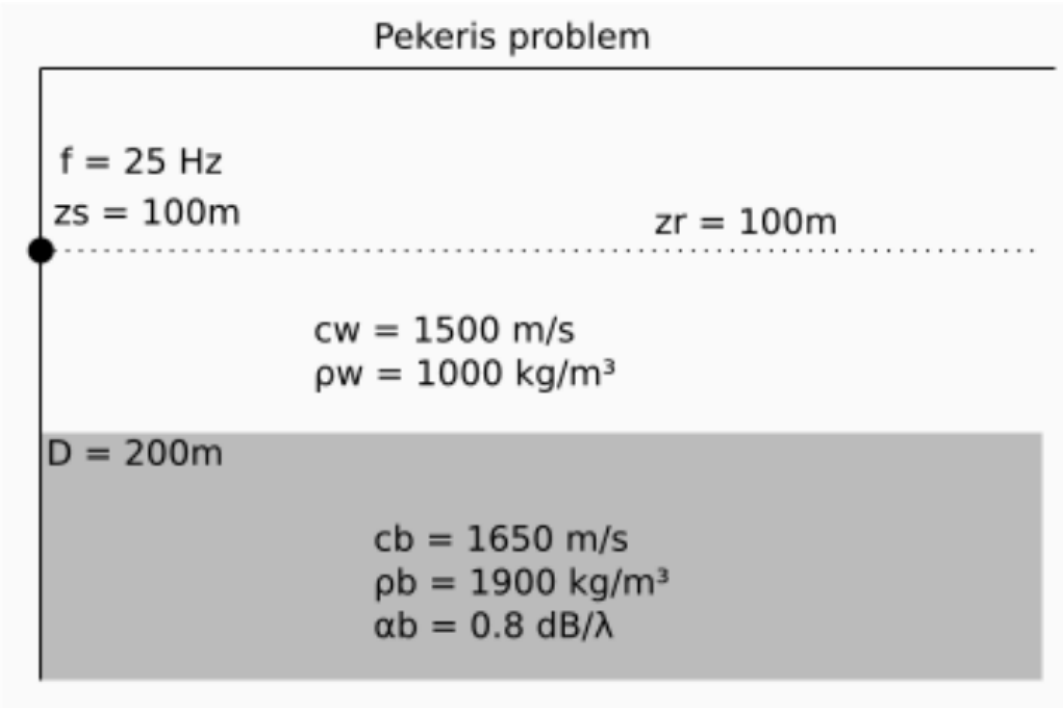


3 Flat-bottomed Waveguide

3.1 Pekeris Problem

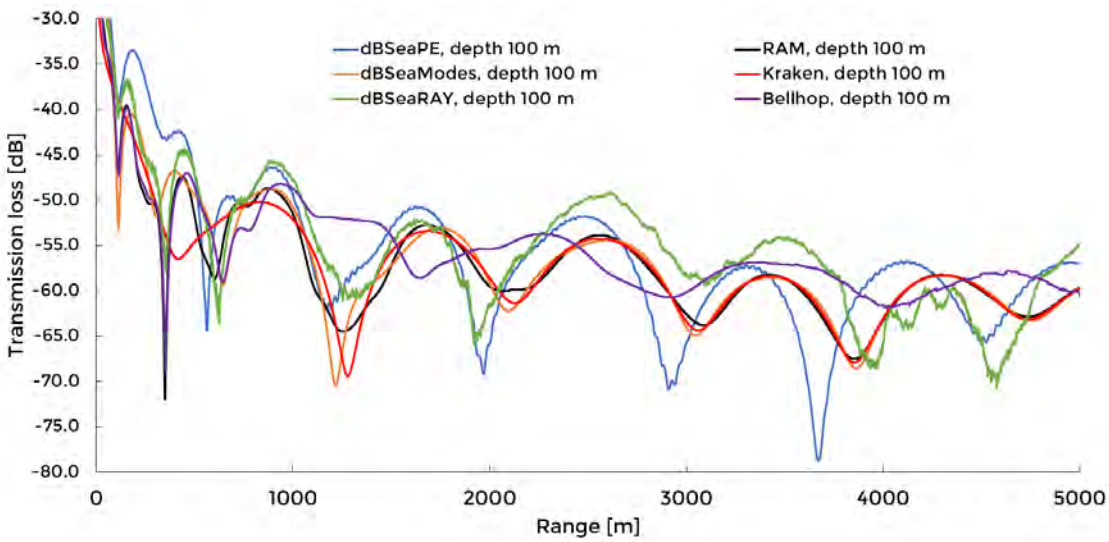
The Pekeris problem is a horizontally flat waveguide, designed to test propagation in an environment with a moderately absorbent sediment

Link:
https://drive.google.com/open?id=0B7cNj3oy6fp0WmJ1eW1jNjNzQTA



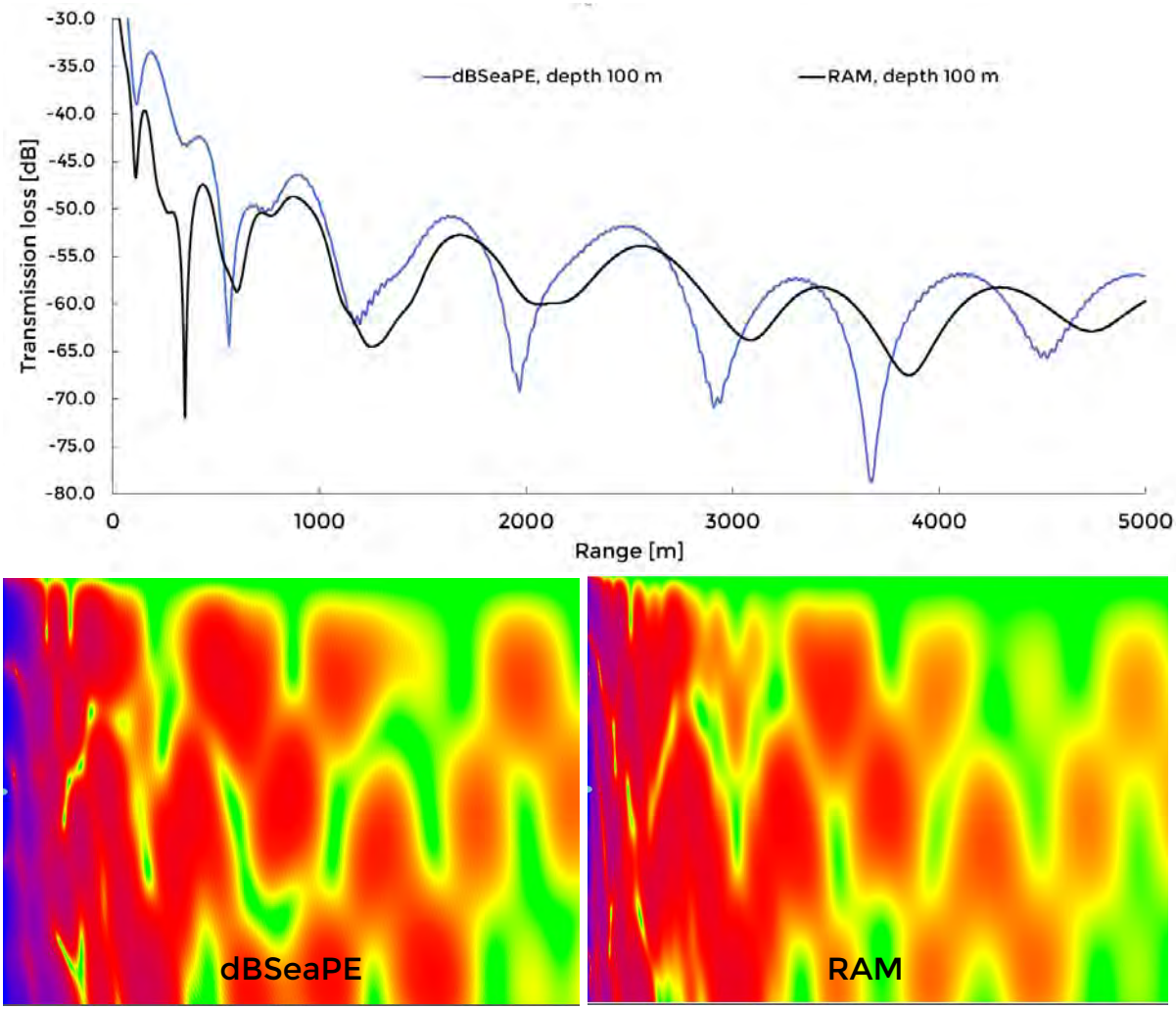
3.1.1 Summary of all Methods

Figure 8. Transmission losses for all three methods in the flat waveguide.



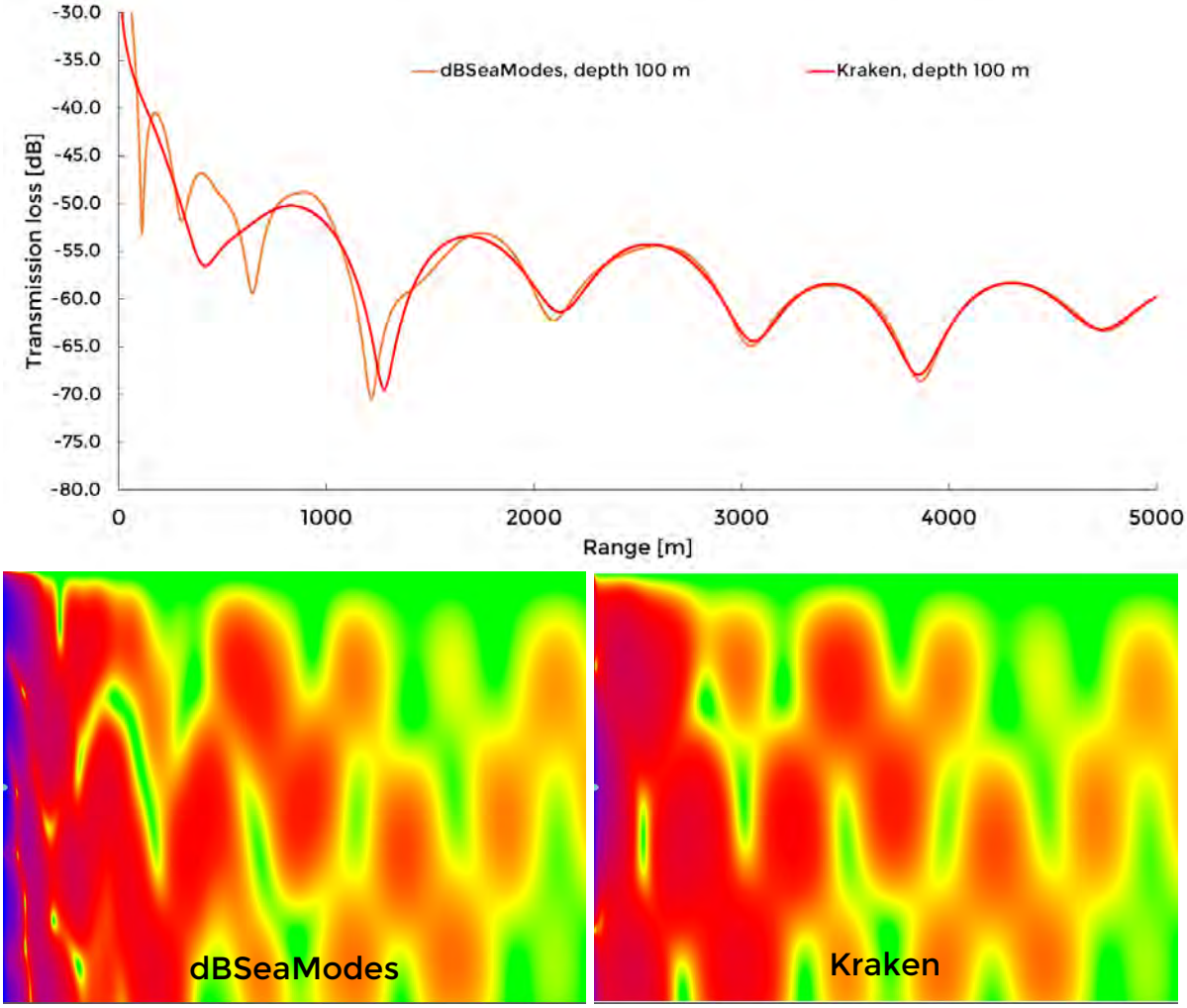
3.1.2 Parabolic Equation Method

Figure 9. Transmission losses for dBSeaPE and RAM. Depth 100 m is shown in chart, while full transects in colour are presented below.



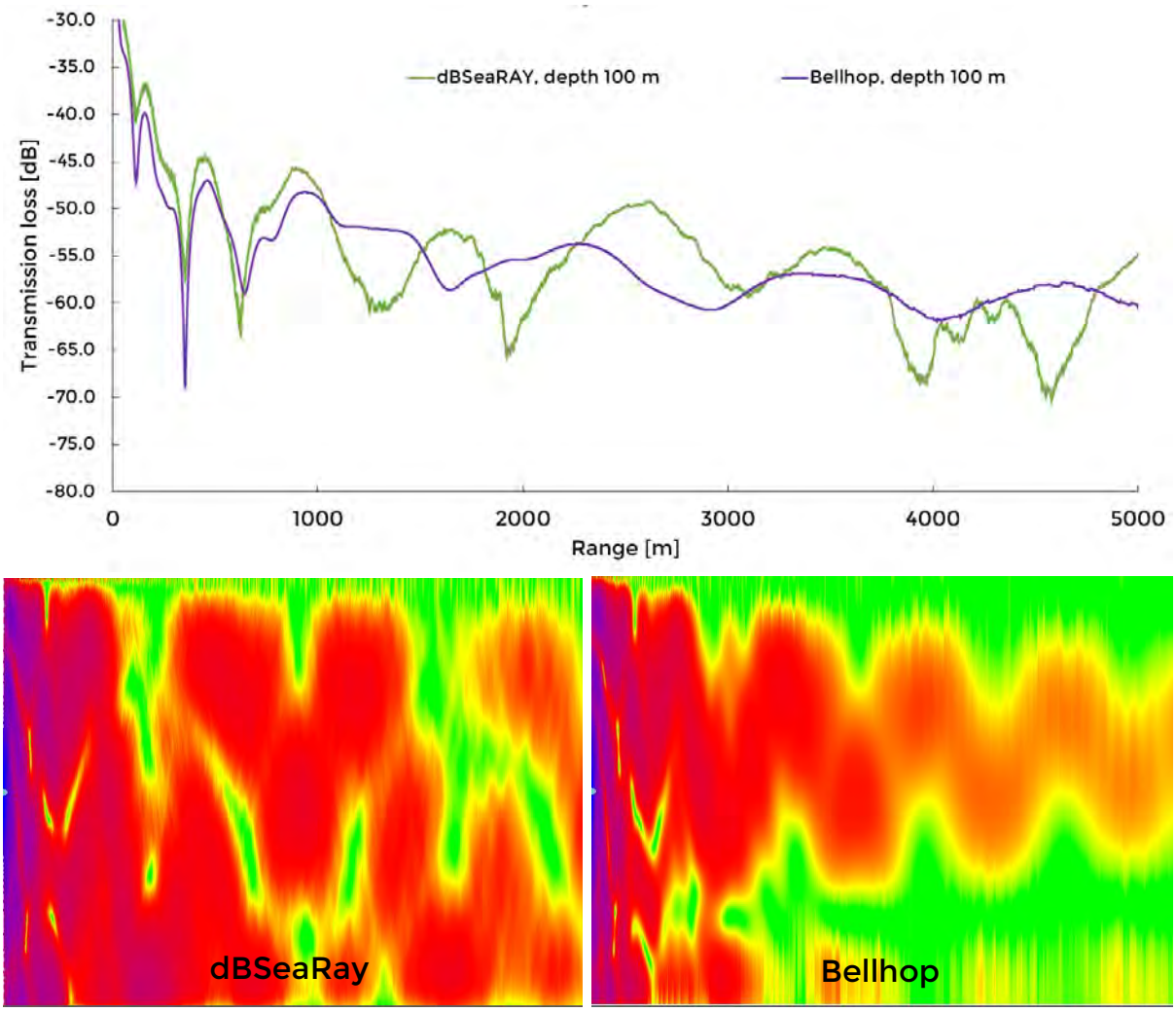
3.1.3 Normal Modes Method

Figure 10. Transmission losses for dBSeaModes and Kraken. Depth 100 m is shown in chart, while full transects in colour are presented below.



3.1.4 Ray Tracing Method

Figure 11. Transmission losses for dBSeaRay and Bellhop. Depth 100 m is shown in chart, while full transects in colour are presented below.



4 References

Chin-Bing, S. A., King, D. B., Davis, J. A. & Evans, R. B., 1993. *PE Workshop II,* Stennis: Naval Research Laboratory.

Jensen, F. B. & Ferla, C. M., 1989. Numerical solutions of range-dependent benchmark problems in ocean acoustics. 4(87).