Learmonth Pipeline Bundle Fabrication Facility

Assessment of Marine Fauna Underwater Sound Exposures

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Contents

Figures

Tables

Executive Summary

JASCO Applied Sciences (JASCO) performed a modelling study of underwater sound levels associated with the Subsea 7 Learmonth Pipeline Fabrication Facility, specifically vessel noise from proposed pipeline bundle launching and tow operations.

Subsea 7 proposes to construct and operate a new pipeline fabrication facility adjacent to the western shoreline of Exmouth Gulf, at Learmonth, approximately 35 km south of the Exmouth townsite. The proposed facility will allow the construction and launching of pipeline Bundles for the offshore oil and gas industry.

The tow route starts at the pipeline fabrication facility adjacent to the western shoreline of Exmouth Gulf, at Learmonth, approximately 35 km south of the Exmouth townsite. It then passes through Exmouth Gulf and between North West Cape and the Muiron Islands to beyond the 3 nm coastal waters limit. The modelling study considers the following three operational scenarios:

- Launch of the pipeline bundle,
- Towing of the bundle below the sea surface but above the seabed (off bottom tow) out to a parking area, and
- Towing of the bundle at the sea surface.

The modelling study specifically assessed distances from operations where underwater sound levels reached thresholds corresponding to various levels of potential impact to marine fauna. The animals considered here included marine mammals, turtles, and fish (including fish eggs and larvae). Due to the variety of species considered, there are several different thresholds for evaluating effects, including: mortality, injury, temporary reduction in hearing sensitivity, and behavioural disturbance.

The modelling methodology considered vessel specific source levels and range-dependent environmental properties. Estimated underwater acoustic levels are presented as sound pressure levels (SPL, L_p), and as accumulated sound exposure levels (SEL, L_E) as appropriate for non-impulsive (continuous) noise sources. The key results of this acoustic modelling study are summarised below.

Marine mammals

- The results for the Southall et al. (2019) criteria applied for marine mammal PTS and TTS for vessel operations are assessed here for two scenarios, each encompassing a day of operations (a 24 h period). The maximum distances to PTS for each scenario are summarised in Table 1. The maximum overall distance at which PTS in low-frequency (LF) cetaceans could be reached is 80 m during the surface tow scenario, PTS is not predicted to occur for other marine mammal hearing groups. TTS, a temporary reduction in hearing sensitivity, is predicted to occur a maximum distance of 1.63 km for LF cetaceans. TTS is not predicted to occur in dugongs.
- The maximum distances to the NMFS (2014) marine mammal behavioural response criterion of 120 dB re 1 µPa (SPL) are summarised in Table 2 for each scenario considered. The maximum distance for the bundle launch and off bottom tow is 13.4 km, and for the surface tow is 18.7 km. The distances to this isopleth are calculated in relation to the centroid of all sources within the scenario.

Table 1. *Marine mammal injury*: Maximum (R_{max}) horizontal distances (km) to modelled maximum-over-depth PTS and TTS thresholds from Southall et al. (2019).

Hearing group	Threshold for SEL_{24h} ($L_{E,24h}$; dB re 1 µPa²·s) #	Distance R_{max} (km)	
		Bundle launch and off bottom tow	Surface tow
PTS			
LF cetaceans†	199	0.03	0.08
HF cetaceans*	198	—	—
Sirenians (Dugong)	206	—	—
TTS			
LF cetaceans†	179	0.74	1.63
HF cetaceans*	178	—	—
Sirenians (Dugong)	186	—	—

† Mysticetes, e.g. humpback whales
* Odontocetes, e.g. Snub-fin dolphin, Australian humpback dolphin, Indo-pacific bottlenose dolphin

Table 2. *Marine mammal behaviour*: Summary of maximum behavioural disturbance distances for each scenario

SPL (L_p; dB re 1 µPa)	Distance R_{max} (km)				
	Scenario 1 (Bundle launch)	Scenario 2 (Off bottom tow, start)	Scenario 3 (Off bottom tow, end)	Scenario 4 (Surface tow, start)	Scenario 5 (Surface tow, end)
120†	5.40	11.5	13.4	18.7	17.7

† Threshold for marine mammal behavioural response to continuous noise (NMFS 2014).

Turtles

Considering the Finneran et al. (2017) criteria for turtle PTS and TTS for vessels, assessed here for each scenario, PTS is not predicted to occur. TTS could occur; however, the distances are 30 m for the bundle launch and off bottom tow, and 90 m for the surface tow, scenarios. These distances are associated with the lead tugs and are calculated from the bundle tow route.

Fish

Sound produced by the vessel operations reach the sound levels associated with physiological effects, recoverable injury, and TTS for some fish species in close proximity to the sound sources, but in order for the thresholds to be exceeded, the fish must remain at those distances for either 12 or 48h.

While the SPL distances are not time dependent, the threshold for predicted effects are. As the vessels are almost always moving, the predicted effect thresholds will not be exceeded, because the exposure will only occur over a short period of time, not 12 or 48 h.

1. Introduction

JASCO Applied Sciences (JASCO) performed a modelling study of expected underwater sound levels associated with the Learmonth Pipeline Fabrication Facility, specifically vessel noise from proposed pipeline bundle tow operations. The tow route passes from Learmonth, through Exmouth Gulf and between North West Cape and the Muiron Islands to beyond the 3 nm coastal waters limit (Figure 1). The modelling study considers the following three operational scenarios:

- Launch of the bundle,
- Towing of the bundle below the sea surface but above the seabed (off bottom tow) out to a parking area, and
- Towing of the bundle at the sea surface.

The modelling study specifically assessed distances from operations where underwater sound levels reached thresholds corresponding to various levels of potential impact to marine fauna. The animals considered here included marine mammals, turtles, and fish (including fish eggs and larvae). Due to the variety of species considered, there are several different thresholds for evaluating effects, including: mortality, injury, temporary reduction in hearing sensitivity, and behavioural disturbance.

The modelling methodology considered vessel specific source levels and range-dependent environmental properties. Estimated underwater acoustic levels are presented as sound pressure levels (SPL, L_p), and accumulated sound exposure levels (SEL, L_E), as appropriate for non-impulsive (continuous) noise sources.

Section 3 explains the metrics used to represent underwater acoustic fields and the impact criteria considered. Section 4 details the methodology for predicting the source levels and modelling the sound propagation, including the specifications of the vessel sources and all environmental parameters the propagation models require. Section 5 presents the results, which are then discussed and summarised in Section 6.

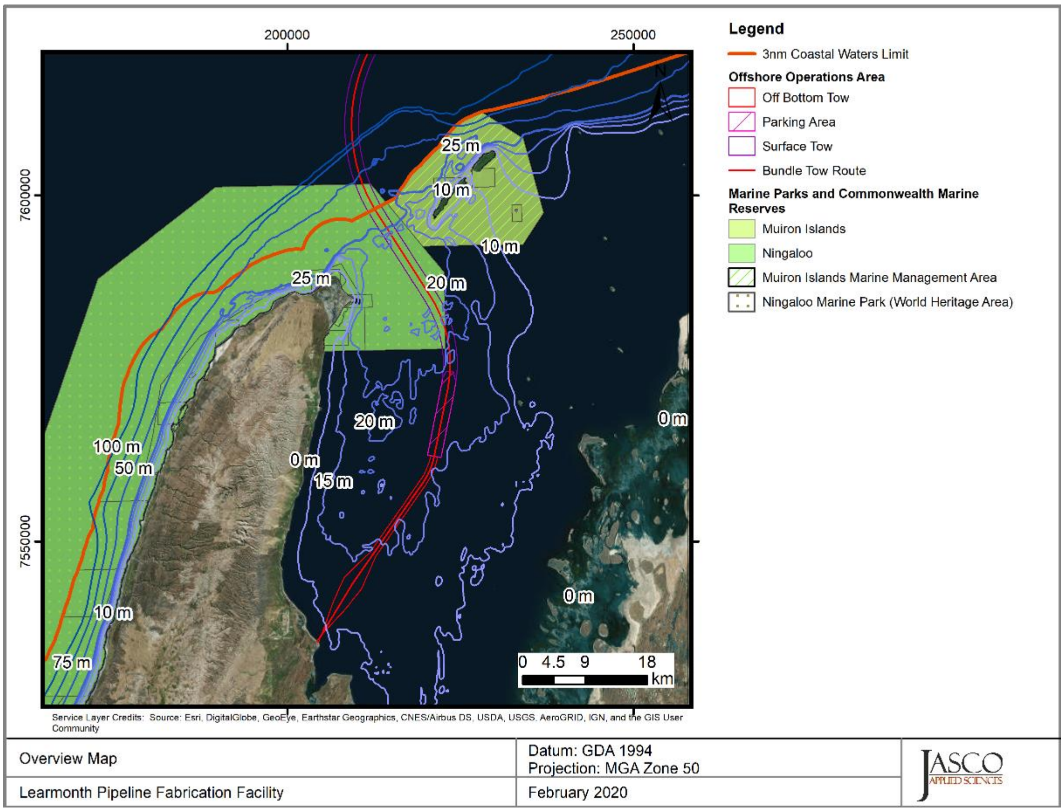

Figure 1. Overview of the modelled area and local features.

2. Acoustic Modelling Scenario Details

JASCO's Marine Operations Noise Model (MONM) was used to perform the acoustic modelling to understand the propagation of noise emissions from the project. This model calculated noise levels in frequency bands and produced broadband noise maps over a wide area. Distances to several noise thresholds were calculated, including thresholds used to predict marine mammal injury and disturbance (see Section 3).

The bundles will be towed along the tow route in two stages: bundle launch and off bottom tow, and then following checks within the 'parking area', the surface tow will occur. These events will not happen on the same day. Therefore, this study considered two 24 h accumulated (SEL_{24h}) scenarios resulting from vessels transiting along the bundle tow route. The acoustic modelling scope was not designed to consider operations once the vessels and bundle had passed beyond the 3 nm coastal waters limit. Predicted SPL footprints were considered for five specific locations, or scenarios, along the tow route to inform the distance to marine mammal disturbance thresholds. As adverse weather conditions are planned to be avoided in the launch plan schedule for bundle tow operations, the modelling conducted here-in reflects operational scenarios conducted in calm weather conditions representative of those likely to occur during project activities.

The first 24-hour scenario contains both the bundle launch, off bottom tow operational scenarios, while the second 24-hour scenario considers only the Surface Tow scenario. Each scenario included up to four different vessels under different operational capacities, the different vessel types consisted of two lead tugs, a command vessel, and a following (trailing) tug. Section 4.1 provides detail on the vessel specifications.

The approaches used to calculate the SPL and SEL_{24h} fields are described in Sections 4.4 and 4.5, respectively. The methods are based on combining the source levels (SL) from multiple vessels for each scenario with modelled propagation loss calculated at several sites within the Exmouth Gulf area.

The geographic coordinates for the modelled propagation loss sites are provided in Table 3 and an overview of the modelled area with the sites is shown in Figure 2. The vessel tracks for each respective SEL_{24h} scenario are shown in Figures 3 and 4, and the locations of each vessel for SPL modelling are also shown in these figures. Table 4 provides a listing of each SPL scenario, the vessels, their coordinates, and the associated modelled propagation loss site.

Table 3. Location details for the modelled transmission loss sites and the water depth during Highest Astronomical Tide (HAT)

24 h Scenario	Site	Latitude (S)	Longitude (E)	MGA* Zone 50		HAT Water depth (m)
				X (m)	*Y* (m)	
Bundle Launch and Off Bottom Tow	1	22° 14' 30.5593"	114° 08' 38.4610"	205618	7537628	10.2
	2	22° 10' 51.2251"	114° 11' 07.9291"	209775	7544458	14.9
	3	22° 06' 28.0793"	114° 14' 32.8711"	215501	7552663	17.6
	4	22° 01' 58.3517"	114° 17' 45.7526"	220885	7561062	17.3
	5	21° 56' 41.4221"	114° 19' 02.9627"	222929	7570853	19.9
Surface Tow	5	21° 56' 41.4221"	114° 19' 02.9627"	222929	7570853	19.9
	6	21° 51' 20.0905"	114° 19' 04.3180"	222795	7580741	21.9
	7	21° 46' 32.8293"	114° 16' 24.3314"	218043	7589500	23.9
	8	21° 41' 55.4518"	114° 13' 22.8194"	212672	7597942	38.6

* Map Grid of Australia (MGA)

Table 4. Location details for the modelled sites.

SPL Scenario	Operational Scenario	Vessel	Latitude (S)	Longitude (E)	MGA* Zone 50 X (m)	MGA* Zone 50 Y (m)	Site
1	Bundle Launch and Off Bottom Tow	Command Vessel	22° 14' 07.6335"	114° 08' 33.1236"	205452	7538330	1
		Lead Tug 1	22° 14' 28.6576"	114° 08' 39.5097"	205647	7537687	
		Lead Tug 2	22° 14' 14.9103"	114° 08' 48.8217"	205906	7538115	
2	Off Bottom Tow	Command Vessel	22° 11' 01.1626"	114° 10' 39.3529"	208961	7544137	2
		Trailing Tug	22° 12' 43.5438"	114° 09' 50.6619"	207625	7540960	
		Lead Tug 1	22° 09' 48.8287"	114° 11' 56.5868"	211134	7546404	
		Lead Tug 2	22° 09' 35.6843"	114° 12' 06.8319"	211420	7546813	
3		Command Vessel	22° 01' 58.0146"	114° 17' 27.2673"	220354	7561063	4
		Trailing Tug	22° 03' 41.9747"	114° 16' 42.2572"	219120	7557841	
		Lead Tug 1	22° 00' 28.4672"	114° 18' 09.8904"	221528	7563840	
		Lead Tug 2	22° 00' 12.5947"	114° 18' 13.6026"	221626	7564331	
4	Surface Tow	Command Vessel	21° 51' 40.8120"	114° 18' 49.1098"	222369	7580096	6
		Trailing Tug	21° 54' 26.6604"	114° 19' 25.7632"	223511	7575011	5
		Lead Tug 1	21° 50' 50.0610"	114° 18' 51.8315"	222420	7581659	6
		Lead Tug 2	21° 50' 48.6180"	114° 18' 56.1978"	222545	7581706	
5		Command Vessel	21° 42' 43.6220"	114° 13' 29.9831"	212905	7596464	8
		Trailing Tug	21° 44' 58.0573"	114° 15' 21.9006"	216197	7592384	7
		Lead Tug 1	21° 41' 51.5660"	114° 13' 18.1645"	212536	7598059	8
		Lead Tug 2	21° 41' 50.1927"	114° 13' 21.9064"	212643	7598104	

* Map Grid of Australia (MGA)

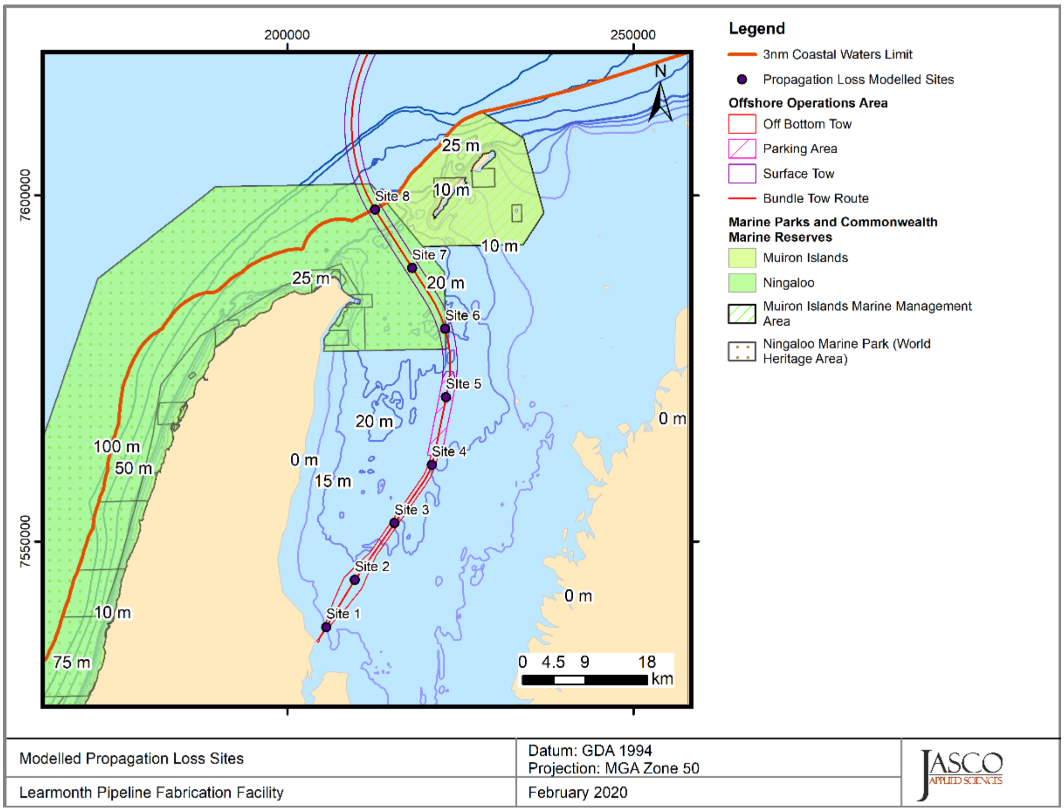

Figure 2. Overview of the modelled propagation loss sites.

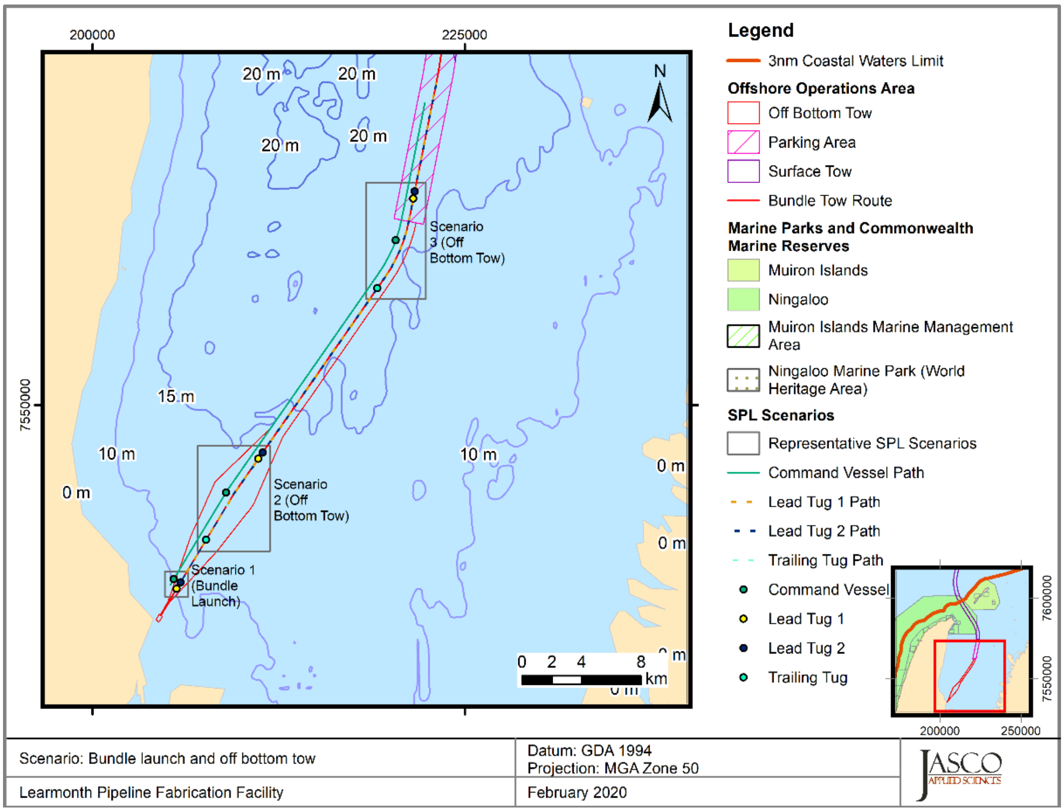

Figure 3. Vessel paths for bundle launch and off bottom tow, including vessel locations for modelled SPL scenarios.

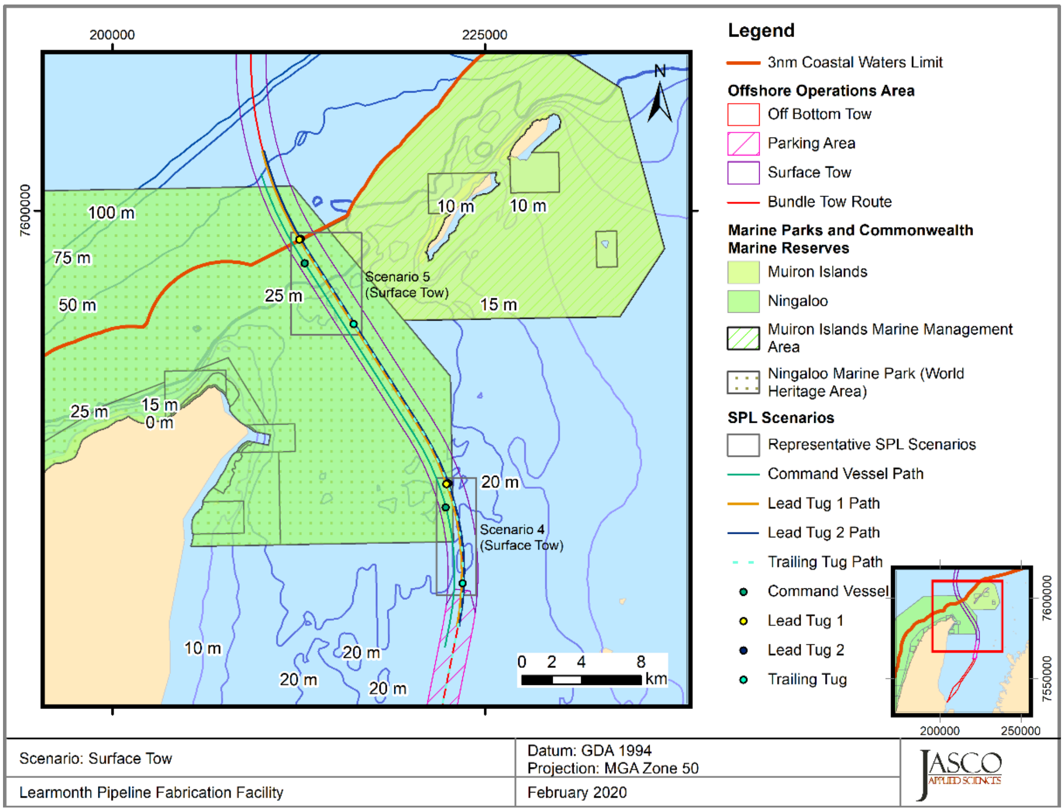

Figure 4. Vessel paths for surface tow, including vessel locations for modelled SPL scenarios.

3. Noise Effect Criteria

To assess the potential impacts of a sound-producing activity, it is necessary to first establish exposure criteria (thresholds) for which sound levels may be expected to have a negative impact on animals. Whether acoustic exposure levels might injure or disturb marine fauna is an active research topic. Since 2007, several expert groups have developed SEL-based assessment approaches for evaluating auditory injury, with key works including Southall et al. (2007), Finneran and Jenkins (2012), Popper et al. (2014), United States National Marine Fisheries Service (NMFS 2018), and Southall et al. (2019). The number of studies that investigate the level of behavioural disturbance to marine fauna by anthropogenic sound has also increased substantially.

Several sound level metrics, such as PK, SPL, and SEL, are commonly used to evaluate noise and its effects on marine life (Appendix A). In this report, the duration of the SEL accumulation is defined as integrated over a 24 h time period.

Appropriate subscripts indicate any frequency weighting applied (Appendix A.3). The acoustic metrics in this report reflect the updated ANSI and ISO standards for acoustic terminology, ANSI S1.1 (R2013) and ISO 18405:2017 (2017).

This study applies the following noise criteria (Sections 3.1–3.2 and Appendix A.2), chosen for their acceptance by regulatory agencies and because they represent current best available science:

1. Frequency-weighted accumulated sound exposure levels (SEL; $L_{E,24h}$) from Southall et al. (2019) for the onset of permanent threshold shift (PTS) and temporary threshold shift (TTS) in marine mammals.
2. Marine mammal behavioural threshold based on the current interim U.S. National Marine Fisheries Service (NMFS) criterion NMFS (2014) for marine mammals of 120 dB re 1 µPa SPL (L_p) for non-impulsive sound sources.
3. Sound exposure guidelines for fish, fish eggs, and larvae (Popper et al. 2014).
4. Frequency-weighted accumulated sound exposure levels (SEL; $L_{E,24h}$) from Finneran et al. (2017) for the onset of permanent threshold shift (PTS) and temporary threshold shift (TTS) in turtles.

3.1. Marine Mammals

The criteria applied in this study to assess possible effects from vessel noise on marine mammals are summarised in Table 5 and detailed in Sections 3.1.1 and 3.1.2. Marine mammal species are separated into three functional hearing groups based on the frequency range of their hearing: low-frequency (LF), high-frequency (HF) cetaceans, and sirenians (dugong). Frequency weighting is further explained in Appendix A.3.

Table 5. Acoustic effects of continuous noise on marine mammals: Unweighted SPL and SEL_{24h} thresholds.

Hearing group	NMFS (2014)	Southall et al. (2019)	
	Behaviour	PTS onset thresholds (received level)	TTS onset thresholds (received level)
	SPL (L_p; dB re 1 µPa)	Weighted SEL_{24h} ($L_{E,24h}$; dB re 1 µPa^2·s)	Weighted SEL_{24h} ($L_{E,24h}$; dB re 1 µPa^2·s)
LF cetaceans (mysticetes, e.g. humpback whales)	120	199	179
HF cetaceans (odontocetes, e.g. Snub-fin dolphin, Australian humpback dolphin, Indo-pacific bottlenose dolphin)		198	178
Sirenians (Dugong)		206	186

L_p denotes sound pressure level period and has a reference value of 1 µPa.
$L_{E,24h}$ denotes cumulative sound exposure over a 24 h period and has a reference value of 1 µPa^{2}s.

3.1.1. Behavioural response

Numerous studies on marine mammal behavioural responses to sound exposure have not resulted in consensus in the scientific community regarding the appropriate metric for assessing behavioural reactions. However, it is recognised that the context in which the sound is received affects the nature and extent of responses to a stimulus (Southall et al. 2007, Ellison and Frankel 2012, Southall et al. 2016). Because of the complexity and variability of marine mammal behavioural responses to acoustic exposure, NMFS has not yet released technical guidance on behaviour thresholds for use in calculating animal exposures (NMFS 2018). The NMFS currently uses a step function to assess behavioural impact. A 50% probability of inducing behavioural responses at a SPL of 160 dB re 1 µPa was derived from the HESS (1999) report which, in turn, was based on the responses of migrating mysticete whales to airgun sounds (Malme et al. 1983, Malme et al. 1984). The HESS team recognised that behavioural responses to sound may occur at lower levels, but significant responses were only likely to occur above a SPL of 140 dB re 1 µPa. An extensive review of behavioural responses to sound was undertaken by Southall et al. (2007, their Appendix B). Southall et al. (2007) found varying responses for most marine mammals between a SPL of 140 and 180 dB re 1 µPa, consistent with the HESS (1999) report, but lack of convergence in the data prevented them from suggesting explicit step functions.

The NMFS non-pulsed noise criterion was selected for this assessment because it represents the most commonly applied behavioural response criterion by regulators. The distances at which behavioural responses could occur were therefore determined to occur in areas ensonified above an unweighted SPL of 120 dB re 1 µPa (NMFS 2014).

3.1.2. Injury and hearing sensitivity changes

There are two categories of auditory threshold shifts or hearing loss: permanent threshold shift (PTS), a physical injury to an animal’s hearing organs; and Temporary Threshold Shift (TTS), a temporary reduction in an animal’s hearing sensitivity as the result of receptor hair cells in the cochlea becoming fatigued.

To assist in assessing the potential for effects to marine mammals, this report applies the criteria recommended by Southall et al. (2019), considering both PTS and TTS (Table 5). Appendix A.2 provides more information about the Southall et al. (2019) criteria, and the preceding literature upon which they are based.

3.2. Fish, Turtles, Fish Eggs, and Fish Larvae

In 2006, the Working Group on the Effects of Sound on Fish and Turtles was formed to continue developing noise exposure criteria for fish and turtles, work begun by a NOAA panel two years earlier. The Working Group developed guidelines with specific thresholds for different levels of effects for several species groups (Popper et al. 2014). The guidelines define quantitative thresholds for three types of immediate effects:

- Mortality, including injury leading to death,
- Recoverable injury, including injuries unlikely to result in mortality, such as hair cell damage and minor haematoma, and
- TTS.

Masking and behavioural effects can be assessed qualitatively, by assessing relative risk rather than by specific sound level thresholds. However, as these depend upon activity-based subjective ranges, these effects are not addressed in this report and are included in Table 6 for completeness only. Because the presence or absence of a swim bladder has a role in hearing, fish’s susceptibility to injury from noise exposure depends on the species and the presence and possible role of a swim bladder in hearing. Thus, different thresholds were proposed for fish without a swim bladder (also appropriate for sharks and applied to whale sharks in the absence of other information), fish with a swim bladder not used for hearing, and fish that use their swim bladders for hearing. Turtles, fish eggs, and fish larvae are considered separately.

Table 6 lists the relevant effects thresholds from Popper et al. (2014) for shipping and continuous noise. Some evidence suggests that fish sensitive to acoustic pressure show a recoverable loss in hearing sensitivity, or injury when exposed to high levels of noise (Scholik and Yan 2002, Amoser and Ladich 2003, Smith et al. 2006); this is reflected in the SPL thresholds for fish with a swim bladder involved in hearing.

Finneran et al. (2017) presented revised thresholds for turtle injury, considering frequency weighted SEL, which have been applied in this study for vessels (Table 7).

Table 6. Criteria for vessel noise exposure for fish, adapted from Popper et al. (2014).

Type of animal	**Mortality and Potential mortal injury**	**Impairment**			**Behaviour**
		Recoverable injury	TTS	Masking	
Fish: No swim bladder (particle motion detection)	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) High (I) High (F) Moderate	(N) Moderate (I) Moderate (F) Low
Fish: Swim bladder not involved in hearing (particle motion detection)	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) High (I) High (F) Moderate	(N) Moderate (I) Moderate (F) Low
Fish: Swim bladder involved in hearing (primarily pressure detection)	(N) Low (I) Low (F) Low	170 dB SPL for 48 h	158 dB SPL for 12 h	(N) High (I) High (F) High	(N) High (I) Moderate (F) Low
Turtles	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) High (I) High (F) Moderate	(N) High (I) Moderate (F) Low
Fish eggs and fish larvae	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) High (I) Moderate (F) Low	(N) Moderate (I) Moderate (F) Low

Sound pressure level dB re 1 µPa.
Relative risk (high, moderate, low) is given for animals at three distances from the source defined in relative terms as near (N), intermediate (I), and far (F).

Table 7. Acoustic effects of continuous noise on turtles, weighted SEL_{24h}, Finneran et al. (2017).

PTS onset thresholds (received level)	**TTS onset thresholds (received level)**
Weighted SEL_{24h} ($L_{E,24h}$; dB re 1 µPa2·s)	Weighted SEL_{24h} ($L_{E,24h}$; dB re 1 µPa2·s)
220	200

$L_{E,24h}$ denotes cumulative sound exposure over a 24 h period and has a reference value of 1 µPa^{2}s.

4. Methods

4.1. Acoustic Source Parameters

A summary of the modelled vessel types is presented in Table 8, each modelled vessel operates at different percentages of their maximum continuous rating (MCR) during each of the three modelled scenarios. Conservative estimates of the acoustic source levels for each vessel were based on the parameters of the propulsion system, and the percentage MCR at which the vessel is expected to be operating at during each scenario. In cases where the modelled source levels were derived from the source levels of other vessels, the modelled source levels were adjusted using Equation 1.

$$\mathrm{SL} = \mathrm{SL}_{\mathrm{ref}} + 10\log_{10}\left(\frac{P}{P_{\mathrm{ref}}}\right) \tag{1}$$

Here the modelled source level (SL) is estimated from the source level of the proxy source (SL_{ref}) and the propulsion powers of the modelled and proxy sources (P and P_{ref}, respectively).

Table 8. Vessel specifications for the three types of modelled vessels.

Specification		Lead Tug	Command Vessel	Trailing Tug
Bollard pull (t)		285-310	N/A	90
Length overall (m)		91.0	87.8	37.0
Beam (m)		22.0	22.0	14.0
Depth (m)		7.95	5.5	7.55
Percentage MCR	Bundle launch (0.5 kn)	20%	15%	N/A
	Off bottom tow (2.5 kn)	30%	20%	30%
	Surface tow (5.5 kn)	70%	30%	20%

Source levels used in the pull off, off-bottom tow, and surface tow are presented in Figures 5 to 7 respectively. Details of the derivation of source levels for each vessel are presented in Sections 4.1.1 to 4.1.3.

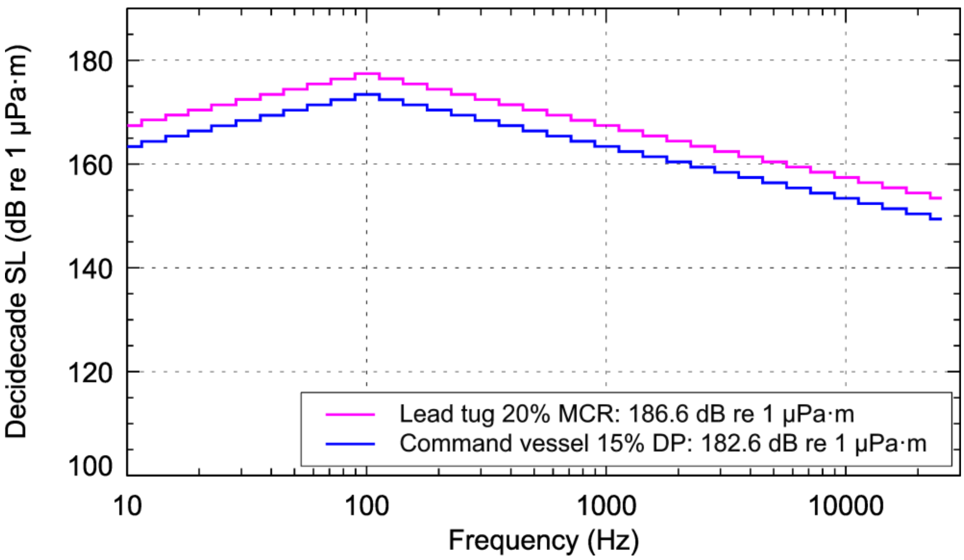

Figure 5. Acoustic source spectra for vessels undertaking bundle launch.

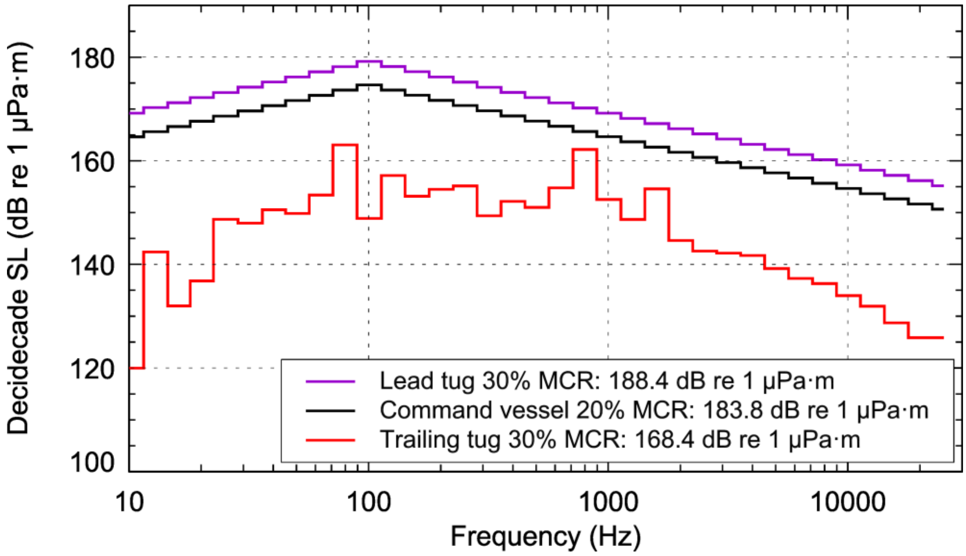

Figure 6. Acoustic source spectra for vessels undertaking off bottom tow.

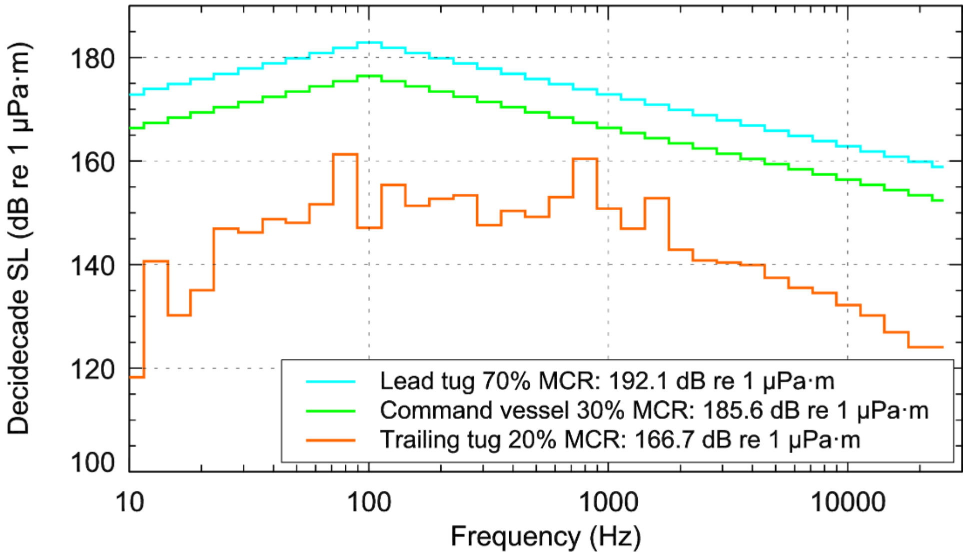

Figure 7. Acoustic source spectra for vessels undertaking surface tow.

4.1.1. Lead tugs

The estimates of the source levels for the lead tugs were based on the Siem Offshore VS491 CD design Anchor Handling Tug Supply (AHTS) vessels (Figure 8). The main propulsion system of the lead tugs comprises two Wärtsilä LIPS Controllable Pitch Propellers (CPP). Each LIPS CPP has the following parameters:

- 4.2 m propeller diameter
- 144 rpm nominal propeller speed, and
- 9215 kW maximum continuous power input.

In addition to the main propellers, the lead tug is also equipped with a single bow azimuth thruster rated at 830 kW with the following parameters:

- Assumed 1.65 m propeller diameter
- 364 rpm nominal propeller speed, and
- 830 kW maximum continuous power input.

Furthermore, the lead tugs also feature two bow tunnel thrusters rated at 1000 kW each and two stern tunnel thrusters rated at 880 kW each, these tunnel thrusters are unlikely to be used in normal operations, however they could potentially be engaged if the tugs have to hold station.

Source spectra for the main propellers and bow azimuth thruster were determined by the method described in Appendix B. Source spectra for the bow and stern thrusters were based on those of the Damen platform supply vessel 3300CD, which was used in previous studies (Zykov 2016). For the Damen 3300CD, the tunnel thrusters are 735 kW maximum continuous power input, hence the spectra were offset according to Equation 1. The full power source spectrum was determined by summing the spectra for the individual thrusters and main propellers, and the spectrum for each modelling scenario was determined by offsetting the full power spectrum by $10\log_{10}$(MCR), where the MCR is represented as a fraction of full power for each scenario. All thrusters have been included in the source level calculation as part of a conservative modelling approach.

Figure 8. Photo of a Siem Anchor Handling Tug Supply (AHTS) vessel (Siem Offshore 2010).

4.1.2. Command vessel

Estimates of the source levels for the command vessel were based on the *MMA Pinnacle*, Figure 9. The *MMA Pinnacle* is propelled by two 2050 kW rated azimuth thrusters and is also equipped with three bow tunnel thrusters with 1000 kW maximum continuous input power each. Acoustic source spectra for both types of thrusters were based on those of the Damen 3300CD, which in addition to the 735 kW maximum continuous power tunnel thrusters is powered by two main azimuth thrusters, each with an input of 2000 kW maximum continuous power. The Damen 3300CD (Zykov 2016) formed the basis for the estimation of the sound levels of the *MMA Inscription* (McPherson et al. 2019), which has a similar output power and design to the *MMA Pinnacle*.

The acoustic spectrum of the main azimuthal thrusters was not offset since the main propulsion of the *MMA Pinnacle* has an approximately equal power rating, while each of the bow tunnel thrusters was scaled according to Equation 1. The full power source spectrum was determined by summing the spectra for the individual thrusters, and the spectrum for each modelling scenario was determined by offsetting the full power spectrum by $10\log_{10}$(MCR). All thrusters have been included in the source level calculation as part of a conservative modelling approach.

Figure 9. Photo of the *MMA Pinnacle* (MMA Offshore 2020).

4.1.3. Trailing tug

Estimates of the source levels for the trailing tug were based on the *BB Worker*, Figure 10. The *BB Worker* is fitted with two 2250 kW main azimuth thrusters and a single 350 kW bow thruster. The acoustic source spectrum for a similar tug, the *Svitzer Njal* (length 30.8 m, breadth 11.1 m, laden draft 5.2 m), transiting at 5 kn was used to represent the source spectrum for the trailing tug. This spectrum was considered suitable to represent the spectrum for the surface tow scenario, where the trailing tug is travelling at approximately this speed (5.5 kn, 20% MCR). The spectrum for the off bottom tow scenario was then determined by offsetting this spectrum by $10\log_{10}(0.3/0.2)$, where 0.3 and 0.2 are the fractional MCR values for off bottom tow and surface tow respectively. The single bow thruster represents only a fraction of the vessel power, however all thrusters have been included in the source level calculation as part of a conservative modelling approach.

Figure 10. Photo of the *BB Worker* (Buskér og Berging 2018).

4.2. Environmental Parameter Overview

A single sound speed profile for July was used in the propagation modelling, which represented the most conservative choice (i.e., the profile leading to the longest acoustic propagation) within the potential months of operation (December-July). The seabed in the region consists predominantly of calcareous sediments both on the continental shelf and the continental slope; suitable geoacoustic parameters were chosen to reflect this. Bathymetry data for the modelled region were obtained from a publicly available dataset and adjusted to account for the highest astronomical tide (HAT).

The environmental parameters used in the modelling are described in detail in Appendix D.2.

4.3. Sound Propagation Models

JASCO's Marine Operations Noise Model (MONM-BELLHOP; Appendix C.2) was used to predict the acoustic field at frequencies of 10 Hz to 25 kHz for all vessels.

To assess sound levels with MONM-BELLHOP, the sound field modelling calculated propagation losses within model bounds of approximately 115 km × 160 km around Exmouth Gulf. The sound fields were modelled with a horizontal angular resolution of $\Delta\theta$ = 2.5° for a total of N = 144 radial planes with a horizontal separation of 20 m between receiver points along the modelled radials. A single source depth of 7 m was used for predictions based on the average draft of the three vessel types considered. Receiver depths were chosen to span the entire water column over the modelled areas, from 2 m to a maximum of 1000 m, with step sizes that increased with depth. To supplement the MONM results, high-frequency results for propagation loss were modelled using BELLHOP for frequencies from 2.5 to 25 kHz. The MONM and Bellhop results were combined to produce results for the full frequency range of interest.

4.4. Aggregate SPL Scenarios

The SPL footprints for the five scenarios in Table 4 were calculated by considering the modelled propagation loss sites (Table 3, Figure 2) and the instantaneous offset positions of each vessel during the bundle tow in Table 4. The SPL for each scenario was calculated at each modelled site with the associated source level for each vessel. The aggregate SPL for each scenario was calculated by translating to the appropriate vessel location and summing the individual SPL footprints.

The estimation of the aggregate SPL sound field with this approach acceptably captures the difference source characteristics and the large-scale features that effect the propagation loss and thus provides a meaningful estimate of the SPL.

4.5. Accumulated SEL

During vessel transit, new sound energy is constantly being introduced to the environment, and many of the criteria used in this report (Section 3) account for the total acoustic energy marine fauna is subjected to over a specified duration; defined in this report as 24 hours. The noise footprint for the transiting vessels considered in this report were analysed by modelling the SEL for each vessel type at the individual transmission loss modelling sites (Table 3, Figure 2), and by transposing and summing this footprint along the vessel paths to emulate the vessel moving.

Footprints were spaced at uniform steps of 50 m along each vessel path and were chosen based on which of the modelled propagation loss sites was closest to that point along the path. The SEL sound field at any given point along the path is dependent upon the duration of exposure, which with a fixed footprint spacing depends upon the speed of the vessel during each segment of the tow. The SPL modelling results at each transmission loss site for each vessel were therefore converted to SEL according to Equation 2 where v represents the vessel speed in m/s.

$$\mathrm{SEL} = \mathrm{SPL} + 10\log_{10}\left(\frac{50}{v}\right) \tag{2}$$

The present method acceptably reflects large-scale sound propagation features, primarily dependent on water depth, which dominate the cumulative field and is thus considered to provide a meaningful estimate of the SEL field.

5. Results

5.1. Tabulated results

Sound field results for the modelled scenarios are presented for SPL (Tables 9 and 10) and SEL_{24h} (Table 11). Two distances (R_{max} and $R_{95\%}$) have been provided in the tabulated results below. The distances to specific isopleths were computed from predicted maximum-over-depth sound field contours. The R_{max} distance is provided to assist in assessment of the greatest range to effect criteria, while the $R_{95\%}$ has been provided for context on the spatial distribution of the sound field footprints, which are often irregular in shape due to non-uniformity of the acoustic environment. See Appendix D.1 for further detail on isopleth distances.

Table 9. *SPL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) to modelled maximum-over-depth SPL isopleths. Distances are calculated from the centroid of the vessel(s) contributing to the largest isopleth.

SPL (L_p; dB re 1 µPa)	Scenario 1 (Bundle launch)		Scenario 2 (Off bottom tow, start)		Scenario 3 (Off bottom tow, end)		Scenario 4 (Surface tow, start)		Scenario 5 (Surface tow, end)	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
190	–	–	–	–	–	–	<0.02	<0.02	<0.02	<0.02
180	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.03
170	0.02	0.02	0.03	0.03	0.02	0.02	0.02	0.02	0.03	0.03
160	0.04	0.04	0.05	0.05	0.04	0.04	0.13	0.12	0.12	0.11
150	0.12	0.12	0.16	0.15	0.16	0.15	0.41	0.37	0.35	0.33
140	1.04	0.96	1.28	1.19	1.32	1.22	2.42	2.15	2.05	1.85
130	2.41	2.21	5.99	5.38	6.23	5.63	7.58	6.74	7.37	6.59
120†	5.40	4.92	11.5	10.4	13.4	11.8	18.7	15.7	17.7	15.5
110	15.1	13.5	31.1	27.0	36.2	30.8	41.1	34.9	52.0	44.1
100	46.5	41.5	92.5	74.0	*	*	*	*	*	*

† Threshold for marine mammal behavioural response to continuous noise (NMFS 2014).
* Radii extend beyond the modelling boundary
A dash indicates the level was not reached.

Table 10. *SPL, fish effect thresholds*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (km) for each representative SPL scenario to modelled maximum-over-depth SPL thresholds based on the quantifiable thresholds for fish with a swim bladder involved in hearing (Popper et al. 2014). Distances are calculated from the centroid of the vessel(s) contributing to the largest isopleth.

SPL (L_p; dB re 1 µPa)	Scenario 1 (Bundle launch)		Scenario 2 (Off bottom tow, start)		Scenario 3 (Off bottom tow, end)		Scenario 4 (Surface tow, start)		Scenario 5 (Surface tow, end)	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
170[I]	0.02	0.02	0.03	0.03	0.02	0.02	0.02	0.02	0.03	0.03
158[II]	0.05	0.04	0.06	0.05	0.06	0.05	0.16	0.14	0.15	0.13

[I] Recoverable injury after 48 h of exposure.
[II] TTS after 12 h of exposure.

Table 11. SEL_{24h}: Maximum-over-depth distances (in km) to PTS and TTS thresholds for marine mammals (Southall et al. 2019) and turtles (Finneran et al. 2017).

Hearing group	Threshold for SEL24h ($L_{E,24h}$; dB re 1 µPa²·s) #	Bundle launch and off bottom tow		Surface tow	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
PTS					
LF cetaceans	199	0.03	0.02	0.08	0.08
HF cetaceans	198	—	—	—	—
Sirenians (Dugong)	206	—	—	—	—
Turtles	220	—	—	—	—
TTS					
LF cetaceans	179	0.74	0.58	1.63	0.57
HF cetaceans	178	—	—	—	—
Sirenians (Dugong)	186	—	—	—	—
Turtles	200	0.03	0.02	0.09	0.08

A dash indicates the level was not reached within the resolution of the modelling

5.2. Sound Field Maps and Graphs

Maps of the estimated sound fields, threshold contours, and isopleths of interest are presented for the SPL scenarios in Figures 11 to 15, and for SEL_{24h} results in Figures 16 and 17.

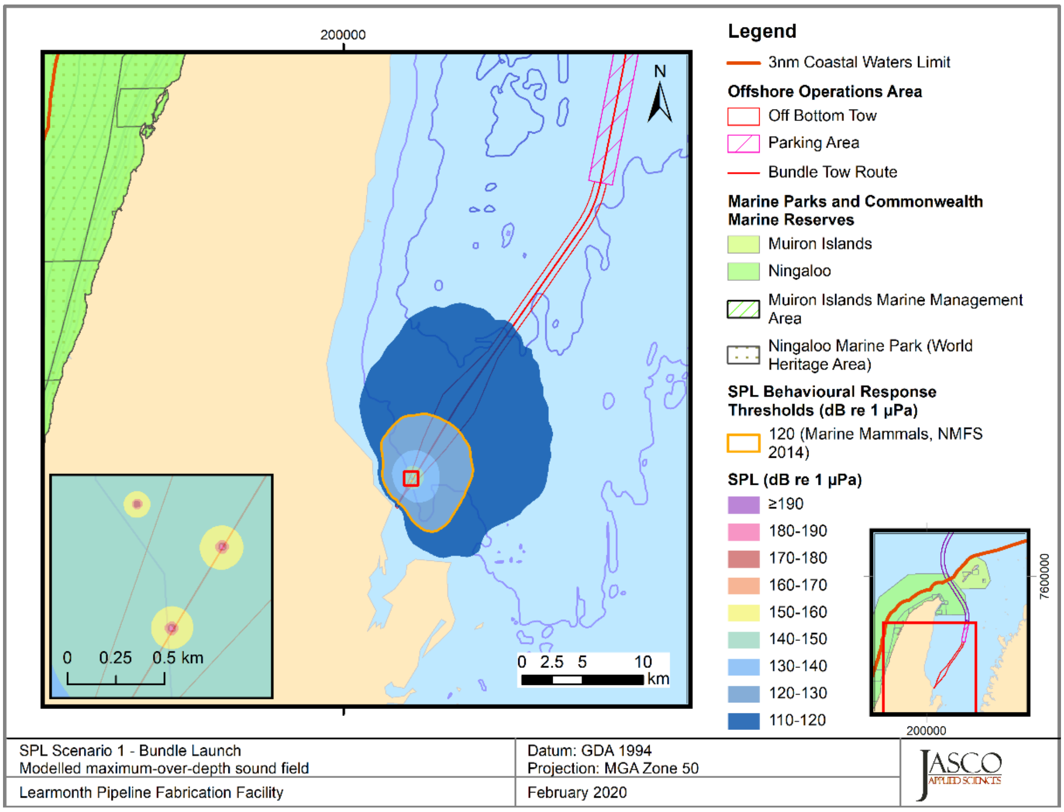

Figure 11. *Scenario 1 SPL*: Sound level contour map, showing maximum-over-depth results. Isopleth for marine mammal behavioural criteria (120 dB re 1 µPa) is shown.

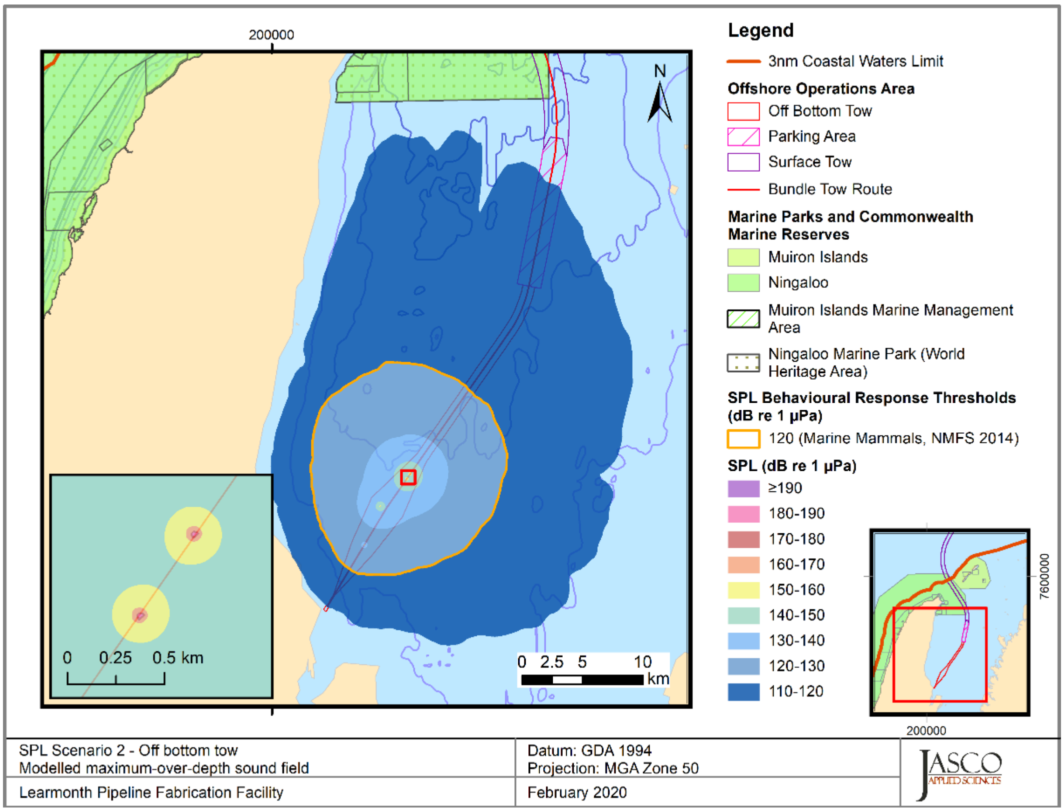

Figure 12. *Scenario 2 SPL*: Sound level contour map, showing maximum-over-depth results. Isopleth for marine mammal behavioural criteria (120 dB re 1 µPa) is shown.

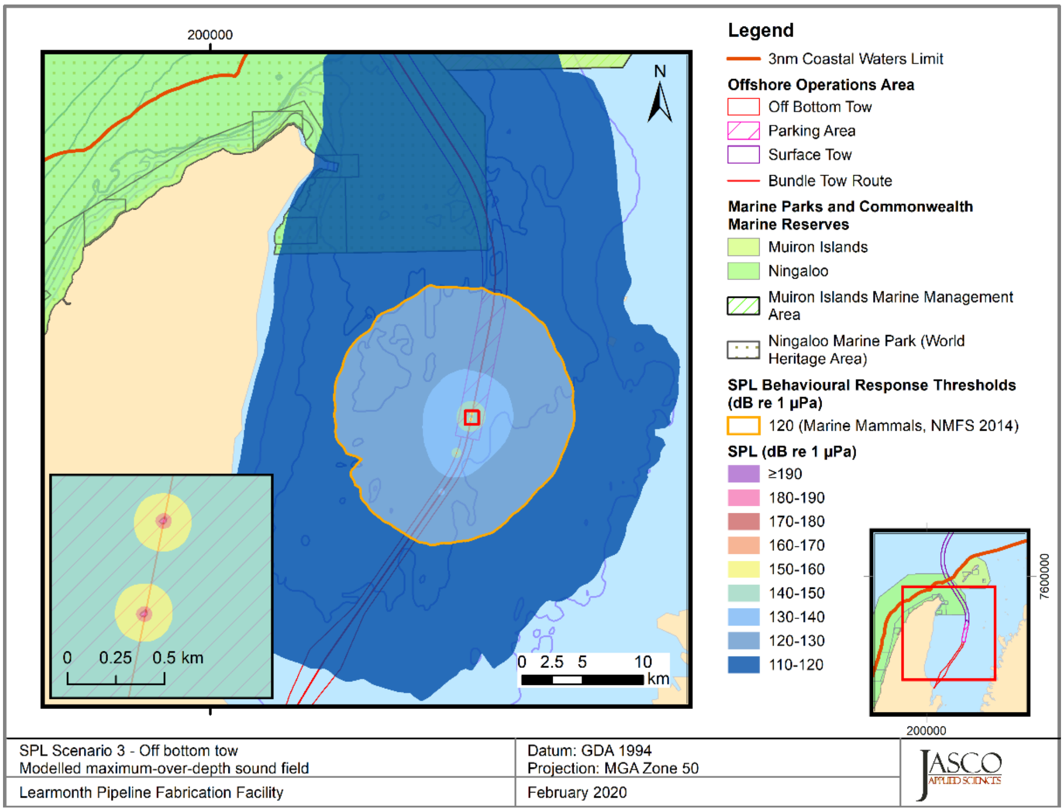

Figure 13. *Scenario 3 SPL*: Sound level contour map, showing maximum-over-depth results. Isopleth for marine mammal behavioural criteria (120 dB re 1 µPa) is shown.

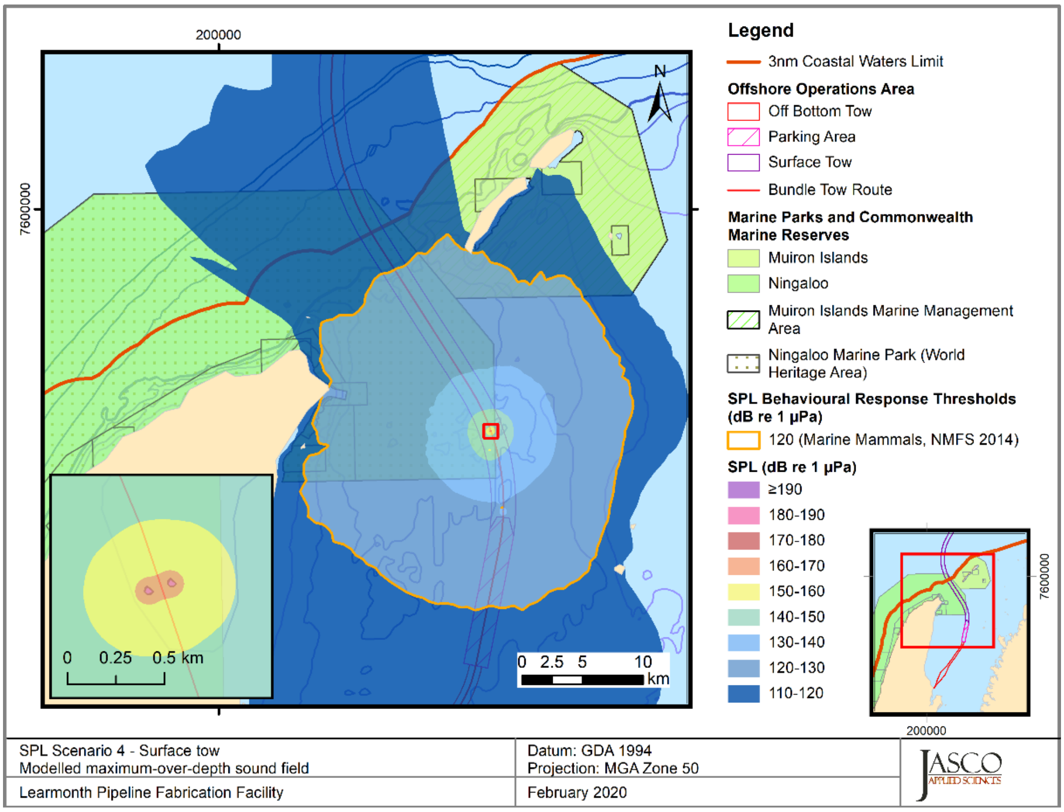

Figure 14. *Scenario 4 SPL*: Sound level contour map, showing maximum-over-depth results. Isopleth for marine mammal behavioural criteria (120 dB re 1 µPa) is shown.

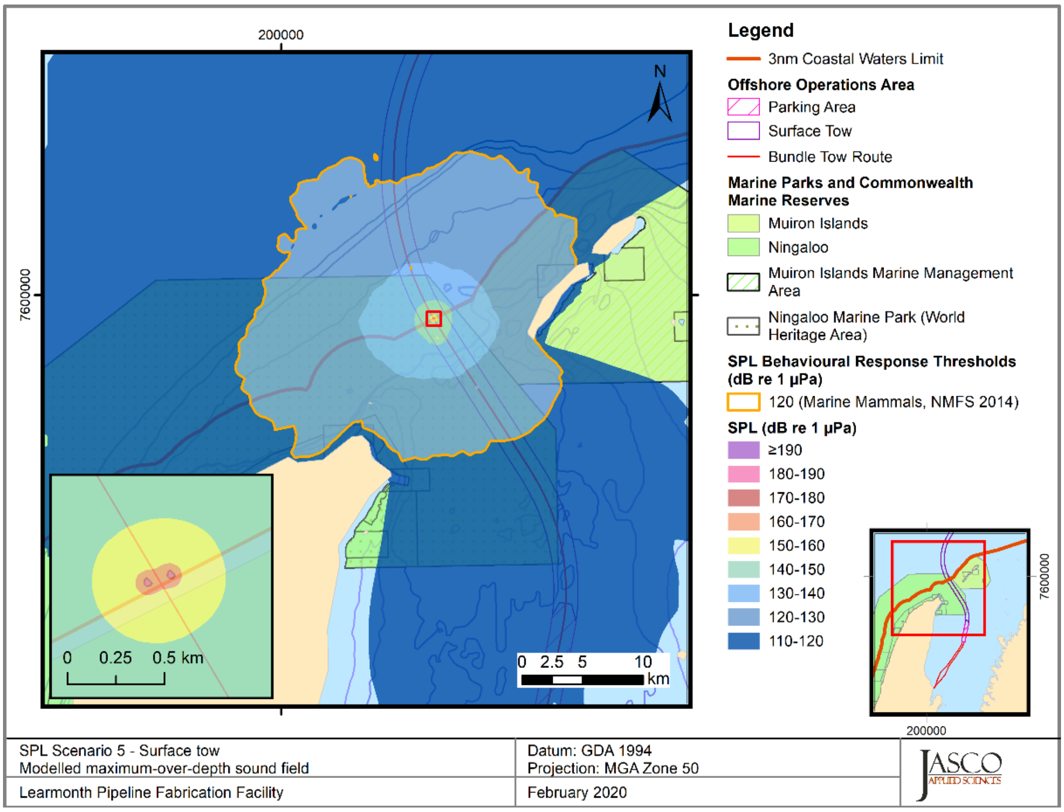

Figure 15. *Scenario 5 SPL*: Sound level contour map, showing maximum-over-depth results. Isopleth for marine mammal behavioural criteria (120 dB re 1 µPa) is shown.

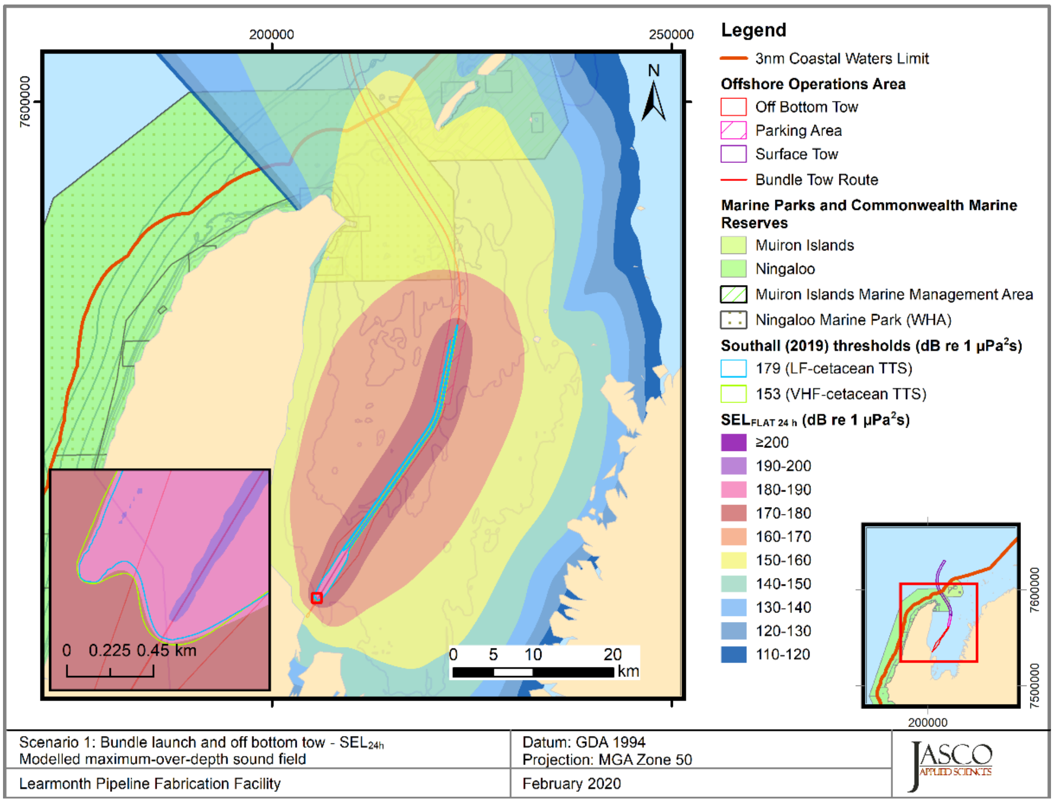

Figure 16. Bundle launch and off bottom tow, *SEL24h*: Sound level contour map showing unweighted maximum-over-depth SEL_{24h} results, along with isopleths for cetacean hearing groups and turtles.

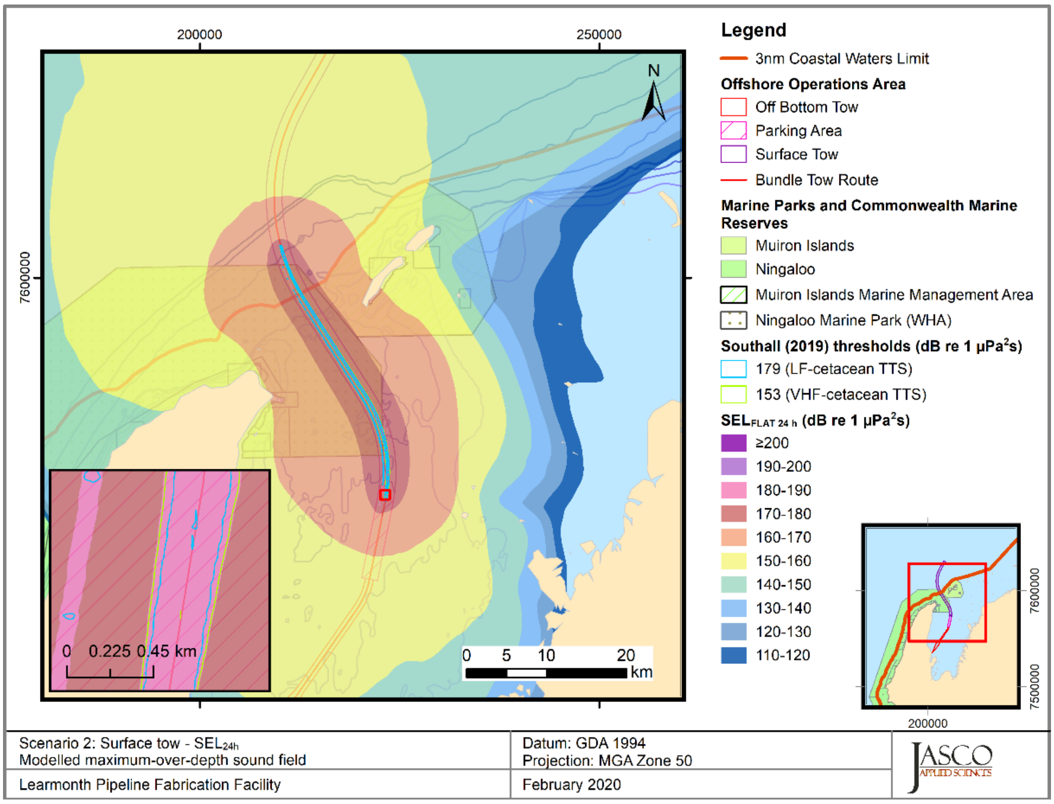

Figure 17. Surface tow, *SEL24h*: Sound level contour map showing unweighted maximum-over-depth SEL_{24h} results, along with isopleths for cetacean hearing groups and turtles.

6. Discussion and Summary

6.1. Noise emissions and acoustic propagation

The sound speed profile (Figure D-2) was derived from data from the U.S. Naval Oceanographic Office's Generalized Digital Environmental Model V 3.0 (GDEM; Teague et al. 1990, Carnes 2009). The month of July was chosen based on an analysis of the temperature, salinity and sound speed profiles extracted from this database. The final profile consisted of an average of profiles within the modelled area to capture propagation effects associated with shallow and deep-water regimes.

The profile was primarily downward refracting apart from a slight upward refracting layer, which extended approximately 40 m from the sea surface. This layer has the potential to trap high frequency energy near the sea surface that would otherwise dissipate more rapidly in range due to propagation, absorption, and seabed losses. The slight upward refracting layer in the sound speed profile only has the potential to effective trap frequencies above 741 Hz based on the thickness of the refracting layer (Jensen et al. 2011).

The modelled propagation loss sites for vessel noise prediction(s) along the bundle tow route were located in water depths ranging from of 10-39 m. The average water depth along the tow route within the 3 nm coastal waters limit boundary was approximately 21 m. The variations in bathymetry and source levels of the vessels during scenarios had a considerable effect on sound propagation at longer distances, with lobes of sound energy extending into the deeper waters within the mouth of Exmouth Gulf to the northwest of the bundle tow route. In the onshore directions from the bundle tow route the rapid decrease in depths, as the water intersects with land, significantly attenuated the sound fields.

The shallow water propagation between the seabed and the sea-surface can be described in terms of the "cut-off frequency (f_c)". The cut-off frequency is a single number that describes how much acoustic energy can propagate with minimal loss between then sea-surface and seafloor interfaces. For a given acoustic signal, frequencies below f_c are subject to higher loss compared to frequencies above the f_c (Jensen et al. 2011).

For a source located in 10-20 metres of water the "cut-off frequency (f_c)" would vary between 136 and 68 Hz. Considering that the loudest modelled vessel SLs that have a decidecade spectral maximum within a band centred on 100 Hz, the water depth that will support propagation at or above this frequency is about 13.8 m. Therefore, the majority of the modelled sites will support propagation of the loudest parts of the vessel SL spectrum. This effect can be seen in the increasing isopleth radii with the increase in water depth.

Lower level isopleth thresholds were more sensitive to shallow water waveguide propagation phenomena primarily created by seabed and sea-surface reflections. These phenomena allow for low level isopleths to persist at longer ranges as levels decay gradually at large distances from the source. The ranges to the injury thresholds are generally confined to ranges near the source as they are associated with high level isopleths and minimal seabed interaction.

6.2. Summary

Marine mammals

The results for the Southall et al. (2019) criteria applied for marine mammal PTS and TTS for vessels are assessed here for two scenarios, each encompassing a day of operations (a 24 h period). The maximum distances to PTS are summarised in Table 12, with complete results for PTS and TTS presented in Table 11.

The maximum distances to the NMFS (2014) marine mammal behavioural response criterion of 120 dB re 1 µPa (SPL) are summarised in Table 13, with complete results presented in Table 9. The distances to this isopleth are calculated in relation to the centroid of all sources within the scenario, as the isopleths for this sound level have coalesced, as demonstrated in the maps in Section 5.2.

Table 12. *Marine mammal injury*: Maximum (R_{max}) horizontal distances (km) to modelled maximum-over-depth PTS threshold from Southall et al. (2019).

Hearing group	Threshold for SEL_{24h} ($L_{E,24h}$; dB re 1 µPa²·s)	Distance R_{max} (km)	
		Bundle launch and off bottom tow	Surface tow
PTS			
LF cetaceans	199	0.03	0.08
HF cetaceans	198	—	—
Sirenians (Dugong)	206	—	—
TTS			
LF cetaceans	179	0.74	1.63
HF cetaceans	178	—	—
Sirenians (Dugong)	186	—	—

Table 13. *Marine mammal behaviour*: Summary of maximum behavioural disturbance distances for each scenario, derived from Table 9.

SPL (L_p; dB re 1 µPa)	Distance R_{max} (km)				
	Scenario 1 (Bundle launch)	Scenario 2 (Off bottom tow, start)	Scenario 3 (Off bottom tow, end)	Scenario 4 (Surface tow, start)	Scenario 5 (Surface tow, end)
120†	5.40	11.5	13.4	18.7	17.7

† Threshold for marine mammal behavioural response to continuous noise (NMFS 2014).

Turtles

Considering the Finneran et al. (2017) criteria for turtle PTS and TTS for vessels, assessed here for each scenario, PTS is not predicted to occur. TTS could occur; however, the distances are 30 m for the bundle launch and off bottom tow, and 90 m for the surface tow (Table 11). These distances are associated with the lead tugs and are measured from the bundle tow route.

Fish

Sound produced by the vessel operations reach the sound levels associated with physiological effects, recoverable injury, and TTS for some fish species in close proximity to the sound sources, but in order for the thresholds to be exceeded, the fish must remain at those distances for either 12 or 48h (Table 10).

While the SPL distances are not time dependent, the threshold for predicted effects are. As the vessels are almost always moving, the predicted effect thresholds will not be exceeded, because the exposure will only occur over a short period of time, not 12 or 48 h, these thresholds will not be exceeded.

Glossary

1/3-octave
One third of an octave. Note: A one-third octave is approximately equal to one decidecade (1/3 oct ≈ 1.003 ddec; ISO 2017).

1/3-octave-band
Frequency band whose bandwidth is one one-third octave. Note: The bandwidth of a one-third octave-band increases with increasing centre frequency.

absorption
The reduction of acoustic pressure amplitude due to acoustic particle motion energy converting to heat in the propagation medium.

acoustic impedance
The ratio of the sound pressure in a medium to the rate of alternating flow of the medium through a specified surface due to the sound wave.

ambient noise
All-encompassing sound at a given place, usually a composite of sound from many sources near and far (ANSI S1.1-1994 R2004), e.g., shipping vessels, seismic activity, precipitation, sea ice movement, wave action, and biological activity.

attenuation
The gradual loss of acoustic energy from absorption and scattering as sound propagates through a medium.

Auditory frequency weighting (auditory weighting function, frequency-weighting function)
The process of band-pass filtering sounds to reduce the importance of inaudible or less-audible frequencies for individual species or groups of species of aquatic mammals (ISO 2017). One example is M-weighting introduced by Southall et al. (2007) to describe "Generalized frequency weightings for various functional hearing groups of marine mammals, allowing for their functional bandwidths and appropriate in characterizing auditory effects of strong sounds".

azimuth
A horizontal angle relative to a reference direction, which is often magnetic north or the direction of travel. In navigation it is also called bearing.

bandwidth
The range of frequencies over which a sound occurs. Broadband refers to a source that produces sound over a broad range of frequencies (e.g., seismic airguns, vessels) whereas narrowband sources produce sounds over a narrow frequency range (e.g., sonar) (ANSI/ASA S1.13-2005 R2010).

bar
Unit of pressure equal to 100 kPa, which is approximately equal to the atmospheric pressure on Earth at sea level. 1 bar is equal to 10^5 Pa or 10^{11} µPa.

broadband sound level
The total sound pressure level measured over a specified frequency range. If the frequency range is unspecified, it refers to the entire measured frequency range.

cavitation
A rapid formation and collapse of vapor cavities (i.e., bubbles or voids) in water, most often caused by a rapid change in pressure. Fast-spinning vessel propellers typically cause cavitation, which creates a lot of noise.

cetacean
Any animal in the order Cetacea. These are aquatic, mostly marine mammals and include whales, dolphins, and porpoises.

compressional wave
A mechanical vibration wave in which the direction of particle motion is parallel to the direction of propagation. Also called primary wave or P-wave.

continuous sound
A sound whose sound pressure level remains above ambient sound during the observation period (ANSI/ASA S1.13-2005 R2010). A sound that gradually varies in intensity with time, for example, sound from a marine vessel.

decade
Logarithmic frequency interval whose upper bound is ten times larger than its lower bound (ISO 2006).

decidecade
One tenth of a decade (ISO 2017). Note: An alternative name for decidecade (symbol ddec) is "one-tenth decade". A decidecade is approximately equal to one third of an octave (1 ddec ≈ 0.3322 oct) and for this reason is sometimes referred to as a "one-third octave".

decidecade band
Frequency band whose bandwidth is one decidecade. Note: The bandwidth of a decidecade band increases with increasing centre frequency.

decibel (dB)
One-tenth of a bel. Unit of level when the base of the logarithm is the tenth root of ten, and the quantities concerned are proportional to power (ANSI S1.1-1994 R2004).

ensonified
Exposed to sound.

far-field
The zone where, to an observer, sound originating from an array of sources (or a spatially distributed source) appears to radiate from a single point. The distance to the acoustic far-field increases with frequency.

fast Fourier transform (FFT)
A computationally efficiently algorithm for computing the discrete Fourier transform.

frequency
The rate of oscillation of a periodic function measured in cycles-per-unit-time. The reciprocal of the period. Unit: hertz (Hz). Symbol: f. 1 Hz is equal to 1 cycle per second.

hearing group
Groups of marine mammal species with similar hearing ranges. Commonly defined functional hearing groups include low-, mid-, and high-frequency cetaceans, pinnipeds in water, and pinnipeds in air.

geoacoustic
Relating to the acoustic properties of the seabed.

hearing threshold
The sound pressure level for any frequency of the hearing group that is barely audible for a given individual in the absence of significant background noise during a specific percentage of experimental trials.

hertz (Hz)
A unit of frequency defined as one cycle per second.

impulsive sound
Sound that is typically brief and intermittent with rapid (within a few seconds) rise time and decay back to ambient levels (NOAA 2013, ANSI S12.7-1986 R2006). For example, seismic airguns and impact pile driving.

low-frequency (LF) cetacean
The functional cetacean hearing group that represents mysticetes (baleen whales) specialized for hearing low frequencies (Southall et al. 2019)..

masking
Obscuring of sounds of interest by sounds at similar frequencies.

median
The 50th percentile of a statistical distribution.

high-frequency (HF) cetacean
The functional cetacean hearing group that represents those odontocetes (toothed whales) specialized for mid-frequency hearing (Southall et al. 2019).

mysticete
Mysticeti, a suborder of cetaceans, use their baleen plates, rather than teeth, to filter food from water. They are not known to echolocate, but they use sound for communication. Members of this group include rorquals (Balaenopteridae), right whales (Balaenidae), and grey whales (*Eschrichtius robustus*).

non-impulsive sound
Sound that is broadband, narrowband or tonal, brief or prolonged, continuous or intermittent, and typically does not have a high peak pressure with rapid rise time (typically only small fluctuations in decibel level) that impulsive signals have (ANSI/ASA S3.20-1995 R2008). For example, marine vessels, aircraft, machinery, construction, and vibratory pile driving (NIOSH 1998, NOAA 2015).

octave
The interval between a sound and another sound with double or half the frequency. For example, one octave above 200 Hz is 400 Hz, and one octave below 200 Hz is 100 Hz.

odontocete
The presence of teeth, rather than baleen, characterizes these whales. Members of the Odontoceti are a suborder of cetaceans, a group comprised of whales, dolphins, and porpoises. The skulls of toothed whales are mostly asymmetric, an adaptation for their echolocation. This group includes sperm whales, killer whales, belugas, narwhals, dolphins, and porpoises.

parabolic equation method
A computationally efficient solution to the acoustic wave equation that is used to model transmission loss. The parabolic equation approximation omits effects of back-scattered sound, simplifying the computation of transmission loss. The effect of back-scattered sound is negligible for most ocean-acoustic propagation problems.

percentile level, exceedance
The sound level exceeded *n*% of the time during a measurement.

permanent threshold shift (PTS)
A permanent loss of hearing sensitivity caused by excessive noise exposure. PTS is considered auditory injury.

point source
A source that radiates sound as if from a single point (ANSI S1.1-1994 R2004).

pressure, acoustic
The deviation from the ambient hydrostatic pressure caused by a sound wave. Also called overpressure. Unit: pascal (Pa). Symbol: p.

pressure, hydrostatic
The pressure at any given depth in a static liquid that is the result of the weight of the liquid acting on a unit area at that depth, plus any pressure acting on the surface of the liquid. Unit: pascal (Pa).

received level (RL)
The sound level measured (or that would be measured) at a defined location.

rms
root-mean-square.

sound
A time-varying pressure disturbance generated by mechanical vibration waves travelling through a fluid medium such as air or water.

sound exposure
Time integral of squared, instantaneous frequency-weighted sound pressure over a stated time interval or event. Unit: pascal-squared second ($Pa^2 \cdot s$) (ANSI S1.1-1994 R2004).

sound exposure level (SEL)
A cumulative measure related to the sound energy in one or more pulses. Unit: dB re 1 $\mu Pa^2 \cdot s$. SEL is expressed over the summation period (e.g., per-pulse SEL [for airguns], single-strike SEL [for pile drivers], 24-hour SEL).

sound exposure spectral density
Distribution as a function of frequency of the time-integrated squared sound pressure per unit bandwidth of a sound having a continuous spectrum (ANSI S1.1-1994 R2004). Unit: $\mu Pa^2 \cdot s/Hz$.

sound field
Region containing sound waves (ANSI S1.1-1994 R2004).

sound intensity
Sound energy flowing through a unit area perpendicular to the direction of propagation per unit time.

sound pressure level (SPL)
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).

For sound in water, the reference sound pressure is one micropascal (p_0 = 1 µPa) and the unit for SPL is dB re 1 μPa^2:

$$L_p = 10\log_{10}(p^2/p_0^2) = 20\log_{10}(p/p_0)$$

Unless otherwise stated, SPL refers to the root-mean-square (rms) pressure level. See also 90% sound pressure level and fast-average sound pressure level. Non-rectangular time window functions may be applied during calculation of the rms value, in which case the SPL unit should identify the window type.

sound speed profile
The speed of sound in the water column as a function of depth below the water surface.

source level (SL)
The sound level measured in the far-field and scaled back to a standard reference distance of 1 metre from the acoustic centre of the source. Unit: dB re 1 µPa·m (pressure level) or dB re 1 µPa²·s·m (exposure level).

spectrogram
A visual representation of acoustic amplitude compared with time and frequency.

spectrum
An acoustic signal represented in terms of its power, energy, mean-square sound pressure, or sound exposure distribution with frequency.

temporary threshold shift (TTS)
Temporary loss of hearing sensitivity caused by excessive noise exposure.

transmission loss (TL)
The decibel reduction in sound level between two stated points that results from sound spreading away from an acoustic source subject to the influence of the surrounding environment. Also referred to as propagation loss.

very high-frequency (VHF) cetacean
The functional cetacean hearing group that represents those odontocetes (toothed whales) specialized for hearing high frequencies (Southall et al. 2019).

wavelength
Distance over which a wave completes one cycle of oscillation. Unit: metre (m). Symbol: λ.

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Appendix A. Acoustic Metrics

A.1. Pressure Related Acoustic Metrics

Underwater sound pressure amplitude is measured in decibels (dB) relative to a fixed reference pressure of p_0 = 1 μPa. Because the perceived loudness of sound, especially impulsive noise such as from seismic airguns, pile driving, and sonar, is not generally proportional to the instantaneous acoustic pressure, several sound level metrics are commonly used to evaluate noise and its effects on marine life. We provide specific definitions of relevant metrics used in the accompanying report. Where possible we follow the ANSI and ISO standard definitions and symbols for sound metrics, but these standards are not always consistent.

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

$$L_{p,pk} = 20\log_{10}\left[\frac{\max(|p(t)|)}{p_0}\right] \tag{A-1}$$

PK is often included as a criterion for assessing whether a sound is potentially injurious; however, because it does not account for the duration of a noise event, it is generally a poor indicator of perceived loudness.

The peak-to-peak sound pressure level (PK-PK; L_{pk-pk}; $L_{p,pk-pk}$; dB re 1 µPa) is the difference between the maximum and minimum instantaneous sound pressure levels in a stated frequency band attained by an impulsive sound, $p(t)$:

$$L_{p,pk-pk} = 10\log_{10}\left\{\frac{[\max(p(t)) - \min(p(t))]^2}{p_0^2}\right\} \tag{A-2}$$

The sound pressure level (SPL; L_p; dB re 1 µPa) is the rms pressure level in a stated frequency band over a specified time window (T, s) containing the acoustic event of interest. It is important to note that SPL always refers to a rms pressure level and therefore not instantaneous pressure:

$$L_p = 10\log_{10}\left(\frac{1}{T}\int_T p^2(t)dt \Big/ p_0^2\right) \tag{A-3}$$

The SPL represents a nominal effective continuous sound over the duration of an acoustic event, such as the emission of one acoustic pulse, a marine mammal vocalization, the passage of a vessel, or over a fixed duration. Because the window length, T, is the divisor, events with similar sound exposure level (SEL) but more spread out in time have a lower SPL. A fixed window length of 0.125 s (critical duration defined by Tougaard et al. (2015)) is used in this study for impulsive sounds.

The sound exposure level (SEL; L_E; $L_{E,p}$; dB re 1 µPa²·s) is a measure related to the acoustic energy contained in one or more acoustic events (N). The SEL for a single event is computed from the time-integral of the squared pressure over the full event duration (T):

$$L_E = 10\log_{10}\left(\int_T p^2(t)dt \Big/ T_0 p_0^2\right) \tag{A-4}$$

where T_0 is a reference time interval of 1 s. The SEL continues to increase with time when non-zero pressure signals are present. It therefore can be construed as a dose-type measurement, so the integration time used must be carefully considered in terms of relevance for impact to the exposed recipients.

SEL can be calculated over periods with multiple acoustic events or over a fixed duration. For a fixed duration, the square pressure is integrated over the duration of interest. For multiple events, SEL can be computed by summing (in linear units) SEL of the *N* individual events:

$$L_{E,N} = 10\log_{10}\left(\sum_{i=1}^{N} 10^{\frac{L_{E,i}}{10}}\right). \tag{A-5}$$

If applied, the frequency weighting of an acoustic event should be specified, as in the case of weighted SEL (e.g., $L_{E,LFC,24h}$; Appendix A.3). The use of fast, slow, or impulse exponential-time-averaging or other time-related characteristics should else be specified.

A.2. Marine Mammal Impact Criteria

It has been long recognised that marine mammals can be adversely affected by underwater anthropogenic noise. For example, Payne and Webb (1971) suggested that communication distances of fin whales are reduced by shipping sounds. Subsequently, similar concerns arose regarding effects of other underwater noise sources and the possibility that impulsive sources—primarily airguns used in seismic surveys—could cause auditory injury. This led to a series of workshops held in the late 1990s, conducted to address acoustic mitigation requirements for seismic surveys and other underwater noise sources (NMFS 1998, ONR 1998, Nedwell and Turnpenny 1998, HESS 1999, Ellison and Stein 1999). In the years since these early workshops, a variety of thresholds have been proposed for both injury and disturbance. The following sections summarize the recent development of thresholds; however, this field remains an active research topic.

A.2.1. Injury

In recognition of shortcomings of the SPL-only based injury criteria, in 2005 NMFS sponsored the Noise Criteria Group to review literature on marine mammal hearing to propose new noise exposure criteria. Some members of this expert group published a landmark paper (Southall et al. 2007) that suggested assessment methods similar to those applied for humans. The resulting recommendations introduced dual acoustic injury criteria for impulsive sounds that included peak pressure level thresholds and SEL_{24h} thresholds, where the subscripted 24h refers to the accumulation period for calculating SEL. The peak pressure level criterion is not frequency weighted whereas SEL_{24h} is frequency weighted according to one of four marine mammal species hearing groups: low-, mid- and high-frequency cetaceans (LF, MF, and HF cetaceans, respectively) and Pinnipeds in Water (PINN). These weighting functions are referred to as M-weighting filters (analogous to the A-weighting filter for human; Appendix A.3). The SEL_{24h} thresholds were obtained by extrapolating measurements of onset levels of Temporary Threshold Shift (TTS) in belugas by the amount of TTS required to produce Permanent Threshold Shift (PTS) in chinchillas. The Southall et al. (2007) recommendations do not specify an exchange rate, which suggests that the thresholds are the same regardless of the duration of exposure (i.e., it implies a 3 dB exchange rate).

Wood et al. (2012) refined Southall et al.'s (2007) thresholds, suggesting lower injury values for LF and HF cetaceans while retaining the filter shapes. Their revised thresholds were based on TTS-onset levels in harbour porpoises from Lucke et al. (2009), which led to a revised impulsive sound PTS threshold for HF cetaceans of 179 dB re 1 µPa^2·s. Because there were no data available for baleen whales, Wood et al. (2012) based their recommendations for LF cetaceans on results obtained from MF cetacean studies. In particular they referenced Finneran and Schlundt (2010) research, which found mid-frequency cetaceans are more sensitive to non-impulsive sound exposure than Southall et al. (2007) assumed. Wood et al. (2012) thus recommended a more conservative TTS-onset level for LF cetaceans of 192 dB re 1 µPa^2·s.

As of 2017, an optimal approach is not apparent. There is consensus in the research community that an SEL-based method is preferable either separately or in addition to an SPL-based approach to assess the potential for injuries. In August 2016, after substantial public and expert input into three draft versions and based largely on the above-mentioned literature (NOAA 2013, 2015, 2016), NMFS finalised technical guidance for assessing the effect of anthropogenic sound on marine mammal hearing (NMFS 2016). The guidance describes injury criteria with new thresholds and frequency weighting functions for the five hearing groups described by Finneran and Jenkins (2012). The latest revision to this work was published in 2018 (NMFS 2018). Southall et al. (2019) revisited the interim criteria published in 2007; all noise exposure criteria in NMFS (2018) and Southall et al. (2019) are identical (for impulsive and non-impulsive sounds), however the mid-frequency cetaceans from NMFS (2018) are classified as high-frequency cetaceans in Southall et al. (2019), and high-frequency cetaceans from NMFS (2018) are classified as very-high-frequency cetaceans in Southall et al. (2019).

A.3. Marine Mammal Frequency Weighting

The potential for noise to affect animals depends on how well the animals can hear it. Noises are less likely to disturb or injure an animal if they are at frequencies that the animal cannot hear well. An exception occurs when the sound pressure is so high that it can physically injure an animal by non-auditory means (i.e., barotrauma). For sound levels below such extremes, the importance of sound components at particular frequencies can be scaled by frequency weighting relevant to an animal's sensitivity to those frequencies (Nedwell and Turnpenny 1998, Nedwell et al. 2007).

A.3.1. Marine mammal frequency weighting functions

In 2015, a U.S. Navy technical report by Finneran (2015) recommended new auditory weighting functions. The overall shape of the auditory weighting functions is similar to human A-weighting functions, which follows the sensitivity of the human ear at low sound levels. The new frequency-weighting function is expressed as:

$$G(f) = K + 10\log_{10}\left[\left(\frac{(f/f_{lo})^{2a}}{\left[1+(f/f_{lo})^2\right]^a\left[1+(f/f_{hi})^2\right]^b}\right)\right] \tag{A-6}$$

Finneran (2015) proposed five functional hearing groups for marine mammals in water: low-, mid-, and high-frequency cetaceans, phocid pinnipeds, and otariid pinnipeds. The parameters for these frequency-weighting functions were further modified the following year (Finneran 2016) and were adopted in NOAA's technical guidance that assesses noise impacts on marine mammals (NMFS 2016, NMFS 2018). Mid-frequency cetaceans from NMFS (2018) are classified as high-frequency cetaceans in Southall et al. (2019), and high-frequency cetaceans from NMFS (2018) are classified as very-high-frequency cetaceans, but the weighting functions remain the same. Table A-1 lists the frequency-weighting parameters for each hearing group; Figure A-1 shows the resulting frequency-weighting curves.

Table A-1. Parameters for the auditory weighting functions as recommended by Southall et al. (2019).

Hearing group	a	b	f_{lo} (Hz)	f_{hi} (kHz)	K (dB)
LF cetaceans (baleen whales)	1.0	2	200	19,000	0.13
HF cetaceans (dolphins, plus toothed, beaked, and bottlenose whales)	1.6	2	8,800	110,000	1.20
VHF cetaceans (true porpoises, *Kogia*, river dolphins, cephalorhynchid, *Lagenorhynchus cruciger* and *L. australis*)	1.8	2	12,000	140,000	1.36
Sirenians (dugongs and manatees)	1.8	2	4,300	25,000	2.62

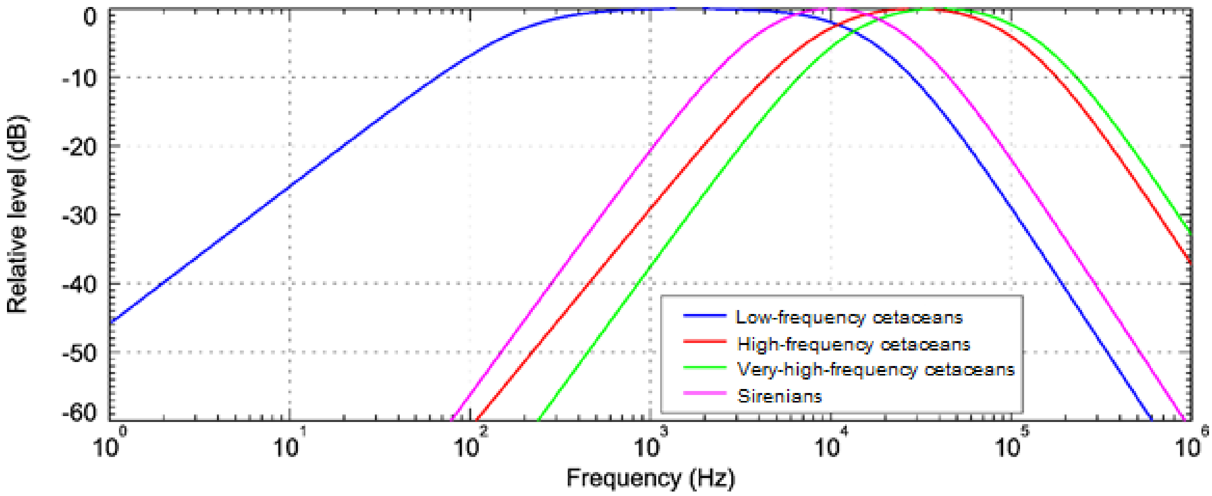

Figure A-1. Auditory weighting functions for functional marine mammal hearing groups as recommended bySouthall et al. (2019).

Appendix B. Thruster Source Level Estimation

Underwater sound that radiates from vessels is produced mainly by propeller and thruster cavitation, with a smaller fraction of sound produced by sound transmitted through the hull, such as by engines, gearing, and other mechanical systems. Sound levels tend to be the highest when thrusters are used to position the vessel and when the vessel is transiting at high speeds. A vessel's sound signature depends on the vessel's size, power output, propulsion system, and the design characteristics of the given system (e.g., blade shape and size). A vessel produces broadband acoustic energy with most of the energy emitted below a few kilohertz. Sound from onboard machinery, particularly sound below 200 Hz, dominates the sound spectrum before cavitation begins—normally around 8–12 knots on many commercial vessels (Spence et al. 2007). Under higher speeds and higher propulsion system load, the acoustic output from the cavitation processes on the propeller blades dominates other sources of sound on the vessel such as machinery or hull vibration (Leggat et al. 1981).

A vessel equipped with propellers/thrusters has two primary sources of sound that propagate from the unit: the machinery and the propellers. For thrusters operating in the heavily loaded conditions, the acoustic energy generated by the cavitation processes on the propeller blades dominates (Leggat et al. 1981). The sound power from the propellers is proportional to the number of blades, the propeller diameter, and the propeller tip speed.

Based on an analysis of acoustic data, Ross (1976) provided the following formula for the sound levels from a vessel's propeller, operating in calm, open ocean conditions:

$$L_{100} = 155 + 60\log(u/25) + 10\log(B/4) \,, \qquad \text{(B-1)}$$

where L_{100} is the spectrum level at 100 Hz, u is the propeller tip speed (m/s), and B is the number of propeller blades. Equation B-1 gives the total energy produced by the propeller cavitation at frequencies between 100 Hz and 10 kHz. This equation is valid for a propeller tip speed between 15 and 50 m/s. The spectrum is assumed to be flat below 100 Hz. Its level is assumed to fall off at a rate of −6 dB per octave above 100 Hz (Figure B-1).

Another method of predicting the source level of a propeller was suggested by Brown (1977). For propellers operating in heavily loaded conditions, the formula for the sound spectrum level is:

$$\mathrm{SL}_B = 163 + 40\log D + 30\log N + 10\log B + 20\log f + 10\log(A_c/A_D) \,, \qquad \text{(B-2)}$$

where D is the propeller diameter (m), N is the propeller revolution rate per second, B is the number of blades, A_C is the area of the blades covered by cavitation, and A_D is the total propeller disc area. Similar to Ross's approach, the spectrum below 100 Hz is assumed to be flat. The tests with a naval propeller operating at off-design heavily loaded conditions showed that Equation B-2 should be used with a value of $(A_c/A_D) = 1$ (Leggat et al. 1981). The maximum level from these two methods was used for modelling.

The combined source level for multiple thrusters operating together can be estimated using the formula:

$$\mathrm{SL}_{\mathrm{total}} = 10\log_{10}\sum_i 10^{\frac{SL_i}{10}}, \qquad \text{(B-3)}$$

where $\mathrm{SL}_{1,\ldots,N}$ are the source levels of individual thrusters. If the vessel is equipped with the same type of thrusters, the combined source level can be estimated using the formula:

$$\mathrm{SL}_N = \mathrm{SL} + 10\log N \qquad \text{(B-4)}$$

where N is the total number of thrusters of the same type.

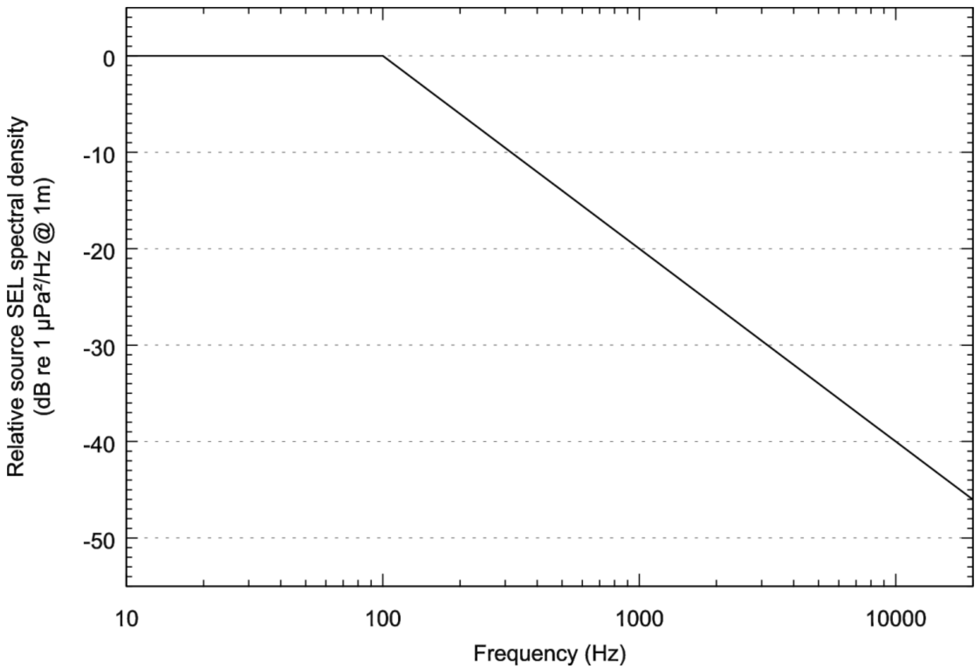

Figure B-1. Estimated sound spectrum from cavitating propeller (Leggat et al. 1981).

Appendix C. Sound Propagation Models

C.1. Propagation Loss

The propagation of sound through the environment was modelled by predicting the acoustic propagation loss—a measure, in decibels, of the decrease in sound level between a source and a receiver some distance away. Geometric spreading of acoustic waves is the predominant way by which propagation loss occurs. Propagation loss also happens when the sound is absorbed and scattered by the seawater, and absorbed scattered, and reflected at the water surface and within the seabed. Propagation loss depends on the acoustic properties of the ocean and seabed; its value changes with frequency.

If the acoustic source level (SL), expressed in dB re 1 µPa^{2}m^2, and propagation (PL), in units of dB, at a given frequency are known, then the received level (RL) at a receiver location can be calculated in dB re 1 µPa by:

$$RL = SL - PL \quad \text{(C-1)}$$

C.2. MONM-BELLHOP

Long-range sound fields were computed using JASCO's Marine Operations Noise Model (MONM). MONM less accurately predicts steep-angle propagation for environments with higher shear speed but is well suited for effective longer-range estimation. This model computes sound propagation at frequencies of 10 Hz to 2 kHz via a wide-angle parabolic equation solution to the acoustic wave equation (Collins 1993) based on a version of the U.S. Naval Research Laboratory's Range-dependent Acoustic Model (RAM), which has been modified to account for a solid seabed (Zhang and Tindle 1995). MONM computes sound propagation at frequencies >2 kHz via the BELLHOP Gaussian beam acoustic ray-trace model (Porter and Liu 1994).

The parabolic equation method has been extensively benchmarked and is widely employed in the underwater acoustics community (Collins et al. 1996). MONM accounts for the additional reflection loss at the seabed, which results from partial conversion of incident compressional waves to shear waves at the seabed and sub-bottom interfaces, and it includes wave attenuations in all layers. MONM incorporates the following site-specific environmental properties: a bathymetric grid of the modelled area, underwater sound speed as a function of depth, and a geoacoustic profile based on the overall stratified composition of the seafloor.

This version of MONM accounts for sound attenuation due to energy absorption through ion relaxation and viscosity of water in addition to acoustic attenuation due to reflection at the medium boundaries and internal layers (Fisher and Simmons 1977). The former type of sound attenuation is significant for frequencies higher than 5 kHz and cannot be neglected without noticeably affecting the model results.

MONM computes acoustic fields in three dimensions by modelling transmission loss within two-dimensional (2-D) vertical planes aligned along radials covering a 360° swath from the source, an approach commonly referred to as N×2-D. These vertical radial planes are separated by an angular step size of $\Delta\theta$, yielding $N = 360°/\Delta\theta$ number of planes (Figure C-1).

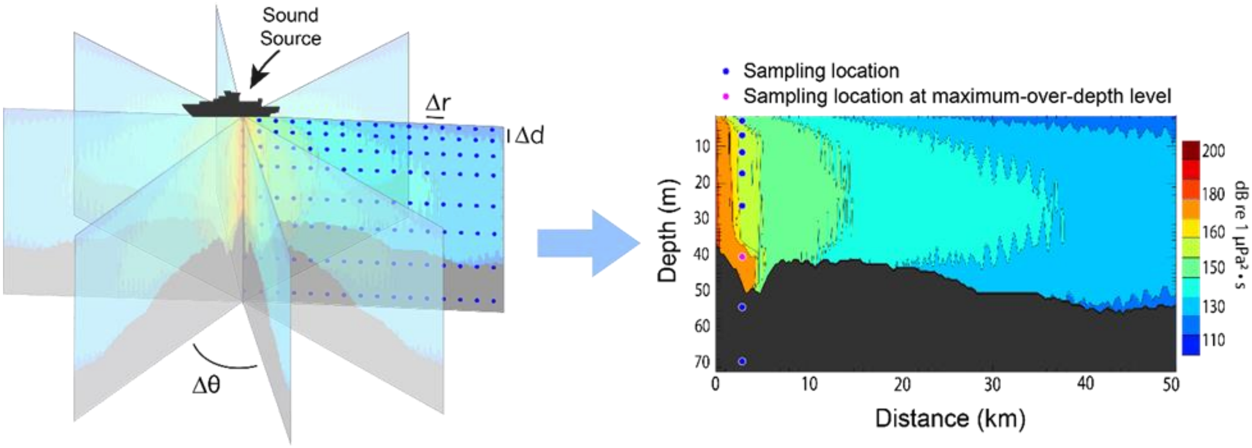

Figure C-1. The N×2-D and maximum-over-depth modelling approach used by MONM.

MONM treats frequency dependence by computing acoustic transmission loss at the centre frequencies of 1/3-octave-bands. Sufficiently many 1/3-octave-bands, starting at 10 Hz, are modelled to include most of the acoustic energy emitted by the source. At each centre frequency, the transmission loss is modelled within each of the N vertical planes as a function of depth and range from the source. The 1/3-octave-band received per-pulse SEL are computed by subtracting the band transmission loss values from the directional source level in that frequency band. Composite broadband received per-pulse SEL are then computed by summing the received 1/3-octave-band levels.

The per-second vessel SEL sound field within each vertical radial plane is sampled at various ranges from the source, generally with a fixed radial step size. At each sampling range along the surface, the sound field is sampled at various depths, with the step size between samples increasing with depth below the surface. The step sizes are chosen to provide increased coverage near the depth of the source and at depths of interest in terms of the sound speed profile. The received per-second SEL at a surface sampling location is taken as the maximum value that occurs over all samples within the water column, i.e., the maximum-over-depth received SEL. These maximum-over-depth SEL values are presented as colour contours around the sources.

Appendix D. Methods and Parameters

This section describes the specifications of the seismic source that was used at all sites and the environmental parameters used in the propagation models.

D.1. Estimating Range to Thresholds Levels

Sound level contours were calculated based on the underwater sound fields predicted by the propagation models, sampled by taking the maximum value over all modelled depths above the sea floor for each location in the modelled region. The predicted distances to specific levels were computed from these contours. Two distances relative to the source are reported for each sound level: 1) R_{max}, the maximum range to the given sound level over all azimuths, and 2) $R_{95\%}$, the range to the given sound level after the 5% farthest points were excluded (see examples in Figure D-1).

The $R_{95\%}$ is used because sound field footprints are often irregular in shape. In some cases, a sound level contour might have small protrusions or anomalous isolated fringes. This is demonstrated in the image in Figure D-1(a). In cases such as this, where relatively few points are excluded in any given direction, R_{max} can misrepresent the area of the region exposed to such effects, and $R_{95\%}$ is considered more representative. In strongly asymmetric cases such as shown in Figure D-1(b), on the other hand, $R_{95\%}$ neglects to account for significant protrusions in the footprint. In such cases R_{max} might better represent the region of effect in specific directions. Cases such as this are usually associated with bathymetric features affecting propagation. The difference between R_{max} and $R_{95\%}$ depends on the source directivity and the non-uniformity of the acoustic environment.

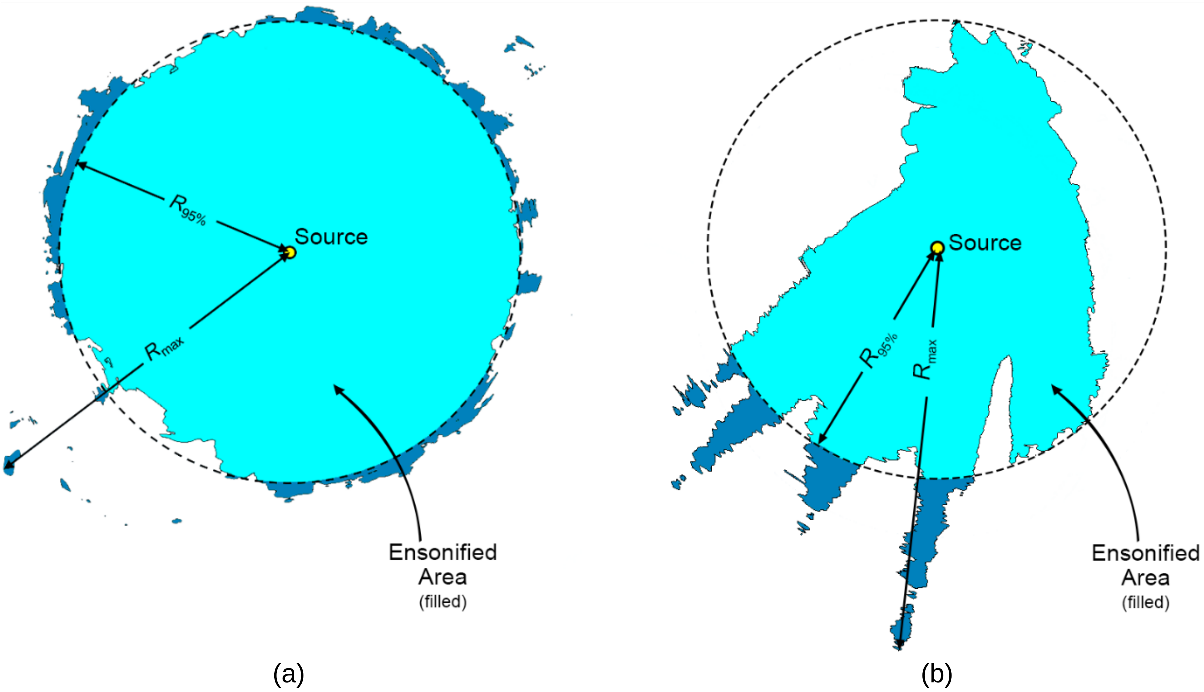

Figure D-1. Sample areas ensonified to an arbitrary sound level with R_{max} and $R_{95\%}$ ranges shown for two different scenarios. (a) Largely symmetric sound level contour with small protrusions. (b) Strongly asymmetric sound level contour with long protrusions. Light blue indicates the ensonified areas bounded by $R_{95\%}$; darker blue indicates the areas outside this boundary which determine R_{max}.

D.2. Environmental Parameters

D.2.1. Bathymetry

Water depths throughout the modelled area were extracted from the Australian Bathymetry and Topography Grid, a 9 arc-second grid rendered for Australian waters (Whiteway 2009). Bathymetry data were extracted and re-gridded onto a Universal Transverse Mercator (UTM) coordinate projection (Zone 50 S) with a regular grid spacing of 100 × 100 m. The water depths were adjusted for highest astronomical tide (HAT) also based on information provided by the client. The water depths were increased by 1.49 metres above the Australian Height Datum (AHD).

D.2.2. Sound speed profiles

The sound speed profile for acoustic modelling was derived from temperature and salinity profiles from the U.S. Naval Oceanographic Office's *Generalized Digital Environmental Model V 3.0* (GDEM; Teague et al. 1990, Carnes 2009). GDEM provides an ocean climatology of temperature and salinity for the world's oceans on a latitude-longitude grid with 0.25° resolution, with a temporal resolution of one month, based on global historical observations from the U.S. Navy's Master Oceanographic Observational Data Set (MOODS). The temperature and salinity profiles were converted to sound speed profiles according to the equations of Coppens (1981). Mean monthly sound speed profiles (all months) were derived from the GDEM profiles within a 60 km box radius of a point with the start of the Exmouth Gulf, the search area encompassed all modelled sites. The July sound speed profile is expected to be most favourable to longer-range sound propagation during the proposed survey time frame. As such, July was selected for sound propagation modelling to ensure precautionary estimates of distances to received sound level thresholds. Figure D-2 shows the resulting profile used as input to the sound propagation modelling.

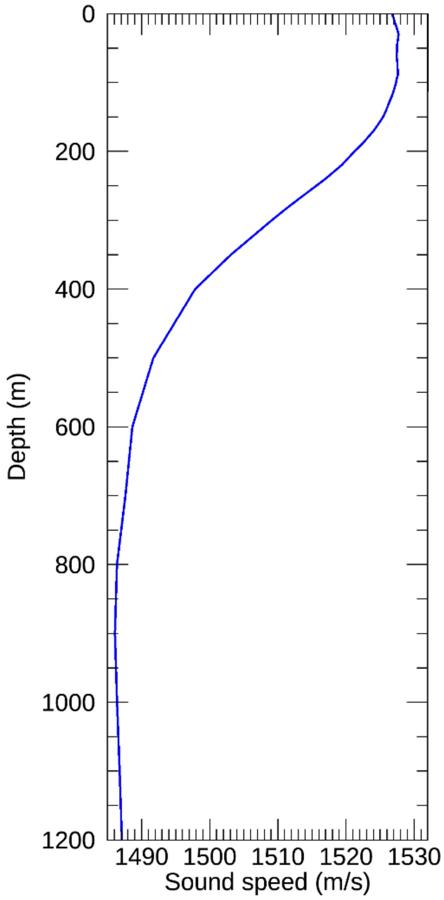

Figure D-2. The final July sound speed profile used for the modelling. The profile was calculated from temperature and salinity profiles from GDEM V 3.0 (Teague et al. 1990, Carnes 2009) for depths 0–1200 m

D.2.3. Geoacoustics

The geoacoustic properties of the seabed were derived from qualitative descriptions of sediment layering structure (Exon and Willcox 1980) and of sediment type (Exon and Willcox 1980, Falkner et al. 2009). For this region, calcium carbonate is the main constituent of seafloor sediments, both at the continental shelf as well as the continental slope. Based on generic properties for calcareous sediments from by Hamilton (1980), we have derived the following set of geoacoustics (Table D-1).

Table D-1. Geoacoustic profile used in the acoustic propagation models. Within each depth range, each parameter varies linearly within the stated range.

Depth below seafloor (m)	Material	Density (g/cm³)	Compressional wave		Shear wave	
			Speed (m/s)	Attenuation (dB/λ)	Speed (m/s)	Attenuation (dB/λ)
0–200	Calcareous sediments	1.52–1.78	1559–1886	0.12–0.21	250	3.75
200–500		1.78–1.98	1886–2321	0.21–0.32		
500–750		1.98–2.05	2321–2631	0.32–0.28		
750–1300		2.05–2.20	2631–3145	0.28–0.13		
>1300	Limestone	2.54	3500	0.11		

D.3. Model Validation Information

Predictions from JASCO's propagation models (MONM, FWRAM, and VSTACK) have been validated against experimental data from a number of underwater acoustic measurement programs conducted by JASCO globally, including the United States and Canadian Artic, Canadian and southern United States waters, Greenland, Russia and Australia (Hannay and Racca 2005, Aerts et al. 2008, Funk et al. 2008, Ireland et al. 2009, O'Neill et al. 2010, Warner et al. 2010, Racca et al. 2012a, Racca et al. 2012b, Matthews and MacGillivray 2013, Martin et al. 2015, Racca et al. 2015, Martin et al. 2017a, Martin et al. 2017b, Warner et al. 2017, MacGillivray 2018, McPherson et al. 2018, McPherson and Martin 2018, Quijano and McPherson 2018).

In addition, JASCO has conducted measurement programs associated with a significant number of anthropogenic activities which have included internal validation of the modelling (including McCrodan et al. 2011, Austin and Warner 2012, McPherson and Warner 2012, Austin and Bailey 2013, Austin et al. 2013, Zykov and MacDonnell 2013, Austin 2014, Austin et al. 2015, Austin and Li 2016, Martin and Popper 2016)