Woodside Browse to NWS Vessel Noise

Animat Modelling

JASCO Applied Sciences (Australia) Pty Ltd

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Executive Summary

JASCO Applied Sciences performed an acoustic exposure analysis study of pygmy blue whales near a migratory and feeding Biologically Important Area (BIA) where they intersected the planned development and installation area for the Brecknock, Calliance, and Torosa fields (collectively known as the Browse resources) proposed by the Browse Joint Venture (BJV). Previously, acoustic modelling was conducted for Mobile Offshore Drilling Unit (MODU) and Floating Production Storage and Offloading (FPSO) operations to determine ranges to acoustic exposure thresholds representing the best available science for potential injury, impairment and behavioural reactions of marine fauna including marine mammals, turtles, and fish (Green et al. 2021).

The aim of the present study was to employ animal movement (animat) modelling simulations in conjunction with these previously computed three-dimensional sound fields to predict the range at which pygmy blue whales are expected to be exposed above threshold criteria for permanent threshold shift (PTS), temporary threshold shift (TTS) and behavioural response. To achieve this, the JASCO Animal Simulation Model Including Noise Exposure (JASMINE) was used to integrate the sound fields with species-typical behaviour, with the pygmy blue whales represented by animats. JASMINE results provide a probabilistic estimate of sound exposure, which can be compared to acoustic thresholds to determine ranges.

Animat modelling focussed on migrating pygmy blue whales (*Balaenoptera musculus brevicauda*) in the migratory BIA and feeding pygmy blue whales in the foraging BIA. The behaviour of migrating pygmy blue whales was modelled with a directional bias of 230 degrees to represent the south-bound migration and 30 degrees to represent the north-bound migration, while feeding pygmy blue whales were presumed to remain in the feeding BIA to represent the behaviour of whales on a feeding stopover during their migration.

To generate statistically reliable probability density functions, and thus range estimates, model simulations were run with animat densities of 3 animats/km^2. The modelling results are not related to real-world density estimates for pygmy blue whales as the number of animals potentially exposed is not calculated.

Four exposure modelling scenarios were simulated to correspond with a selected subset of the scenarios from the acoustic modelling, with each simulation run for a period of 24 hours to match the acoustic modelling approach. Using the distribution of ranges of animats predicted to be exposed to sound levels above threshold, the 95th percentile exposure range ($ER_{95\%}$) was computed. Within the $ER_{95\%}$, there is generally some proportion of animats that do not exceed threshold criteria. This reason is different for different thresholds, however could include animats not being exposed long enough to exceed accumulated SEL thresholds, or swimming at depths which are not ensonified to a level which could lead to exposure. Therefore, the probability that an animat within that distance was exposed above threshold within the $ER_{95\%}$ was also computed (P_{exp}).

Noise effect metrics included sound exposure levels (SEL), and sound pressure level (SPL), The results of the animat analysis predicted that the $ER_{95\%}$ of migrating pygmy blue whales potentially exposed to sound levels above the U.S National Marine Fisheries Service (NMFS) (2018) PTS and TTS criteria were up to 0.01 km (P_{exp} 3-33%) and 0.05 km (P_{exp} 27-78%) respectively, from all scenarios using SEL_{24h} metrics (Table 1). The maximum $ER_{95\%}$ for exposures above the U.S. National Oceanic and Atmospheric Administration (NOAA) (2019) behavioural threshold from all scenarios was 2.78 km, with a P_{exp} of 81%.

The estimated exposure ranges for PTS and TTS for all scenarios were shorter than comparable ranges to threshold reported in Green et al. (2021). This was expected because previous modelling efforts did not incorporate both moving sources and moving receivers, but rather assumed that, as per the NMFS (2018) criteria, SEL_{24h} is a cumulative metric that reflects the dosimetric effect of noise

levels within 24 hours considering that an animal is consistently exposed to such noise levels at a fixed position.

The estimated exposure ranges for the behavioural SPL criteria were comparable to the acoustic ranges (Green et al. 2021), although $ER_{95\%}$ and (P_{exp}) for foraging animats was consistently higher than for migrating animats. This difference arises from the way in which the foraging and migrating animats sample the water column. Foraging animats dive deeper and spend more time at depth than migrating animats. Because of this, they are exposed to sound levels exceeding the behavioural threshold at longer ranges. There was no quantifiable difference between the northbound and southbound migratory simulations for TTS, PTS, or behavioural thresholds.

One aggregate scenario was run to simulate the potential effects with all sources running simultaneously. As was observed in the acoustic modelling analysis, exposure ranges for the aggregate scenario were not significantly different than during individual operations (Green et al. 2021).

Table 1. Summary of animat simulation results. The 95th percentile exposures ranges ($ER_{95\%}$) in km and probability of animats being exposed above threshold within the $ER_{95\%}$ (P_{exp} (%)) are provided.

Threshold		Scenario 4(a) MODU under DP at TRD		Scenario 7 Torosa FPSO		Scenario 8 Torosa FPSO Offtake		Scenario 9 Aggregate Scenario	
Description	Threshold level (dB)	$ER_{95\%}$ (km)	P_{exp} (%)	$ER_{95\%}$ (km)	P_{exp} (%)	$ER_{95\%}$ (km)	P_{exp} (%)	$ER_{95\%}$ (km)	P_{exp} (%)
South-bound migrating pygmy blue whales									
TTS (SEL_{24h})	179[a]	0.02	27	0	0	0.05	46	0.05	34
PTS (SEL_{24h})	199[a]	0	0	0	0	0	0	0	0
Behavioural response (SPL)	120[b]	2.22	76	0.37	73	1.38	88	2.22	82
North-bound migrating pygmy blue whales									
TTS (SEL_{24h})	179[a]	0.03	39	0	0	0.04	78	0.04	40
PTS (SEL_{24h})	199[a]	0	0	0	0	0.01	25	0.01	3
Behavioural response (SPL)	120[b]	2.28	83	0.37	71	1.49	81	2.28	90
Foraging pygmy blue whales									
TTS (SEL_{24h})	179[a]	0.03	53	0	0	0.01	50	0.03	41
PTS (SEL_{24h})	199[a]	0	0	0	0	0.01	33	0.01	12
Behavioural response (SPL)	120[b]	2.68	92	0.52	100	1.91	92	2.78	81

[a] LF-weighted SEL_{24h} ($L_{E,24h}$; dB re 1 μPa²·s)
[b] SPL (L_p; dB re 1 μPa)

1. Introduction

JASCO Applied Sciences (JASCO), performed an acoustic exposure analysis study for pygmy blue whales (*Balaenoptera musculus brevicauda*) in association with the planned Browse to North West shelf (NWS) Project development of the Brecknock, Calliance, and Torosa fields (collectively known as the Browse resources) by the Browse Joint Venture (BJV). This development will involve drilling wells and installing a subsea production system that will supply two 1100 million standard cubic feet per day (annual daily export average) Floating Production Storage and Offloading (FPSO) facilities. Gas will be transported from the FPSO facilities to the existing NWS Project infrastructure via an approximately 900 km long trunkline. Each FPSO will have a turret mooring system that will be stabilised using mooring lines secured to the seabed by piles.

The acoustic modelling results were used in conjunction with animal movement modelling simulations to predict the distance at which pygmy blue whales are expected to be exposed above threshold criteria for injury (temporary threshold shift (TTS) and permanent threshold shift (PTS)), and behavioural response. Sound exposure distribution estimates are determined by moving large numbers of simulated animals (animats) through a modelled time-evolving sound field, computed using specialised sound source and sound propagation models. This approach provides the most realistic prediction of the maximum expected root-mean-square sound pressure level (SPL, L_p) and the temporal accumulation of sound exposure level (SEL, L_E) for comparison against the relevant thresholds.

The present animat modelling study considers the following scenarios:

- The operations of a Mobile Offshore Drilling Unit (MODU) during drilling operations using four thrusters at the TRD drill centre.
- FPSO operational noise for the Torosa FPSO without heading control.
- Torosa FPSO operational noise during offtake, including the FPSO without heading control, an Offshore Support Vessel (OSV) near the FPSO and a noiseless condensate tanker.
- Aggregate scenarios that include MODU operations at TRD and the Torosa FPSO during offtake operations.

Green et al. (2021) conducted a detailed sound modelling study, and the resulting sound fields were used to predict animat sound exposures. The geographic coordinates for the modelled sites that were used in the current analysis are provided in Table 2 and an overview of the acoustic modelling area is shown in Figure 1.

Table 2. Location details for the modelled sites from Green et al. (2021). Sites and sources used in animat exposure modelling are highlighted in bold.

Site	Source	Latitude (S)	Longitude (E)	MGA (GDA94), Zone 51		Water depth (m)
				X (m)	Y (m)	
TRA Well	MODU (centre)	13° 58′ 12.50″	121° 58′ 37.70″	389521	8455338	425
	OSV (centre)	13° 58′ 12.49″	121° 58′ 35.70″	389461	8455338	425
TRD Well	**MODU (centre)**	**14° 00′ 26.64″**	**121° 57′ 23.58″**	**387315**	**8451207**	**392**
	OSV (centre)	14° 00′ 26.63″	121° 57′ 21.58″	387255	8451207	392
Torosa FPSO	**FPSO (centre)**	**13° 58′ 15.06″**	**122° 01′ 28.53″**	**394647**	**8455281**	**463**
	OSV (centre)	**13° 58′ 14.94″**	**122° 00′ 59.03″**	**393762**	**8455281**	**460**

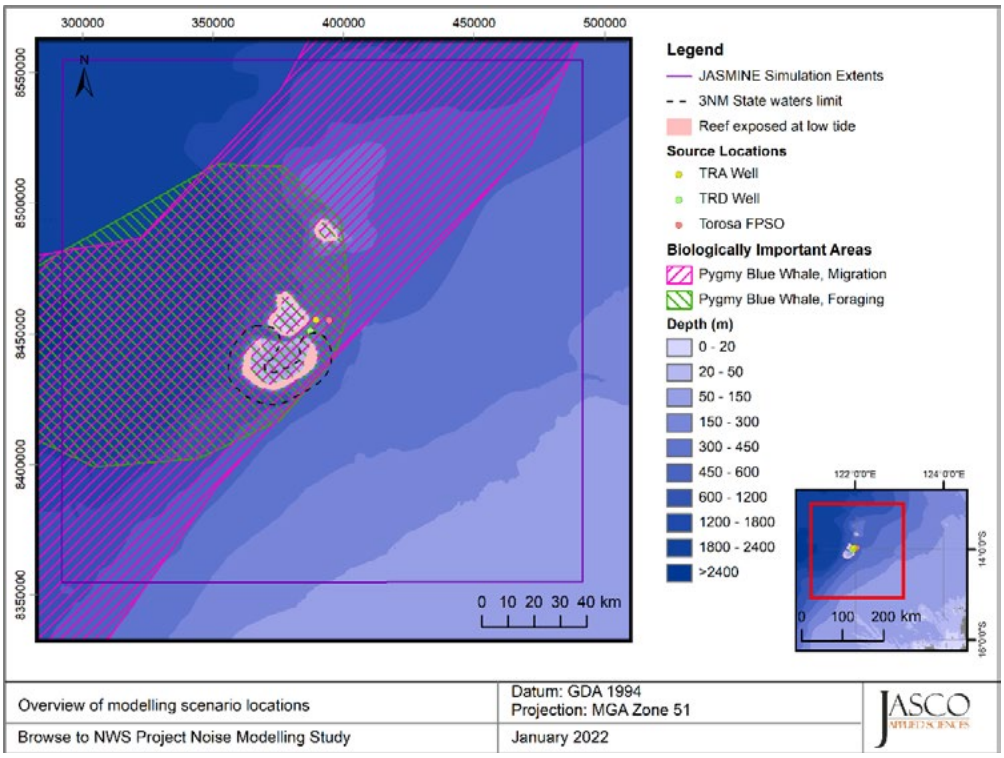

Figure 1. Overview of the modelled area and local features.

1.1. Exposure Modelling Scenario Details

For the planned Browse to NWS Project development, source and propagation modelling were conducted (Green et al. 2021) to generate sound fields which were used in conjunction with animal movement modelling. The acoustic modelled sources were as follows:

- *An FPSO facility* that is 370 m long and 67 m wide. This was modelled under:
  - Typical operations, with no heading control and no offtake, only operating processing and associated equipment,
  - Heading control (thrusters operating), representative of typical operational conditions,
  - Heading control (thrusters operating) with optimised thrusters, representative of typical operational conditions, and
  - Offtake, during which the FPSO is only operating processing and associated equipment.
- *A representative MODU* that is 100 × 80 m under DP, representative of typical operational noise during 1-year (non-cyclonic) return interval metocean conditions. This was modelled using:
  - Four thruster sources operating at 40% capacity, and
  - A central machinery source, representative of a typical drilling operation.
- *A representative OSV*, a DP vessel 92.95 m long (vessel design based on the Marin Teknikk MT6016 hull) under DP, representative of typical operational noise during maximum safe operating conditions and resupply operations. This was modelled using five thruster sources operating at a defined capacity, based on the specification of the *Fugro Etive*, as follows:
  - Two Rolls-Royce AZP100 thrusters,
  - Two Rolls Royce TT 2200 DPN thrusters, and
  - One Rolls-Royce AZP1001 thruster.

These vessels were modelled in varying configurations at the three different locations shown in Figure 1. Animat exposure modelling scenarios were simulated for Scenarios 4(a), 7, 8, and 9. The acoustic scenarios and animat scenarios are summarised in Table 3.

Table 3. Modelled scenarios from Green et al. (2021). Scenarios used in animat exposure modelling are highlighted in bold.

Scenario	Description	Sources	Length of operation	Animat Modelling
TRA well				
1(a)	MODU drilling	MODU drilling and thrusters (4 × 40%)	24 h	Not Considered
1(b)	MODU drilling (moored)	MODU drilling, no thrusters	24 h	Not Considered
2	Offshore Support Vessel	Support vessel (DP)	6 and 12 h	Not Considered
3	MODU resupply	MODU drilling and thrusters (4 × 40%) Support vessel (DP)	24 h 6 and 12 h	Not Considered
TRD well				
4(a)	**MODU drilling**	**MODU drilling and thrusters (4 × 40%)**	**24 h**	**Considered**
4(b)	MODU drilling (moored)	MODU drilling, no thrusters	24 h	Not Considered
5	Offshore Support Vessel	Support vessel (DP)	6 and 12 h	Not Considered
6	MODU resupply	MODU drilling and thrusters (4 × 40%) Support vessel (DP)	24 hr 6 and 12 h	Not Considered
Torosa				
7	**FPSO**	**Topsides machinery**	**24 h**	**Considered**
7(a)	FPSO using heading control	FPSO thrusters and topsides machinery	24 h	Not Considered
7(b)	FPSO using optimised heading control	Optimised FPSO thrusters and topsides machinery	24 h	Not Considered
8	**FPSO offtake**	**FPSO with topsides machinery Silent Tanker Support vessel (DP)**	**24 h**	**Considered**
TRD well and Torosa				
9	**MODU drilling at TRD, Torosa FPSO Offtake**	**MODU drilling and thrusters (4 × 40%) Support vessel (DP) FPSO with topsides machinery Silent Tanker**	**24 h**	**Considered**

The migratory and foraging BIAs overlap with the project area. Simulated animats were seeded only within the BIAs to represent the spatial distribution of this species. Animat exposure modelling simulation extents and animat seeding areas (BIAs) are shown in Figure 1.

2. Noise Effect Criteria

The noise effect criteria which were considered for pygmy blue whales in this assessment are the same as those applied and described in the acoustic modelling study (Green et al. 2021). The criteria relate to assessing permanent threshold shift (PTS), temporary threshold shift (TTS) and behavioural response in pygmy blue whales and are summarised in Table 4.

Table 4. Criteria for effects of non-impulsive noise exposure, including vessel noise on marine mammals: SPL and Weighted SEL_{24h} thresholds.

Hearing group	NOAA (2019)	NMFS (2018)	
	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	120	199	179
MF cetaceans		198	178
HF cetaceans		173	153

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

3. Methods

3.1. Animal Movement and Exposure Modelling

The JASCO Animal Simulation Model Including Noise Exposure (JASMINE) was used to predict the exposure of animats to sound arising from the vessel and equipment operations. JASMINE integrates the predicted sound field with biologically meaningful movement rules for each marine mammal species (pygmy blue whales for the current analysis) that results in an exposure history for each animat in the model. In JASMINE, the sound received by the animats is determined by the proposed operations. As illustrated in Figure 2, animats are programmed to behave like the marine animals that may be present in an area. The parameters used for forecasting realistic behaviours (e.g., diving and foraging depth, swim speed, surface times) are determined and interpreted from marine mammal studies (e.g., tagging studies) where available, or reasonably extrapolated from related or comparable species. For cumulative metrics, an individual animat's sound exposure levels are summed over a 24 h duration to determine its total received energy, and then compared to the relevant threshold criteria. For single-exposure metrics metrics, the maximum exposure is evaluated against threshold criteria for each 24 h period. For additional information on JASMINE, see Appendix A.

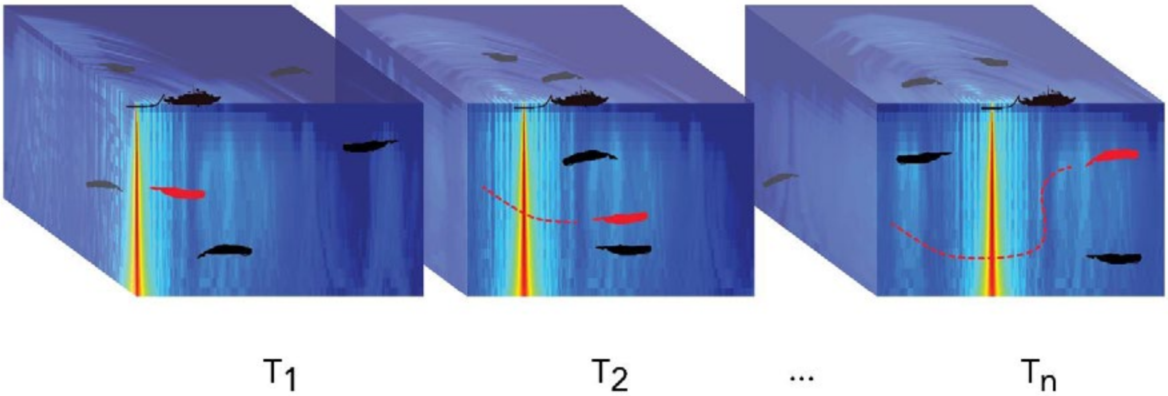

Figure 2. Cartoon of animats in a moving sound field. Example animat (red) shown moving with each time step (T_n). The acoustic exposure of each animat is determined by where it is in the sound field, and its exposure history is accumulated as the simulation steps through time.

The simulation was run for a representative period of 24 hours to coincide with the acoustic modelling effort. The modelling results presented in this report are not related to real-world density estimates for pygmy blue whales within the migration BIA and the number of animals potentially exposed was not calculated. To evaluate PTS, TTS, and behavioural response, exposure results were obtained using detailed behavioural information for migrating and feeding pygmy blue whales (described in Section 3.1.2). The spatial distribution of animats was restricted to the BIAs for all assessed scenarios, with the migration behavioural profile limited to the migration BIA and the feeding behavioural profile limited to the foraging BIA.

Model parameters related to spatial and temporal sampling were selected to appropriately capture both the swimming behaviours and the predicted sound fields. Within the context of the project-specific simulation parameters, including source characteristics, swimming behaviours, and bathymetry, a seeding density of 3 animats per km^2 was determined to provide sufficient sampling of the model space and to generate statistically reliable exposure range estimates (see Appendix A.1.3 for additional details). This resulted in 97 346 south-bound migrating animats, 86 769 north-bound migrating animats and 55 649 foraging animats across all modelling scenarios. Additionally, each animat was programmed to sample the model space every 5 seconds. For example, an animat swimming at 1 m/s would sample the sound field every 5 meters along its track.

3.1.1. Exposure-based Radial Distance Estimation

The results from the animal movement and exposure modelling provided a way to estimate radial distances to effect thresholds. The distance to the closest point of approach (CPA) for each of the animats was recorded. The $ER_{95\%}$ (95% Exposure Range) is the horizontal distance that includes 95% of the animat CPAs that exceeded a given effect threshold (Figure 3). Within the $ER_{95\%}$, there is generally some proportion of animats that do not exceed threshold criteria. The probability that an animat is exposed above threshold within the $ER_{95\%}$ is provided in the results tables.

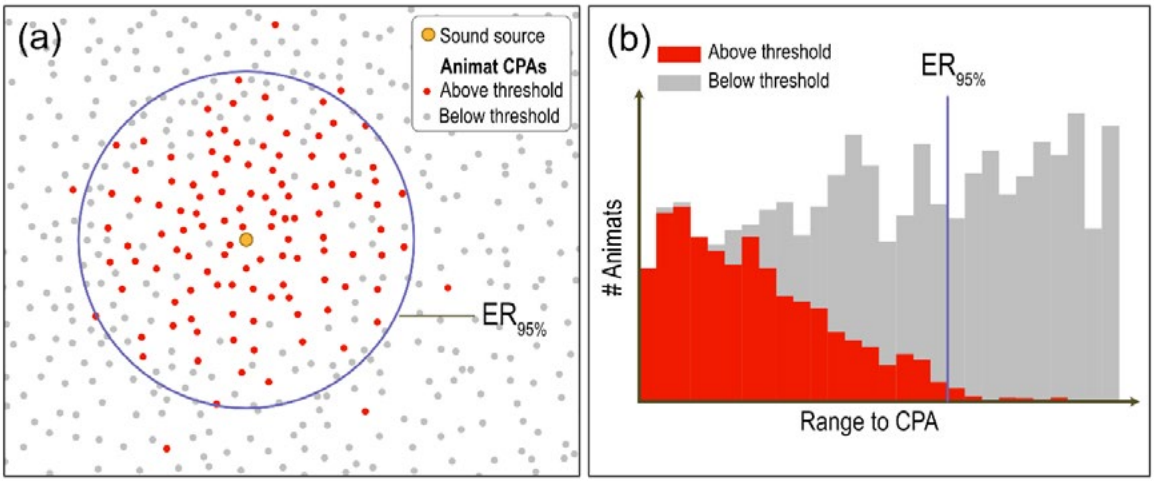

Figure 3. Example distribution of animat closest points of approach (CPAs). Panel (a) shows the horizontal distribution of animats near a sound source. Panel (b) shows the distribution of distances to animat CPAs. The 95% exposure range ($ER_{95\%}$) is indicated in both panels.

3.1.2. Pygmy Blue Whale Behaviour

The Browse to NWS Project development is within the migration and foraging BIAs for pygmy blue whales, therefore both behaviours were considered. Additionally, the south-bound and north-bound migrations were both modelled. Detailed information on pygmy blue whales was derived from a range of sources that used multi-sensor tags to record fine-scale dive and movement behaviour (Owen et al. 2016, AIMS unpublished data 2021), as well as satellite tags to record travel speed (Thums and Ferreira 2021).

Multi-sensor tags typically record the depth of an animal along with various movement parameters such as swim speed and their body’s orientation. Owen et al. (2016) equipped a sub-adult pygmy blue whale with a multi-sensor tag off Western Australia. They identified dives for the tagged animal as migratory, feeding, or exploratory (i.e., no lunges recorded which would indicate feeding). Pygmy blue whales in the simulation area are presumed to be either migrating or feeding depending on the BIA in which they are located, and so the two behavioural profiles were modelled separately. Exploratory dives were considered to be part of migratory behaviour, and so the two dive types were modelled together such that the animats were migrating 95% of the time and engaged in exploratory dives 5% of the time (Owen et al. 2016). For the feeding behavioural profile, animats were assumed to be engaged in feeding behaviour 100% of the time. Using data from Owen et al. (2016), the approximate length of a bout of exploratory dives could be determined, as well as the average (± SD) depth of this dive type.

The speed of travel and turn angle (i.e., the change in heading between satellite locations) for all dive behaviours were calculated from data presented in Thums and Ferreira (2021), who analysed data from satellite tags deployed on pygmy blue whales in the Northwest Marine Region. All remaining parameters were calculated from two multi-sensor tags deployed on pygmy blue whales off Western Australia (AIMS unpublished data 2021).

The behaviour of migrating pygmy blue whales was modelled to reflect animats transiting through the modelling area on a 230° track for the southward migration, and a 30° track for the northward migration. This represents the animals migrating along the west coast of Australia from their breeding grounds in Indonesia (Double et al. 2014, Thums and Ferreira 2021).

4. Results

A summary of radial distances to exposure thresholds for pygmy blue whales, along with probability of exposure for each modelled scenario (Table 3) are included in Table 5-Table 7. Results include $ER_{95\%}$ exposure ranges calculated for the 120 dB behavioural response threshold and SEL thresholds for both TTS and PTS, and the probability of an animat being exposed above the threshold within the $ER_{95\%}$.

Table 5. Summary of animat simulation results for south-bound migrating pygmy blue whales. The 95th percentile exposures ranges ($ER_{95\%}$) in km and probability of animats being exposed above threshold within the $ER_{95\%}$ (P_{exp} (%)) are provided.

Threshold		Scenario 4(a) MODU under DP at TRD		Scenario 7 Torosa FPSO		Scenario 8 Torosa FPSO Offtake		Scenario 9 Aggregate Scenario	
Description	Threshold level (dB)	$ER_{95\%}$ (km)	P_{exp} (%)	$ER_{95\%}$ (km)	P_{exp} (%)	$ER_{95\%}$ (km)	P_{exp} (%)	$ER_{95\%}$ (km)	P_{exp} (%)
TTS (SEL_{24h})	179[a]	0.02	27	0	0	0.05	46	0.05	34
PTS (SEL_{24h})	199[a]	0	0	0	0	0	0	0	0
Behavioural response (SPL)	120[b]	2.22	76	0.37	73	1.38	88	2.22	82

[a] LF-weighted SEL_{24h} ($L_{E,24h}$; dB re 1 µPa²·s)
[b] SPL (L_p; dB re 1 µPa)

Table 6. Summary of animat simulation results for north-bound migrating pygmy blue whales. The 95th percentile exposures ranges ($ER_{95\%}$) in km and probability of animats being exposed above threshold within the $ER_{95\%}$ (P_{exp} (%)) are provided.

Threshold		Scenario 4(a) MODU under DP at TRD		Scenario 7 Torosa FPSO		Scenario 8 Torosa FPSO Offtake		Scenario 9 Aggregate Scenario	
Description	Threshold level (dB)	$ER_{95\%}$ (km)	P_{exp} (%)	$ER_{95\%}$ (km)	P_{exp} (%)	$ER_{95\%}$ (km)	P_{exp} (%)	$ER_{95\%}$ (km)	P_{exp} (%)
TTS (SEL_{24h})	179[a]	0.03	39	0	0	0.04	78	0.04	40
PTS (SEL_{24h})	199[a]	0	0	0	0	0.01	25	0.01	3
Behavioural response (SPL)	120[b]	2.28	83	0.37	71	1.49	81	2.28	90

[a] LF-weighted SEL_{24h} ($L_{E,24h}$; dB re 1 µPa²·s)
[b] SPL (L_p; dB re 1 µPa)

Table 7. Summary of animat simulation results for foraging pygmy blue whales. The 95th percentile exposures ranges ($ER_{95\%}$) in km and probability of animats being exposed above threshold within the $ER_{95\%}$ (P_{exp} (%)) are provided.

Threshold		Scenario 4(a) MODU under DP at TRD		Scenario 7 Torosa FPSO		Scenario 8 Torosa FPSO Offtake		Scenario 9 Aggregate Scenario	
Description	Threshold level (dB)	$ER_{95\%}$ (km)	P_{exp} (%)	$ER_{95\%}$ (km)	P_{exp} (%)	$ER_{95\%}$ (km)	P_{exp} (%)	$ER_{95\%}$ (km)	P_{exp} (%)
TTS (SEL_{24h})	179[a]	0.03	53	0	0	0.01	50	0.03	41
PTS (SEL_{24h})	199[a]	0	0	0	0	0.01	33	0.01	12
Behavioural response (SPL)	120[b]	2.68	92	0.52	100	1.91	92	2.78	81

[a] LF-weighted SEL_{24h} ($L_{E,24h}$; dB re 1 µPa^2·s)
[b] SPL (L_p; dB re 1 µPa)

Figures 4-6 show histograms of CPA ranges for each animat in the migratory and foraging simulations. The exposure ranges from animal movement modelling are indicated along with both the $R_{95\%}$ and R_{max} from acoustic propagation modelling.

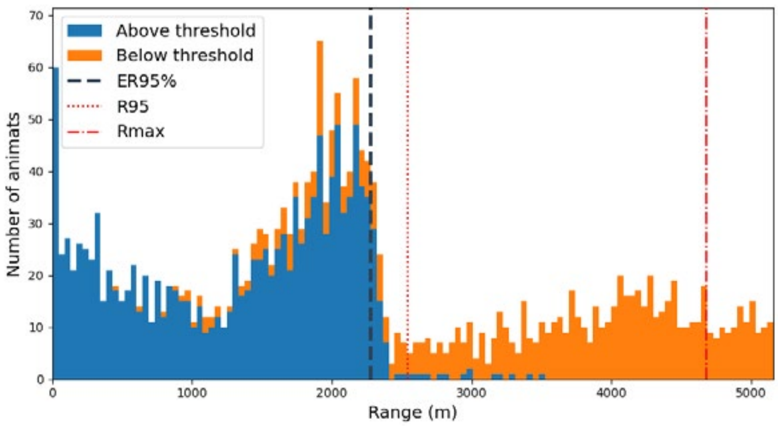

Figure 4. *North-bound migration animats*: CPA range histogram for animats for the MODU under DP at TRD drill centre). Bar colours indicate whether the animats exceeded the SPL behavioural threshold.

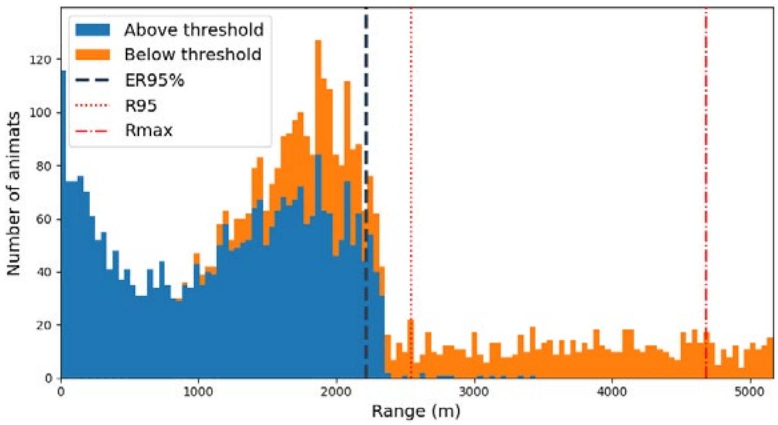

Figure 5. *South-bound migration animats:* CPA range histogram for animats for the MODU under DP at TRD drill centre. Bar colours indicate whether the animats exceeded the SPL behavioural threshold.

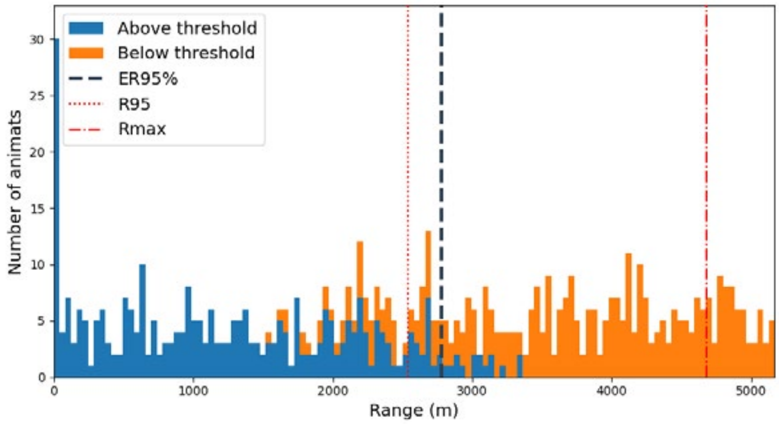

Figure 6. *Foraging animats*: CPA range histogram for animats for the MODU under DP at TRD drill centre.

To provide context and a demonstration of the movements and exposures of animats, during the modelling, 20 random animat tracks were saved from Scenario 9, the aggregate scenario for foraging animats. The animats for which the exposure history is saved are nominated prior to seeding into the simulation, thus their path and exposures are unknown. Of these 20 random animats which had their history saved, only 11 were exposed to the sound field, i.e. came close enough to the source to be exposed. The track for the animat which approached closest to the sound sources (23 km), and thus experienced the highest SPL (95 dB re 1 µPa) and SEL (136 dB re 1 µPa^{2}s) is shown in Figure 7. Figure 8 shows the range to the source as well as the accumulated SEL during the course of the simulation for that animat.

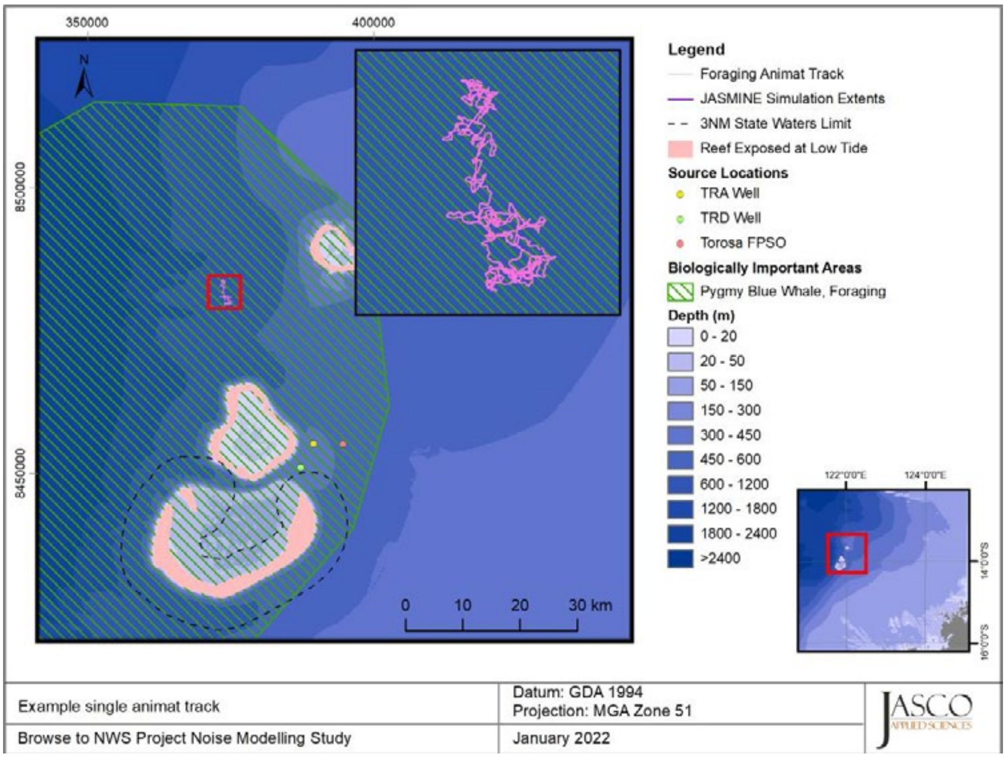

Figure 7. Overview of an example animat track.

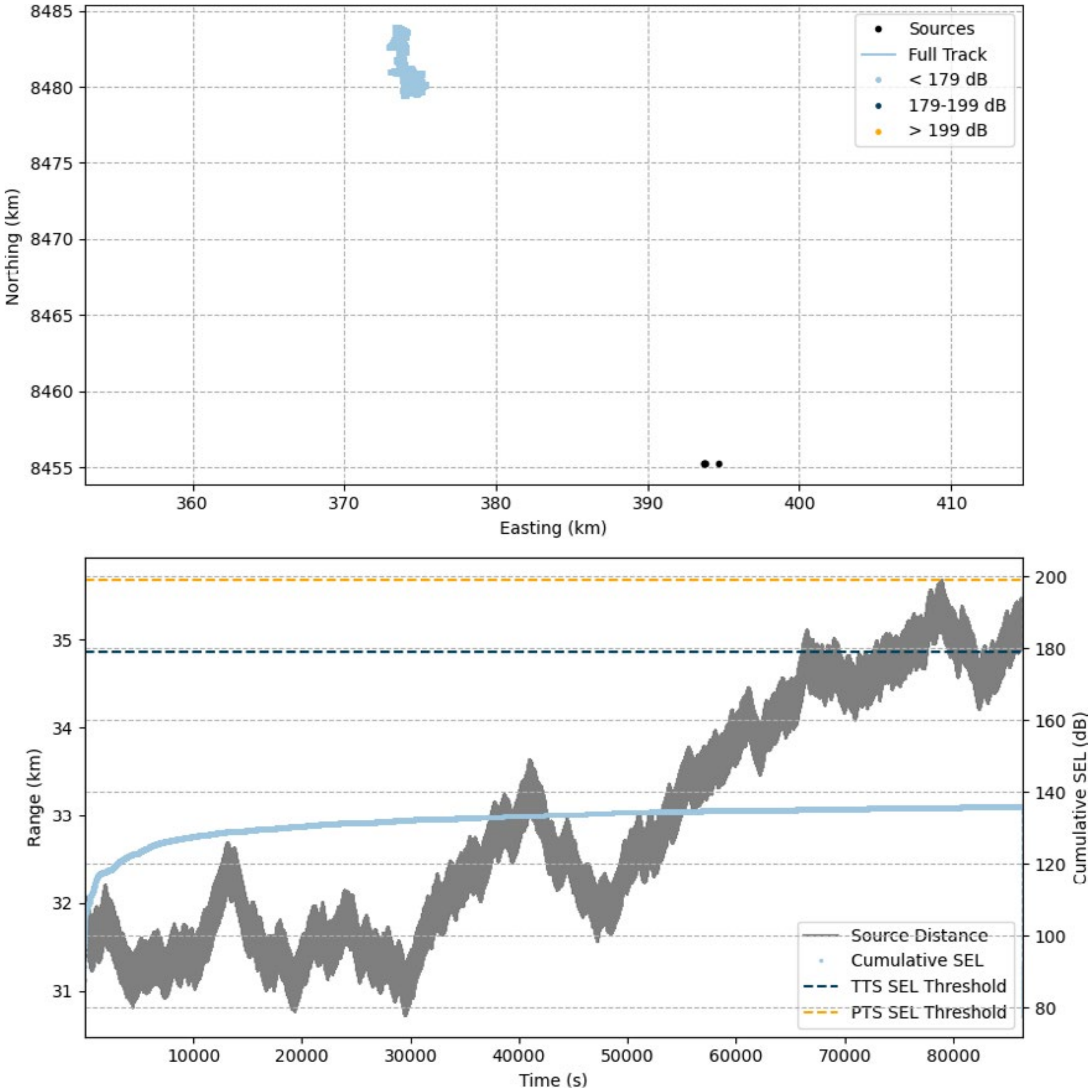

Figure 8. Example animat track from a foraging animat during Scenario 9. TTS and PTS thresholds refer to the criteria for effects of non-impulsive noise exposure on low-frequency cetaceans.

5. Discussion

This animal movement and exposure analysis was done to predict the effects of the development and installation operations for specific scenarios relating to the operation of an MODU under DP at the TRD drill centre, the FPSO at the Torosa location and the aggregate of both activities on both migrating and foraging pygmy blue whales. Exposure ranges for the 120 dB SPL behavioural response threshold aligned with those predicted by acoustic modelling, although the foraging exposure ranges were consistently slightly longer than those calculated for migrating animats. Ranges to PTS and TTS thresholds were minimal for both migrating and foraging behaviours.

Similar to the results presented in the acoustic modelling, exposure ranges for TTS, PTS and behavioural response during the aggregate scenario were not significantly different than during the individual operations (Green et al. 2021). The sites are far enough apart that their summed fields do not contribute to a quantifiable increase in the affected areas.

There was no significant difference between the predicted exposure ranges for northward versus southward migration. While the presence of the reef did influence the movement of the animats near the development area, the distribution of individual animats was not greatly restricted or modified within the TTS, PTS, and behavioural ranges of the sources. The histograms of CPA ranges for these behaviours (Figures 4 and 5) have a similar shape and predict similar exposure ranges, but because the reef effectively blocks a substantial portion of northbound animats from reaching the source area, the number of exposed animats is lower.

For the aggregate scenario (Scenario 9), the probability of exposure (P_{exp}) within $ER_{95\%}$ for the TTS SEL_{24h} threshold (≤0.05 km) varied between 34 and 41%. Within $ER_{95\%}$ for the PTS SEL_{24h} threshold (<0.01 km), P_{exp} varied between 0 and 12%. For behavioural SPL threshold, P_{exp} within $ER_{95\%}$ (<2.3 km) varied between 80 and 90%. These results indicate that some, but not all, animats exposed within the $ER_{95\%}$ were exposed above threshold. This is because the received level at any given position is a function of not only the range to the source but also the vertical position in the water column and the overall path that the animat traversed through the three-dimensional sound field. For example, an animat might approach within the predicted exposure range but if they are traveling more quickly on average than other animats, they may not accumulate as much exposure, or they may be spending more time at depths with quieter sound levels.

5.1. Behavioural effects

Exposure ranges for single exposure metrics, such as the SPL behavioural response criteria, are typically comparable to the predicted acoustic ranges. Acoustic ranges are conservatively calculated using the maximum-over-depth sound fields while exposure ranges account for animats sampling the water column vertically. Because of this, exposure ranges will typically be slightly lower than the corresponding acoustic ranges.

For the behavioural threshold, the maximum $ER_{95\%}$ was 2.78 km. This aligns with the $R_{95\%}$ and R_{max} ranges from static acoustic modelling which were 2.54 km and 4.68 km, respectively. The $ER_{95\%}$ for the 120 dB behavioural threshold was consistently longer for foraging than for migrating pygmy blue whales. This is due to the behavioural profiles of the animats and the way in which they sampled the water column vertically. Migrating animats spend most of their time doing relatively shallow dives that keep them in the upper 30-60 m of the water column, where predicted received levels are lower (see Figure 9).

Although foraging animats may spend a greater amount of time in any given area due to their slower swimming speed and higher course variation (Figure 7), they perform deeper dives than migrating animats (average 312±80m and 30±31m, respectively) and spend more time at those depths.

Therefore, the foraging animats are, on average, exposed to received levels that exceed the behavioural threshold at longer ranges.

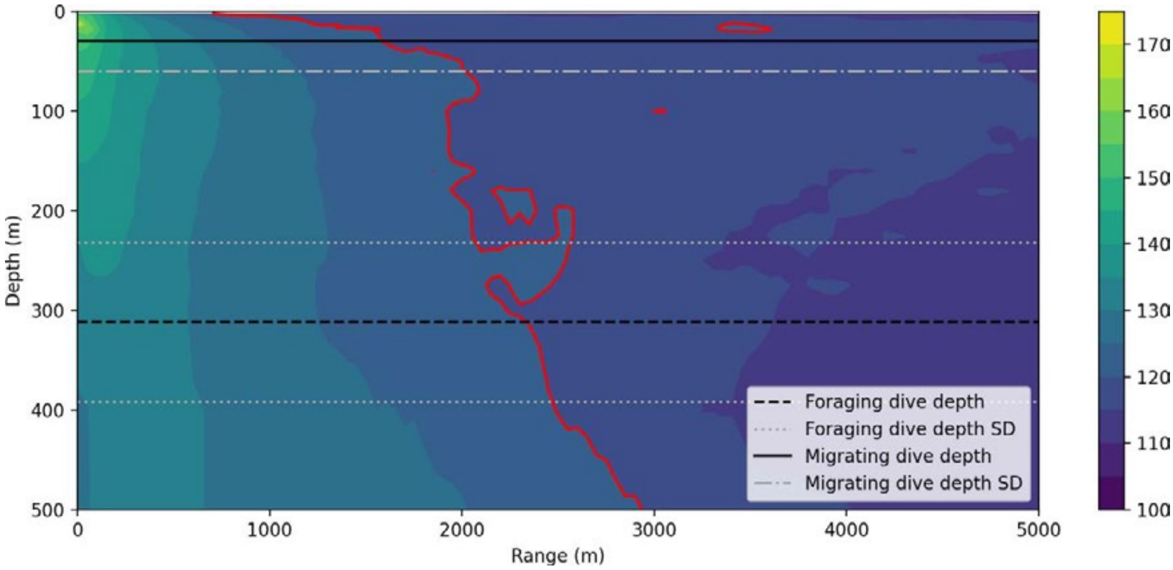

Figure 9. Slice plot showing a profile of the summed SPL sound levels interpolated along a profile centred on the TRD MODU location and extending outward at an azimuth of 45°. The 120 dB contour level is highlighted in red.

5.2. TTS and PTS

Exposure ranges from animal movement modelling for cumulative metrics such as TTS and PTS are typically shorter than those predicted using acoustic propagation modelling because of the shorter dwell time of the moving animats. Results for all scenarios aligned with this pattern, with all exposure ranges being shorter than the corresponding acoustic ranges. In some cases, particularly for Scenario 7 wherein only the FPSO machinery was modelled, there were no animats exposed above threshold, and both PTS and TTS exposure ranges were effectively zero. For the aggregate scenario (Scenario 9), the maximum $ER_{95\%}$ for SEL_{24h} thresholds was ≤0.05 km for TTS and ≤0.01 for PTS, compared to <0.53 km and <0.05 km respectively for the static acoustic modelling. Note that TTS and PTS ranges may be less than the minimum range step in the acoustic model because animats sample the area at a finer resolution.

Glossary

Unless otherwise stated in an entry, these definitions are consistent with ISO 80000-3 (2017).

animal movement modelling

Simulation of animal movement based on behavioural rules for the purpose of predicting an animal's experience of an environment.

auditory frequency weighting

The process of applying an auditory frequency weighting function. In human audiometry, C-weighting is the most commonly used function, an example for marine mammals are the auditory frequency weighting functions published by Southall et al. (2007).

auditory frequency weighting function

Frequency weighting function describing a compensatory approach accounting for a species' (or functional hearing group's) frequency-specific hearing sensitivity. Example hearing groups are low-, mid-, and high-frequency cetaceans, phocid and otariid pinnipeds.

cetacean

Any animal in the order Cetacea. These are aquatic species and include whales, dolphins, and porpoises.

continuous sound

A sound whose sound pressure level remains above ambient sound during the observation period. A sound that gradually varies in intensity with time, for example, sound from a marine vessel.

decibel (dB)

Unit of level used to express the ratio of one value of a power quantity to another on a logarithmic scale. Unit: dB.

flat weighting

Term indicating that no frequency weighting function is applied. Synonymous with unweighted.

frequency weighting

The process of applying a frequency weighting function.

frequency-weighting function

The squared magnitude of the sound pressure transfer function. For sound of a given frequency, the frequency weighting function is the ratio of output power to input power of a specified filter, sometimes expressed in decibels. Examples include the following:

- *Auditory frequency weighting function*: compensatory frequency weighting function accounting for a species' (or functional hearing group's) frequency-specific hearing sensitivity.
- *System frequency weighting function*: frequency weighting function describing the sensitivity of an acoustic acquisition system, typically consisting of a hydrophone, one or more amplifiers, and an analogue to digital converter.

geoacoustic

Relating to the acoustic properties of the seabed.

hearing group

Category of animal species when classified according to their hearing sensitivity and to the susceptibility to sound. Examples for marine mammals include very low-frequency (VLF) cetaceans, low-frequency (LF) cetaceans, mid-frequency (MF) cetaceans, high-frequency (HF) cetaceans, very high-frequency (VHF) cetaceans, otariid pinnipeds in water (OPW), phocid pinnipeds in water (PPW), sirenians (SI), other marine carnivores in air (OCA), and other marine carnivores in water (OCW) (NMFS 2018, Southall et al. 2019). See **auditory frequency weighting functions**, which are often applied to these groups. Examples for fish include species for which the swim bladder is involved in hearing, species for which the swim bladder is not involved in hearing, and species without a swim bladder (Popper et al. 2014).

level

A measure of a quantity expressed as the logarithm of the ratio of the quantity to a specified reference value of that quantity. Examples include sound pressure level, sound exposure level, and peak sound pressure level. For example, a value of sound exposure level with reference to 1 μPa^2 s can be written in the form *x* dB re 1 μPa^2 s.

low-frequency (LF) cetacean

See **hearing group**.

non-impulsive sound

Sound that is not an impulsive sound. A non-impulsive sound is not necessarily a continuous sound.

permanent threshold shift (PTS)

An irreversible loss of hearing sensitivity caused by excessive noise exposure. PTS is considered auditory injury.

pressure, acoustic

The deviation from the ambient pressure caused by a sound wave. Also called sound pressure. Unit: pascal (Pa).

received level

The level measured (or that would be measured) at a defined location. The type of level should be specified.

reference values

standard underwater references values used for calculating sound **levels**, e.g., the reference value for expressing sound pressure level in decibels is 1 μPa.

Quantity	Reference value
Sound pressure	1 μPa
Sound exposure	1 μPa^2 s
Sound particle displacement	1 pm
Sound particle velocity	1 nm/s
Sound particle acceleration	1 μm/s^2

sound

A time-varying disturbance in the pressure, stress, or material displacement of a medium propagated by local compression and expansion of the medium.

sound exposure

Time integral of squared sound pressure over a stated time interval. The time interval can be a specified time duration (e.g., 24 hours) or from start to end of a specified event (e.g., a pile strike, an airgun pulse, a construction operation). Unit: Pa^2 s.

sound exposure level

The level (L_E) of the sound exposure (E). Unit: decibel (dB). Reference value (E_0) for sound in water: 1 μPa^2 s.

$$L_E := 10 \log_{10}(E/E_0)\ \mathrm{dB} \ = 20 \log_{10}\left(E^{1/2}/E_0^{1/2}\right)\ \mathrm{dB}$$

The frequency band and integration time should be specified. Abbreviation: SEL.

sound field

Region containing sound waves.

sound pressure

The contribution to total pressure caused by the action of sound.

sound pressure level (rms sound pressure level)

The level ($L_{p,\mathrm{rms}}$) of the time-mean-square sound pressure (p^2_{rms}). Unit: decibel (dB). Reference value (p_0^2) for sound in water: 1 μPa^2.

$$L_{p,\mathrm{rms}} := 10 \log_{10}(p^2_{\mathrm{rms}}/p_0^2)\ \mathrm{dB} \ = 20 \log_{10}(p_{\mathrm{rms}}/p_0)\ \mathrm{dB}$$

The frequency band and averaging time should be specified. Abbreviation: SPL or Lrms.

temporary threshold shift (TTS)

Reversible loss of hearing sensitivity. TTS can be caused by noise exposure.

unweighted

Term indicating that no frequency weighting function is applied. Synonymous with flat weighting.

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Appendix C - Woodside Browse to NWS Vessel Animat Modelling (Cusano et al 2022)

Appendix A. Animal Movement and Exposure Modelling

Animal movement and exposure modelling considers the movement of both sound sources (if mobile) and animals over time. Acoustic source and propagation modelling are used to generate 3-D sound fields that vary as a function of distance to source, depth, and azimuth. Sound sources are modelled at representative sites and the resulting sound fields are assigned to source locations using the minimum Euclidean distance. The sound received by an animal at any given time depends on its location relative to the source. Because the true locations of the animals within the sound fields are unknown, realistic animal movements are simulated using repeated random sampling of various behavioural parameters. The Monte Carlo method of simulating many animals within the operations area is used to estimate the sound exposure history of the population of simulated animals (animats).

Monte Carlo methods provide a heuristic approach for determining the probability distribution function (PDF) of complex situations, such as animals moving in a sound field. The probability of an event's occurrence is determined by the frequency with which it occurs in the simulation. The greater the number of random samples, in this case the more simulated animats, the better the approximation of the PDF. Animats are randomly placed, or seeded, within the simulation boundary at a specified density (animats/km^2). Higher densities provide a finer PDF estimate resolution but require more computational resources. To ensure good representation of the PDF, the animat density is set as high as practical allowing for computation time. The animat density is much higher than the real-world density to ensure good representation of the PDF. The resulting PDF is scaled using the real-world density.

Several models for marine mammal movement have been developed (Ellison et al. 1987, Frankel et al. 2002, Houser 2006). These models use an underlying Markov chain to transition from one state to another based on probabilities determined from measured swimming behaviour. The parameters may represent simple states, such as the speed or heading of the animal, or complex states, such as likelihood of participating in foraging, play, rest, or travel. Attractions and aversions to variables like anthropogenic sounds and different depth ranges can be included in the models.

The JASCO Animal Simulation Model Including Noise Exposure (JASMINE) was based on the open-source marine mammal movement and behaviour model (3MB, Houser 2006) and used to predict the exposure of animats to sound arising from the anthropogenic activities. Animats are programmed to behave like the species likely to be present in the survey area. The parameters used for forecasting realistic behaviours (e.g., diving, foraging, aversion, surface times, etc.) are determined and interpreted from marine species studies (e.g., tagging studies) where available, or reasonably extrapolated from related species. An individual animat's modelled sound exposure levels are summed over the total simulation duration to determine its total received energy, and then compared to the assumed threshold criteria.

JASMINE uses the same animal movement algorithms as 3MB (Houser, 2006), but has been extended to be directly compatible with JASCO's Marine Operations Noise Model (MONM) and Full Waveform Range-dependent Acoustic Model acoustic field predictions, for inclusion of source tracks, and importantly for animats to change behavioural states based on time and space dependent modelled variables such as received levels for aversion behaviour, although aversion was not considered in this study.

A.1.1. Animal Movement Parameters

JASMINE uses previously measured behaviour to forecast behaviour in new situations and locations. The parameters used for forecasting realistic behaviour are determined (and interpreted) from marine species studies (e.g., tagging studies). Each parameter in the model is described as a probability distribution. When limited or no information is available for a species parameter, a Gaussian or uniform distribution may be chosen for that parameter. For the Gaussian distribution, the user determines the mean and standard deviation of the distribution from which parameter values are drawn. For the uniform distribution, the user determines the maximum and minimum distribution from which parameter values are drawn. When detailed information about the movement and behaviour of a species are available, a user-created distribution vector, including cumulative transition probabilities, may be used (referred to here as a vector model; Houser 2006). Different sets of parameters can be defined for different behaviour states. The probability of an animat starting out in or transitioning into a given behaviour state can in turn be defined in terms of the animat's current behavioural state, depth, and the time of day. In addition, each travel parameter and behavioural state has a termination function that governs how long the parameter value or overall behavioural state persists in simulation.

The parameters used in JASMINE describe animal movement in both the vertical and horizontal planes. The parameters relating to travel in these two planes are briefly described below.

Travel sub-models

- **Direction**– determines an animat's choice of direction in the horizontal plane. Sub-models are available for determining the heading of animats, allowing for movement to range from strongly biased to undirected. A random walk model can be used for behaviours with no directional preference, such as feeding and playing. In a random walk, all bearings are equally likely at each parameter transition time step. A correlated random walk can be used to smooth the changes in bearing by using the current heading as the mean of the distribution from which to draw the next heading. An additional variant of the correlated random walk is available that includes a directional bias for use in situations where animals have a preferred absolute direction, such as migration. A user-defined vector of directional probabilities can also be input to control animat heading. For more detailed discussion of these parameters, see Houser (2006) and Houser and Cross (1999).
- **Travel rate**–defines an animat's rate of travel in the horizontal plane. When combined with vertical speed and dive depth, the dive profile of the animat is produced.

Dive sub-models

- **Ascent rate**–defines an animat's rate of travel in the vertical plane during the ascent portion of a dive.
- **Descent rate**–defines an animat's rate of travel in the vertical plane during the descent portion of a dive.
- **Depth**–defines an animat's maximum dive depth.
- **Reversals**–determines whether multiple vertical excursions occur once an animat reaches the maximum dive depth. This behaviour is used to emulate the foraging behaviour of some marine mammal species at depth. Reversal-specific ascent and descent rates may be specified.
- **Surface interval**–determines the duration an animat spends at, or near, the surface before diving again.

A.1.2. Exposure Integration Time

The interval over which acoustic exposure (L_E) should be integrated and maximal exposure (L_p) determined is not well defined. Both Southall et al. (2007) and the NMFS (2018) recommend a 24 h baseline accumulation period, but state that there may be situations where this is not appropriate (e.g., a high-level source and confined population). Resetting the integration after 24 h can lead to overestimating the number of individual animals exposed because individuals can be counted multiple times during an operation. The type of animal movement engine used in this study simulates realistic movement using swimming behaviour collected over relatively short periods (hours to days) and does not include large-scale movement such as migratory circulation patterns. For this study, a representative 24-hour period was simulated.

Ideally, a simulation area is large enough to encompass the entire range of a population so that any animal that could approach the source during an operation is included. However, there are limits to the simulation area, and computational overhead increases with area. For practical reasons, the simulation area is limited. In the simulation, every animat that reaches a border is replaced by another animat entering at the opposing border—e.g., an animat crossing the northern border of the simulation is replaced by one entering the southern border at the same longitude. When this action places the animat in an inappropriate water depth, the animat is randomly placed on the map at a depth suited to its species definition. The exposures of all animats (including those leaving the simulation and those entering) are kept for analysis. This approach maintains a consistent animat density and allows for longer integration periods with finite simulation areas.

A.1.3. Seeding Density and Scaling

Seeding density refers to the spatial sample rate, in units of animats/ km^2, used in the simulation. It is not related to the real-world animal density, but rather is a model parameter that controls the how samples are drawn from the model space. The minimum required seeding density for any given project depends on several factors such as bathymetry, source characteristics, and the behavioural profile of the animats, with the main constraint being computation time and resources. Seeding density is adjusted as needed based on model conditions specific to a project or project area.

In the present study, the exposure criteria for continuous sounds were used to determine the number of animats exceeding exposure thresholds. To generate statistically reliable probability density functions, all simulations were seeded with an animat density of 3 animat/km^2 over the entire simulation area. The modelling results are not related to real-world pygmy blue whale densities and the number of real-world animals potentially exposed was not calculated.