Blue Whale Acoustic Monitoring Report

Detailed Analysis of Blue Whale Presence on the North West Shelf, April 2023 – September 2024

JASCO Applied Sciences (Australia) Pty Ltd

20 August 2025

Submitted to:

Woodside Energy Limited

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P001735-001
Document 03879
Version 3.0

Suggested citation:

Delarue, J.J.-Y., Kowarski K.A., L.A.E Huijser, C.C. Wilson, T.J. Stephens, A.L. Richardson, and C.R. McPherson. 2025. Blue Whale Acoustic Monitoring Report: Detailed Analysis of Blue Whale Presence on the North West Shelf, April 2023 – September 2024. Document 03879, Version 3.0. Technical report by JASCO Applied Sciences for Woodside Energy Limited.

Report approved by:

Version	*Role*	*Name*	*Date*
3.0	Project Manager	Craig McPherson	20 August 2025
2.0	Project Manager	Craig McPherson	28 July 2025
1.0	Senior Scientific Reviewer	Julien Delarue	14 June 2025

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Executive Summary

JASCO Applied Sciences (Australia) Pty Ltd (JASCO) was contracted by Woodside Energy Limited (Woodside) to conduct an acoustic monitoring program on the North West Shelf (NWS), with stations deployed at Scott Reef and North West Cape, off Western Australia. The primary purposes of the program were to provide information on the presence of Eastern Indian Ocean (EIO) pygmy blue whales (*Balaenoptera musculus brevicauda*) and to characterise the soundscape and the acoustic presence of other marine mammal species in the area. EIO pygmy blue whales have breeding grounds in Indonesia and feeding grounds around the subtropical frontal zone off southern and south-western Australia (Double et al. 2014). The pygmy blue whale migration corridor passes along the west coast of Australia, including through areas monitored in this program (Scott Reef and North West Cape) and is classified as a Biologically Important area (BIA).

This report focuses on the acoustic presence of blue whales and presents the results of the analysis of acoustic data collected at the following monitoring locations:

- **West Scott Reef Station** (West Scott Reef), located at an average depth of 548 m west of Scott Reef and within the pygmy blue whale migration and foraging BIAs.
- **East Scott Reef Station** (East Scott Reef), located at an average depth of 497 m east of Scott Reef and also within the pygmy blue whale migration and foraging BIAs.
- **North West Cape Station** (North West Cape)**,** located off the North West Cape at an average depth of 534 m near the NWS shipping lanes, within the pygmy blue whale migration BIA and adjacent to the foraging BIA to the south.
- **South Scott Reef Station** (South Scott Reef). After the first 12 monitoring months, the North West Cape station was moved to south of Scott Reef at an average depth of 590 m, within the migration BIA but just outside of the foraging BIA.

The program commenced in April 2023, with servicing and redeployments occurring at 6-month intervals in September 2023 and March 2024. Overall, 14 marine mammal species or species groups were detected, including both EIO pygmy blue whales and Antarctic blue whales (*B. m. intermedia*).

EIO pygmy blue whale song occurrence was remarkably similar at the three Scott Reef stations. Pygmy blue whale songs were manually confirmed around Scott Reef in all months of the recording year except February and March (spot checking of automated detections during these months found no valid detections). Songs were detected in at least 50% of days per month in all months except February, March, September and October at West Scott Reef while East Scott Reef saw reduced acoustic occurrence in September and in January, with the first confirmed detection after this on 13 April 2024. South Scott Reef had no song detections in March, but saw sustained acoustic presence (>70% detection-positive days) from April to September 2024. Song detections occurred almost year-round at the North West Cape station, however there was a notable absence in September, and July and August had less than 50% detection-positive days (35-42%) – during these months vessel presence influenced detector performance. There was seemingly no diel trend in pygmy blue whale song occurrence, with songs present throughout all hours of the day, which is expected from a migratory mysticete.

Pygmy blue whale non-song vocalisations (which includes social calls) generally followed the same occurrence trends as pygmy blue whale songs. However, the monthly proportion of detection-positive days was consistently lower for non-song calls than songs, with the exception of January and February 2024 at East Scott Reef. In addition, non-song calls were systematically detected in fewer hours per day than songs. All Scott reef stations considered, non-song vocalisations were manually confirmed at least once in all months – except East Scott Reef in September 2023. The monthly proportions of detection-positive days show more inter-month variability than for songs, with the highest detection rates occurring in June and November at all stations. Similar to song, there was no evidence of a diel trend in pygmy blue whale non-song vocalisations' occurrence, with the signals present throughout all hours of the day. One of the most commonly detected non-song vocalisations, the D-call, is commonly associated with foraging and social interactions and produced by male and female animals from all blue whale populations. The non-song detections typically detected the D-call and EIO-1 calls, experienced analysts confirmed the association of these calls to blue whales based upon contextual information within the file, in addition to the individual vocalisation characteristics. This suggests that the use of the monitored areas, Scott Reef in particular, for foraging activities cannot be ruled out for the periods when non-song vocalisations occurred.

Pygmy blue whale detections associated with the northbound migration stopped earlier at North West Cape, as suggested by the drop in the proportion of detection-positive days happening a month earlier than at Scott Reef, which is consistent with the location of this station in the context of the migratory path. During the southbound migration, the rate of detections increased generally around the same time at all Scott Reef stations. The rate of song detections increased at North West Cape prior to the increase at Scott Reef. The duration of the period when detections was higher for pygmy blue whales in general was substantially longer off North West Cape. The results to date strongly indicate that only a proportion of the whales migrating past North West Cape migrate via Scott Reef, with the rest taking an alternative migratory path, with some of these whales migrating south to the west of Timor Leste and significantly further to the west of Scott Reef (Mustika et al. 2024).

Antarctic blue whales were primarily detected from April to June with a peak in May (90% detection-positive days) at station North West Cape, with a few additional sporadic detection events between July and October. Isolated manual detections occurred between May and September near Scott Reef, primarily at station West Scott Reef.

1. Introduction

1.1. Project Background

JASCO Applied Sciences (Australia) Pty Ltd (JASCO) was contracted by Woodside Energy Limited (Woodside) to conduct an acoustic monitoring program on the North West Shelf, with stations deployed at Scott Reef and North West Cape, off Western Australia. The primary purposes of the program were to provide information on the presence of Eastern Indian Ocean (EIO) pygmy blue whales (*Balaenoptera musculus brevicauda*) and to characterise the acoustic presence of other marine mammal species in the area.

To achieve these objectives, the first year of the program was delivered via three Autonomous Long-Term Observatory (ALTO) landers being deployed (Figures 1 and 2), for two periods of six months at three stations: West Scott Reef, East Scott Reef, and North West Cape. This positioned stations at both ends of the North West Shelf and allowed the EIO pygmy blue whale migration to be characterised across it. After a year was completed, the North West Cape station was moved to a new location south of Scott Reef (South Scott Reef) for Monitoring Period 3. Monitoring Period 1 spanned from April to September 2023, Monitoring Period 2 from September 2023 to March 2024, and Monitoring Period 3 from March to September 2024.

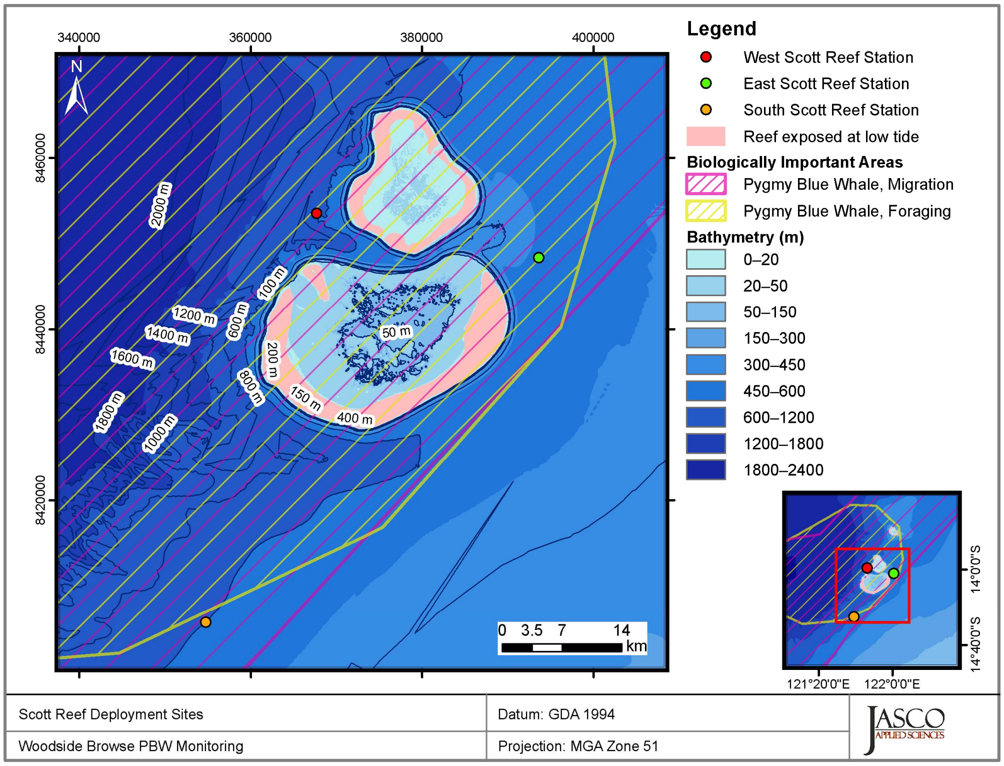


Figure 1. Monitoring Periods 1, 2 and 3: Scott Reef, Western Australia: Map of locations of the acoustic recorders (ALTO mooring systems) including Biologically Important Areas for pygmy blue whales. South Scott Reef Station was only present for Monitoring Period 3.

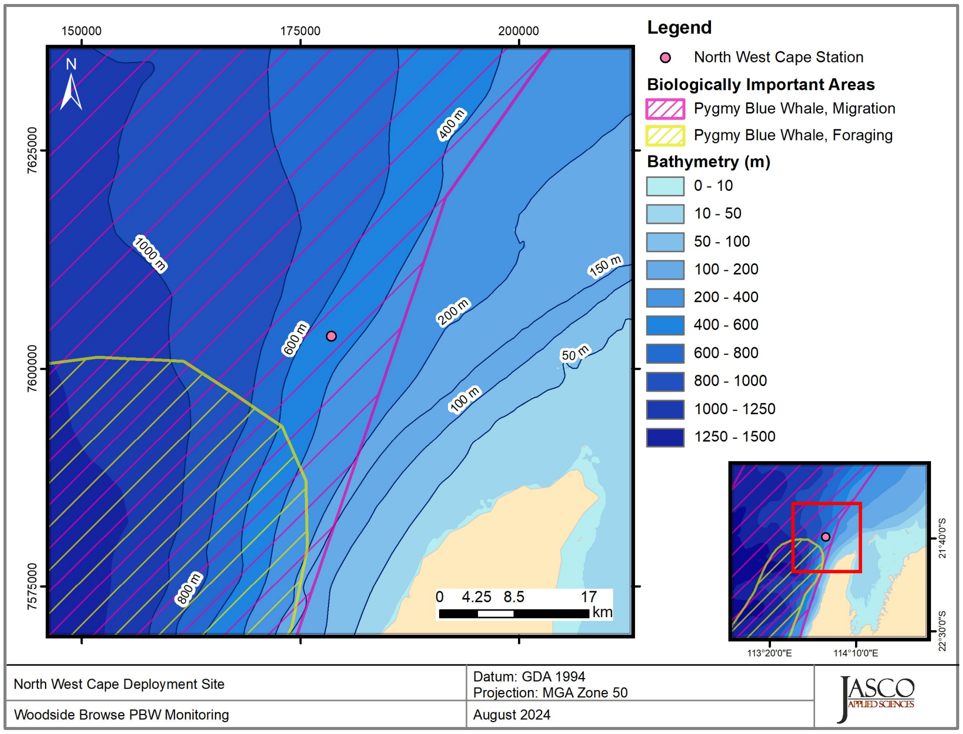


Figure 2. Monitoring Periods 1 and 2: North West Cape, Western Australia: Map of location of the acoustic recorder (ALTO mooring system) including Biologically Important Areas for pygmy blue whales.

1.2. Marine Biological Sound and Species in Western Australia

The long-term monitoring of marine species in remote areas is challenging but important for understanding the temporal and spatial distributions of animals and for designing conservation measures for species at risk. Visual monitoring techniques are important, but they can be spatially and temporally limited, and they rely on good visibility conditions. Given that most marine mammals produce sounds underwater, acoustic monitoring is generally an effective way to monitor for the presence of multiple species of marine mammals in remote environments year-round. Compared to visual techniques, acoustic monitoring is unaffected by visibility and depends less on weather conditions. However, acoustic monitoring requires animals to make sounds, and those sounds must be sufficiently loud to be detected. Because not all species vocalise regularly and vocalisation activity often depends on context such as behaviour and season, acoustic monitoring effectiveness varies by species and seasonally.

Biological sources of sound are diverse, and many marine taxa produce sounds. Animals that are known to produce acoustic signals include crustaceans, fish, and marine mammals. Biophonic signals include those generated for communicating, navigating, breeding, and foraging by sound-producing species. Marine mammals have received the most attention in terms of the description of their vocal repertoire and acoustic behaviour.

For an acoustic recording device to detect a marine mammal vocalisation, its received amplitude at the monitoring location must be above background noise levels in at least one of the vocalisation's frequency bands (although some more complex acoustic systems can detect sounds below background noise level). The distance over which vocalisations can be detected consequently depends on the background sound levels, source levels of the vocalisation (which often vary by season, sex, etc.), calling depth of the animal, and acoustic propagation properties of the environment. Background or ambient sound levels vary due to fluctuations in natural sounds (e.g., wind, precipitation, waves, seismic activity, and biologic activity) and anthropogenic sounds (mainly vessels but also marine construction and oil and gas exploration). Acoustic propagation also varies seasonally due to changing temperature and salinity properties of the water column.

The acoustic signal characteristics of some marine mammal species that may be present off Western Australia are well described in the scientific literature, while others are less understood with limited confirmed recordings and vocalisation descriptions. For those with inadequate signal descriptions, reliable systematic manual identification and automated detector processing of large data sets are challenging, simply because it is difficult to associate the species with the sounds observed. Even when the signals of a species have been described, similarities with the signals of related species can prevent positive identification. This is often the case with oceanic delphinids. Table 1 summarises the sounds produced by blue whales, which produce the same or similar types of calls across their range, specific descriptions of their vocal repertoire are not always available for Western Australia.

Table 1. List of vocalisations that have been described for blue whales and non-exhaustive list of supporting scientific publications.

Species	Vocalisations Described	Reference(s)
	Baleen whales	
Antarctic blue whale	Song (Z calls) and D calls/Downsweeps	Cummings and Thompson (1971), Stafford et al. (2004), McDonald et al. (2006), Gavrilov et al. (2011), Gavrilov et al. (2012), Recalde-Salas et al. (2014), Jolliffe et al. (2019), Leroy et al. (2021), Miller et al. (2021a), Miller et al. (2021b), Warren et al. (2021)
Pygmy blue whale	Song and D calls/Downsweeps	

1.2.1. Blue Whales

Two sub-species of blue whale frequent the waters of Western Australia: EIO pygmy blue whales and Antarctic blue whales. EIO pygmy blue whales have breeding grounds in Indonesia and feeding grounds around the subtropical frontal zone off southern and south-western Australia (Double et al. 2014, Thums et al. 2022). The pygmy blue whale migration corridor passes along the west coast of Australia and is classified as a BIA (Figure 1). Table 2 summarises the seasonal movements of pygmy blue whales in the study area based on Double et al. (2014), McCauley and Jenner (2010) and Commonwealth of Australia (2015). They are likely to be present from April to July during the northbound migration and from October to January during the southbound migration.

Table 2. Annual timeline of EIO pygmy blue whale movements and seasons based on Double et al. (2014), McCauley and Jenner (2010), Commonwealth of Australia (2015). Dark orange indicates the peak period of occurrence. Light orange indicates shoulder seasons with lower expected occurrence.

Migration direction [1]	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Northern				▒	🟧	🟧	▒					
Southern	▒									▒	🟧	🟧

[1] Exmouth, Montebello, and Scott Reef

Antarctic blue whales are also a migratory species, with summer feeding grounds around the Antarctic continent and winter breeding grounds in warmer waters at lower latitudes (Branch et al. 2007). Antarctic blue whale songs have been detected off Western Australia from May to October, although primarily off southwestern and southern Australia (Stafford et al. 2004, Tripovich et al. 2015, McCauley et al. 2018). There are only sporadic records of Antarctic blue whale acoustic detections off northwest Australia (JASCO, unpublished data; McCauley (2011)). It has been established that not all Antarctic blue whales migrate every year (Leroy et al. 2016, Thomisch et al. 2016) and there is the possibility of their presence in Australian waters outside of this seasonal window.

Regardless of population or sub-species identity, the blue whale vocal repertoire can be broadly split into two main categories of sounds: those assembled in stereotyped sequences called songs and all others that are not produced as part of songs, which we will refer to as non-song vocalisations. The latter have, for some populations or sub-species, been further divided in distinct call types. Sections 1.2.1.1 and 1.2.1.2 provide detailed description of these song and non-song vocalisations while Section 1.2.1.3 describe the state of knowledge on the type of behaviours associated with the production of non-song vocalisations.

1.2.1.1. Song

Blue whales are known to produce stereotypical sequences of vocalisations that meet the criteria of song. These songs are made up of units that are organised into phrases and repeated for extended periods of times (McDonald et al. 2006, Jolliffe et al. 2019). Blue whale song phrases are typically comprised of only one to four song units, with some level of variability in the production of these units and phrases between the songs of individual animals (Jolliffe et al. 2019, Jolliffe et al. 2023, 2024). While the individual units that comprise songs have been observed being produced by both male and female animals, only males have been observed to arrange their units into phrases and produce them in repetitive song sequences. Songs are thus assumed to be a reproductive display, produced by males to attract females and mediate interactions with other males, consistent with the use of song in other baleen whales and singing animals (Cholewiak et al. 2018, Jolliffe et al. 2019).

The acoustic properties of blue whale song units, which are stereotypically loud and low frequency, mean that signals propagate over vast distances. Song is also population-specific, enabling different populations of blue whales, that are virtually indistinguishable visually, to be identified. Such characteristics make listening for blue whale songs an efficient and effective way of monitoring populations. To date, the body of research into blue whales has been dominated by passive acoustic based research programs and focused largely on using song to identify populations, and their spatial and temporal distributions (McDonald et al. 2006). While this approach has been incredibly valuable, studies focused solely on song may only be representative of a portion of the population, being sexually mature males.

Singing, defined as the structured and repetitive production of song units and phrases is produced during shallow, non-lunging dives, and was typically associated with travelling behaviour (Oleson et al. 2007a, Lewis et al. 2018). Both papers reported that singing rates were highest in autumn, and typically during the evening and night. Visual observations of singing blue whales suggested steady movement in a consistent direction, with no lunge feeding dives on the tag recorded immediately before or after song production (Lewis et al. 2018). Singing blue whales were also not observed to be in association with any other blue whales while they were singing, providing further evidence that song is a reproductive display intended to attract a mate (Oleson et al. 2007b).

Within Australia, three main blue whale sub populations/species are detected and acoustically differentiated based on their songs, Antarctic blue whales and two sub populations of pygmy blue whale – the Eastern Indian Ocean (EIO) and the New Zealand (NZ) (McDonald et al. 2006, McCauley et al. 2018).

The Antarctic blue whales produce a song made of a single note or unit known as the ‘Z’ call (Širović et al. 2004), which is named for its stereotyped shape when visualised as a spectrogram. The ‘Z’ shape starts around 26 Hz and ends at approximately 18 Hz, with a duration of approximately 20 s (Širović et al. 2004, Gavrilov et al. 2012) (Figure 3).

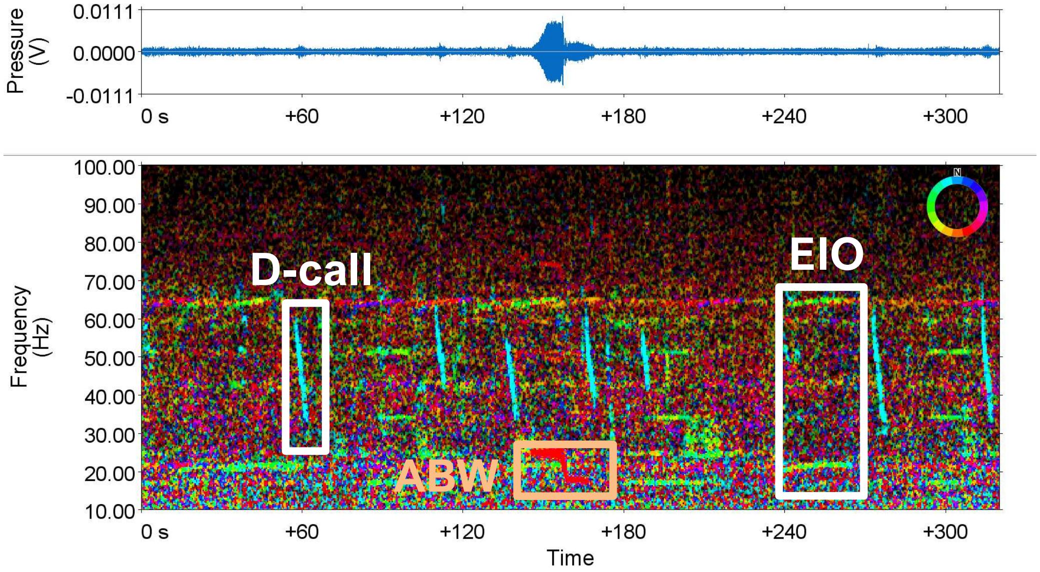


Figure 3. Spectrogram showing Antarctic blue whale (ABW) 'Z call', D-calls and EIO pygmy blue whale song recorded at Scott Reef. (0.4 Hz discrete Fourier Transform (DFT) frequency step, 2 ms DFT temporal observation window (TOW), 0.5 ms DFT time advance, and Hann window resulting in a 75 % overlap and DFT size (N_{DFT}) of 131072).

The EIO and NZ pygmy blue whale produce slightly more complex songs comprised of up to four units that are arranged into phrases and repeated (Gavrilov et al. 2011, Jolliffe et al. 2019, Leroy et al. 2021, Barlow 2022). The EIO is the primary blue whale song detected in Australian waters and in its characteristic form comprises a three unit phrase repeated in sequence. There is a high level of variability in the song production of this population with two and one unit phrases also being produced either in sequence alone or in combination with a different phase type (Jolliffe et al. 2019). There is also a high level of variability in the temporal characteristics of units and phrases, and the spectral appearance of units themselves (Jolliffe et al. 2023, Jolliffe et al. 2024).

Despite there being considerable variability in song production, the second unit of the EIO pygmy blue whale song remains a good target for automatic detection algorithms owing to its high source level, duration and strong fundamental frequency and harmonics (Jolliffe et al. 2019). Automatic detection algorithms typically focus on either the fundamental frequency or the 3rd harmonic of the unit, with performance of the algorithms typically very good, but influenced by the background noise conditions of the environment. While sampling only song biases sampling towards male animals only, the detection of song via automatic detection algorithms remains one of the most efficient and effective passive acoustic monitoring approaches. The efficacy of using song as a monitoring tool is also likely to be influenced by the time of year and environmental context. Outside of ambient noise conditions, the behavioural context of animals within a certain habitat will influence the efficacy of targeting song. Noting that singing behaviour is considered to be mutually exclusive with foraging, animals singing on foraging grounds likely do so at the expense of foraging – which for an animal with such high resource demands and such a limited diet is a considerable trade off (Oleson et al. 2007a, Lewis et al. 2018, Jolliffe et al. 2019). Thus, it is likely that singing while migrating represents a cost-effective strategy to attracting a mate, while singing on foraging grounds is likely to be more prevalent in the months leading up to the reproductive season, being the austral autumn and winter (Lewis et al. 2018, Jolliffe et al. 2019). Such nuances in calling behaviour are important considerations in the design of passive acoustic monitoring programs and the utilisation of their results for environmental management and species conservation planning.

The EIO pygmy blue whale song is characteristically long and low frequency and consists of a phrase of three units (sounds) repeated in a sequence with approximately 180–200 s (the value differs amongst years, below) between the start of one phrase and the start of the next (the ISI value). The first song unit (type I) is the longest with energy centred in the 20 Hz frequency band and harmonics up to 80 Hz. The type I unit starts with a 19 Hz tone that lasts for 21s before jumping to 21 Hz for a further 22 s. This is followed five to ten s later by the type II unit, a frequency modulated upsweep, which for example in 2010 swept upwards from 20 Hz to 26 Hz over a period of 23 s, with energy centred around 24.7 Hz and strong harmonics up to 72 Hz. The last unit of the song, type III, follows ~ 23 s later and is a constant frequency tone between 18 Hz and 19 Hz that lasts between 26 and 28 s. It is accompanied by strong harmonics and a secondary pulsed tone of 60–65 Hz. Recent studies have shown that the EIO pygmy blue whale song has a number of structural variations including shorter one and two part phrases repeated in song, as well as hybrid songs comprised of different length phrases (Jolliffe et al. 2019).

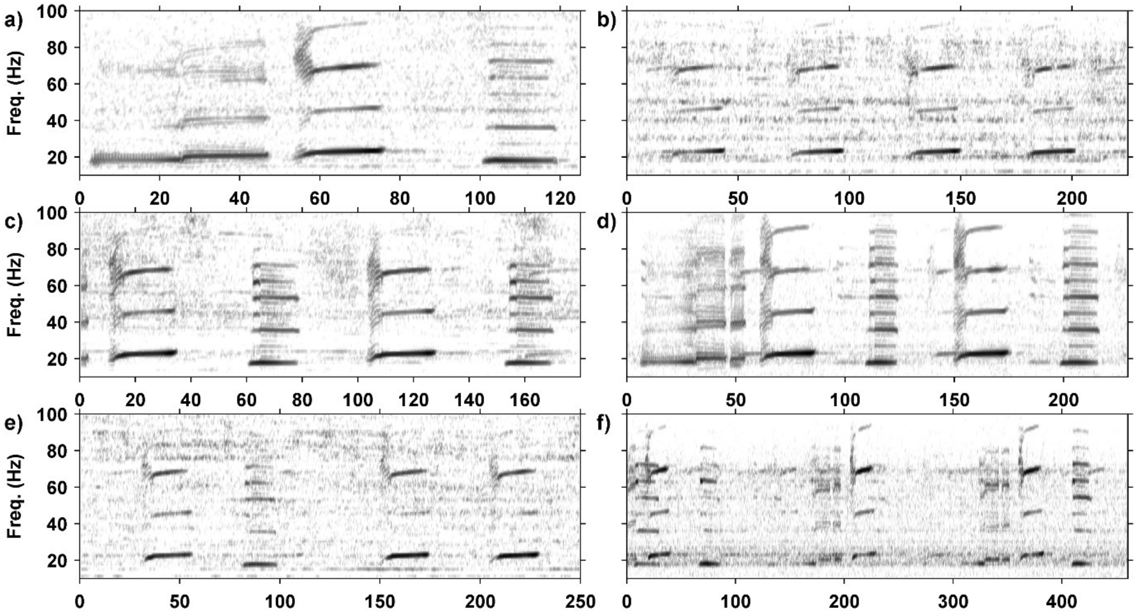
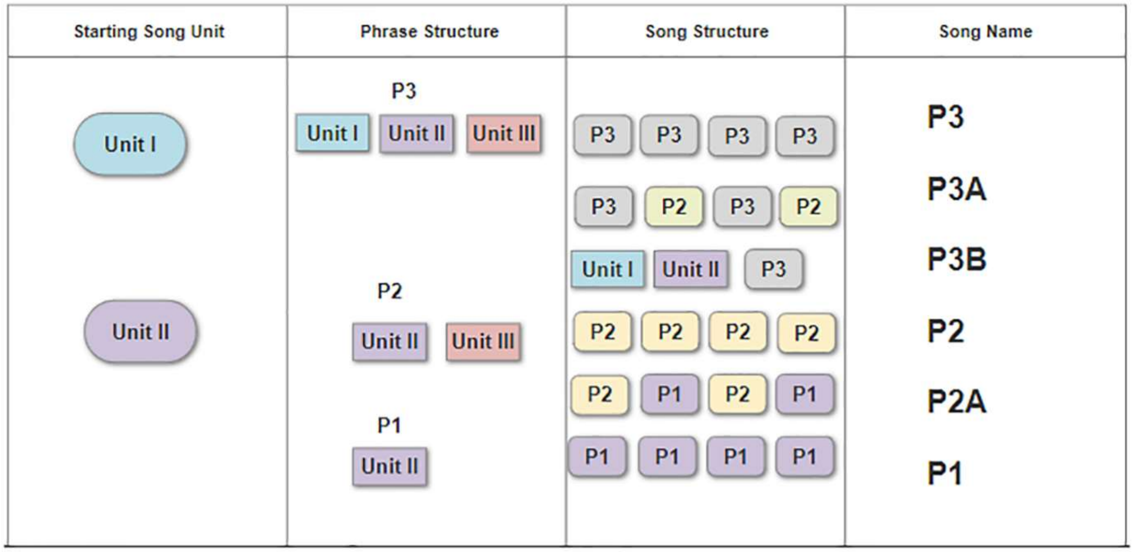


Figure 4. From Jolliffe et al. (2019): The song variations of the EIO pygmy blue whale. The three part P3 song (top left), one part P1 song (top right), two part P2 song (middle left), P3A song (middle right), P2A song (bottom left) and P3B song (bottom right). https://doi.org/10.1371/journal.pone.0208619.g002



Starting Song Unit	Phrase Structure	Song Structure	Song Name
Unit I	P3 Unit I Unit II Unit III	P3 P3 P3 P3	P3
		P3 P2 P3 P2	P3A
		Unit I Unit II P3	P3B
Unit II	P2 Unit II Unit III	P2 P2 P2 P2	P2
		P2 P1 P2 P1	P2A
	P1 Unit II	P1 P1 P1 P1	P1

Figure 5. From Jolliffe et al. 2019: Song structure classification based on phrase composition for the EIO pygmy blue whale song. https://doi.org/10.1371/journal.pone.0208619.g003

Aside from variability in phrase and song structure, variability in the production of individual song units has also been quantified for this population with song sequences with ‘broken’ or ‘pulsed’ song units becoming more prevalent in recent years (Jolliffe et al. 2019). These signals show up in spectrograms with what appears to be a perfect break in sound production of anywhere between 2 and 8 seconds (Figure 6). In some instances, particularly where there is a longer break in signal production in the type II unit, the frequency of the signal may drop to the starting frequency after the break resulting in two distinct but short frequency upsweeps. In other instances, there may be multiple breaks in sound production of the type I unit resulting in a ‘pulsed’ first song unit (Figure 7).

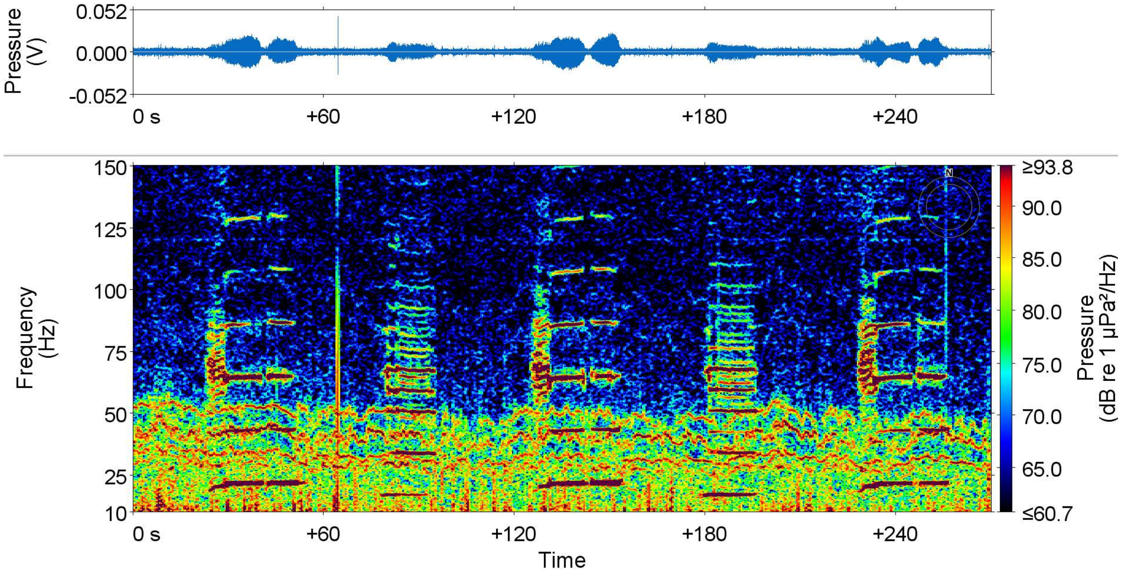


Figure 6. A two part P2 song with a break in the type II unit; (top) waveform and (bottom) directogram (0.4 Hz discrete Fourier Transform (DFT) frequency step, 2 ms DFT temporal observation window (TOW), 0.5 ms DFT time advance, and Hann window resulting in a 75 % overlap and DFT size (N_{DFT}) of 131072).

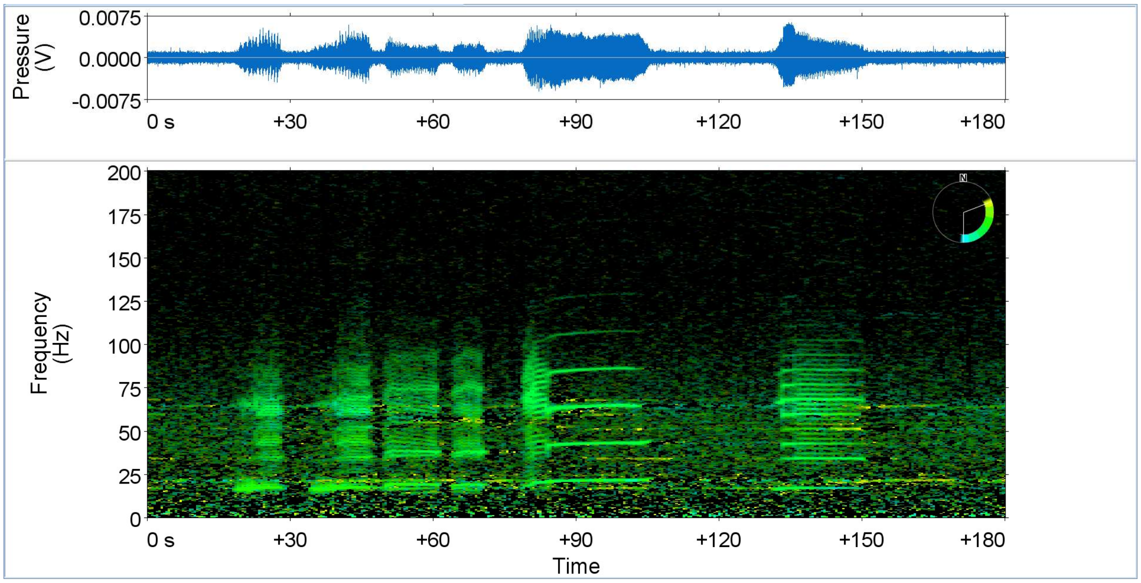


Figure 7. Three part P3 song with multiple breaks in the type I unit resulting in a pulsed first song unit; (top) waveform and (bottom) directogram (0.4 Hz discrete Fourier Transform (DFT) frequency step, 2 ms DFT temporal observation window (TOW), 0.5 ms DFT time advance, and Hann window resulting in a 75 % overlap and DFT size (NDFT) of 131072).

1.2.1.2. Non-Song Vocalisations

Reports of non-song vocalisations in blue whales worldwide have typically been sparse and are mostly limited to observations of singular song units and downswept ‘D-call’ (Oleson et al. 2007b, Erbe et al. 2017, Shabangu et al. 2017, Miller et al. 2021a). While somewhat variable in their acoustic characteristics, these signals are consistently low frequency (< ~ 100 Hz), short in duration (2 to 4 s) and do not present harmonics (Thode et al. 2000, McDonald et al. 2006). Recalde-Salas et al. (2014) provided a description of non-song vocalisations other than D-calls from EIO blue whales passing through Geographe Bay in Western Australia which continues to be built upon with observations of EIO social sounds now being documented throughout their migratory range in Australia (Jolliffe and McPherson, unpublished data). The most common of these calls appears to be the EIO1 calls, a downswept call with harmonics otherwise similar to D-calls (Figure 8 and 9).

Despite the dominance of D-calls in scientific papers describing blue whale non-song vocalisations, a review of the literature reveals that many social sounds (typically AM/FM with harmonics) are typically misclassified as D-calls (Schall et al. 2020) and the vocal repertoire of some populations may therefore be underestimated. Differentiating D-calls from EIO1 signals is complicated by the natural variability of these two call types (Figure 10) and propagation processes that may interfere with the perceived presence or absence of harmonics. For instance, modal dispersion may falsely suggest presence of harmonics in D-calls while long-range propagation may result in the loss of harmonics in EIO1 calls. Expert analysis is typically required to differentiate between these signal types.

Further complicating the identification of downswept, non-song vocalisations is that sounds resembling D-calls are also produced by other mysticete whales, particularly fin, humpback and sei whales (Nguyen Hong Duc et al. 2025). Although downsweeps can generally be confidently attributed to blue whales by human analysts based on context (e.g. when detected in areas where blue whales have been sighted and blue whale songs are detected on the acoustic receiver but other mysticete species known to produce D-calls are not), automated detectors are not always able to reliably distinguish blue whale downsweeps from those of other species. This is primarily because the characteristics of these signals overlap across species and exist along a continuum, with no clear boundaries between call types (Nguyen Hong Duc et al. 2025), particularly in the case of the ever evolving sounds of humpback whales.

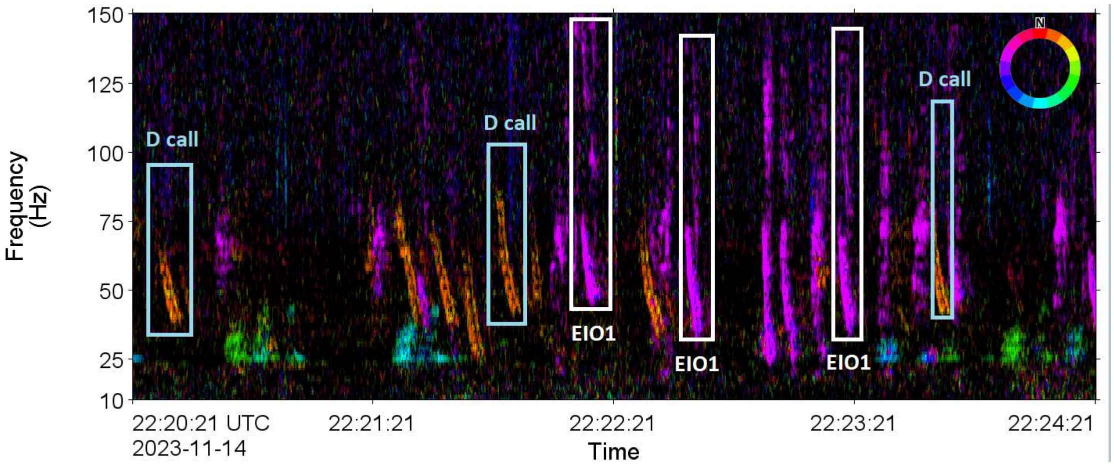


Figure 8. A directogram showing D-calls (orange signals in blue boxes) and EIO1 signals (pink signals in white boxes) being produced by different animals, as is evident from the different directions of origin of the signals. Note the D-calls occasionally appear as though they are ‘double/ have a shadow’ or have harmonics due to propagation characteristics, but they lack any higher frequency tonals and are very inconsistent. The EIO1s while also variable in their characteristics have clear higher frequency harmonics (0.4 Hz discrete Fourier Transform (DFT) frequency step, 2 ms DFT temporal observation window (TOW), 0.5 ms DFT time advance, and Hann window resulting in a 75 % overlap and DFT size (N_{DFT}) of 131072).

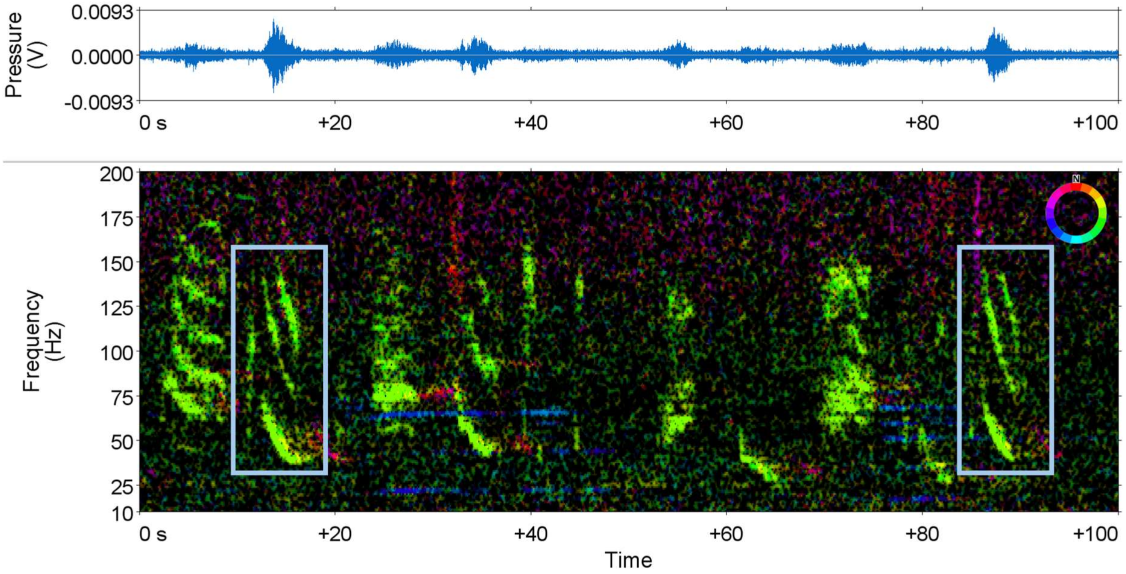


Figure 9. An example of social sounds produced by the EIO pygmy blue whales including two EIO1 signals, which appear to be produced by all blue whale populations and are commonly mistaken for D-calls (1 Hz discrete Fourier Transform (DFT) frequency step, 8 ms DFT temporal observation window (TOW), 0.125 ms DFT time advance, and Hann window resulting in a 93.6 % overlap and DFT size (NDFT) of 32768).

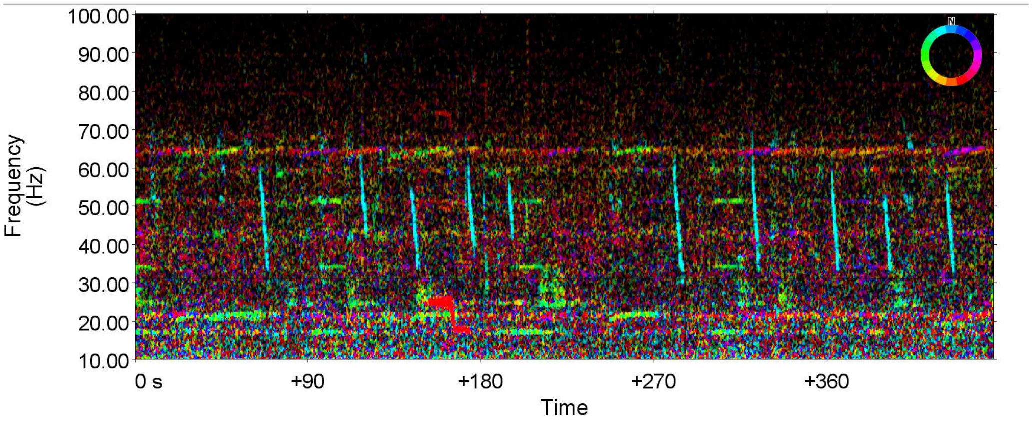


Figure 10. An example directogram of blue whale D-calls (light blue), all produced by one animal but variable within the range 29 to 69 Hz. Also note the background EIO pygmy blue whale song (green) and the Antarctic blue whale 'Z' call in red (0.4 Hz discrete Fourier Transform (DFT) frequency step, 2 ms DFT temporal observation window (TOW), 0.5 ms DFT time advance, and Hann window resulting in a 75 % overlap and DFT size (N_{DFT}) of 131072).

1.2.1.3. Behaviours associated with non-song vocalisation production

Both male and female blue whales are known to produce song units singularly outside of repetitive song structures, as well as a variety of frequency and amplitude modulated non-song vocalisations. Behaviours associated with singular song unit production were different to those associated with singing. Tagging studies have found that the production of singular calls was most common during shallow non lunging dives, and common during surface behaviour. Animals producing singular song units were always observed in close association with at least one other blue whale, and where tissue samples were available, were found to be produced by male and female pairs (Oleson et al. 2007a). Oleson et al. (2007a) reported an instance where an animal was recorded singing while travelling alone and was then observed to transition to producing singular song units once it had joined up with another blue whale.

Another study observed downswept signals, including some with harmonics like the EIO1 signal identified in Recalde-Salas et al. (2014), being produced during a heat run where two males were in pursuit of a female blue whale (Schall et al. 2020). Downswept signals were associated with trios of animals in two populations of blue whales, as well as being recorded on foraging grounds (Schall et al. 2020). Non-song vocalisations sounds appear to be produced by blue whales in a variety of contexts. Based on the results of acoustic tagging studies, these sounds are produced when blue whales are in proximity with other conspecifics and do not appear to be produced at the same time as song, suggesting a social function. Consequently, it would be expected that these signals may be detected acoustically when blue whales are present but blue whale song may not be. This is a common observation during analysis for this report. This reflects the findings of Recalde-Salas et al. (2014) who recorded many non-song social vocalisations but little to no song alongside visual observations of EIO pygmy blue whales on their southbound migration through Geographe Bay in Western Australia.

The behavioural context of D-calls has been studied for several populations of blue whales and appears to be consistent between populations. The signal is primarily detected on known foraging grounds where blue whales are aggregating to feed (Lewis et al. 2018). Acoustic tag data indicates that D-calls are typically produced during shallow dives in breaks between foraging bouts. In general, D-calls were recorded from whales that were loosely associated with other animals, though even those not obviously associated with another animal were within 1 km of other blue whales (Oleson et al., 2007). Based on the result of the acoustic tagging study, D-calls were considered to have a clear behavioural context being produced by both male and female whales during breaks between foraging at depth (Oleson et al. 2007a, Lewis et al. 2018).

Both Oleson et al. (2007a) and Thode et al. (2000) found that blue whales produce multiple D-calls per dive, typically at depths of between 15 and 35 m. It is hypothesised that at these depths, blue whales would be able to visually identify conspecifics and thus D-calls likely have a social function as opposed to reproductive function. This is further supported by the fact D-calls have been observed on foraging grounds as call-counter-call events within a group of two or more blue whales (McDonald et al. 2006, Lewis et al. 2018). Geographically, recordings of D-calls typically overlap known or likely foraging areas, for example the Perth Canyon in Western Australia (McCauley et al. 2001). Similarly, Barlow et al. (Barlow 2022, Barlow et al. 2022) observed seasonal and daily trends in the production of D-calls that aligned with seasonal and daily variability in blue whale foraging effort. Shabangu et al. (2019) also found a correlation of D-Call presence and higher chlorophyll-a concentrations in the Benguelan current ecosystem within the Southern Atlantic, further supporting the association between foraging behaviours and D-calls. D-Calls are also known to be produced during encounters of different group compositions, including mother-calf interactions (Oleson et al. 2007a, Lewis et al. 2018).

2. Methods

This section describes the data sets analysed, as well as the methods used for detecting marine mammals and vessels and for calculating ambient sound.

2.1. Acoustic Data Acquisition

2.1.1. Fieldwork

The monitoring program required the deployment and retrieval of three monitoring stations, at the offshore locations shown in Figure 1. The deployment and retrieval were successfully conducted by JASCO staff. The vessel used for the field work was the 23 m long M/V *Adrianus* from Terrafirma Offshore Pty Ltd (see Figure 11), with Exmouth used as the base of operations.

Figure 11. Photo showing M/V *Adrianus* (source: https://terrafirmaoffshore.com.au/commercial-marine-vessels/).

2.1.2. Underwater Acoustic Recorders

Underwater sound was recorded with three Autonomous Multichannel Acoustic Recorders Generation 4 Ultra Deep (AMAR G4 UD; JASCO; Figure 12) in glass sphere housings. Each AMAR was installed on an Autonomous Long-Term Observatory (ALTO; JASCO) lander (Figure 12). The ALTO is equipped with an orthogonal array of four M36 omnidirectional hydrophones (GeoSpectrum Technologies Inc., −165 ± 3 dB re 1 V/µPa sensitivity) spaced 50 cm apart. By using beamforming analysis methods, the direction of arrival of sounds can be determined from the four hydrophones. The hydrophones were protected by a hydrophone cage, which was covered with an open-cell foam shroud to minimise non-acoustic noise caused by water flowing over the hydrophone transducer (‘flow noise’). The AMARs recorded continuously with a duty cycle of 15 mins at a sampling rate of 32 kHz followed by 1 min at 256 kHz (see Table 3). The recording channel had 24-bit resolution with a spectral noise floor of 20 dB re 1 µPa^2/Hz and a nominal ceiling of 171 dB re 1 µPa. Acoustic data were stored on 7.68 TB of internal solid-state flash memory. Appendix A describes the calibration procedure.

Figure 1 and Table 4 present the deployment locations and depths of the ALTO landers. After each mooring was deployed, its location was ‘boxed in.’ To achieve this, the vessel transits in a circle with a radius that depends upon the water depth and obtains ranges to the acoustic release (i.e., AMAR location) from each of the four cardinal compass points.

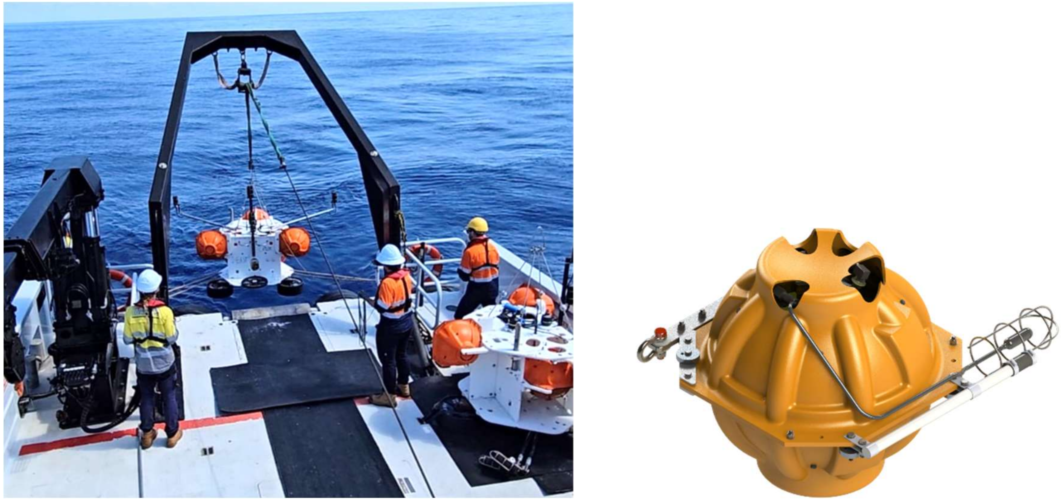


Figure 12. Acoustic recording equipment used in this study: (Left) JASCO’s ALTO lander ready for deployment, containing AMAR, hydrophones, floats, and acoustic release, and (right) JASCO’s AMAR Generation 4 Ultra Deep (AMAR G4 UD) acoustic recorder with hydrophone.

Table 3. ALTO lander recording configuration. This configuration was used during Monitoring Periods 1, 2 and 3.

Duration (s)	Channel	Sample rate	Sensor	Notes
900	**1,2,3,4**	**32000 Hz**	**M36-V35-900**	**All 4 hydrophones**
	22	60 s	AMAR-BATI	Primary supply current
	23	60 s	AMAR-BATV	DC Input 2
	24	60 s	AMAR-BATV	DC Input 1
	25	60 s	AMARG4-TEMPERATURE	On board temperature
	26	60 s	AMARG4-HUMIDITY	On board humidity
60	**1**	**256000 Hz**	**M36-V35-900**	**Top-most hydrophone**
	22	50 s	AMAR-BATI	Primary supply current
	23	50 s	AMAR-BATV	DC Input 2
	24	50 s	AMAR-BATV	DC Input 1
	25	50 s	AMARG4-TEMPERATURE	On board temperature
	26	50 s	AMARG4-HUMIDITY	On board humidity

Table 4. Location, depth, and operation periods of the recorders during Monitoring Periods 1, 2 and 3.

Station	Latitude	Longitude	Depth (m)	Record start	Record end	Duration (Days)
Monitoring Period 1 (Apr to Sep 2023)						
West Scott Reef	-13.9872°S	121.7770°E	594	19 Apr 2023	22 Sep 2023	157
East Scott Reef	-14.0336°S	122.0149°E	443	19 Apr 2023	9 Sep 2023	145
North West Cape	-21.6408°S	113.8943°E	517	27 Apr 2023	30 Sep 2023	158
Monitoring Period 2 (Sep 2023 to Mar 2024)						
West Scott Reef	-13.9869°S	121.7767°E	594	24 Sep 2023	19 Mar 2024	177
East Scott Reef	-14.0333°S	122.0176°E	456	23 Sep 2023	18 Mar 2024	176
North West Cape	-21.6409°S	113.8942°E	550	30 Sep 2023	14 Mar 2024	165
Monitoring Period 3 (Mar to Sep 2024)						
West Scott Reef	-13.9852°S	121.7799°E	455	19 Mar 24	18 Sep 24	184
East Scott Reef	-14.0331°S	122.0144°E	593	18 Mar 24	18 Sep 24	185
South Scott Reef	-14.4165°S	121.6527°E	590	17 Mar 24	18 Sep 24	186

2.2. Marine Mammal Detection Overview

We used a combination of automated detector-classifiers (referred to as automated detectors) and manual review by experienced analysts to determine the presence of sounds produced by marine mammals in the acoustic data. First, a suite of automated tonal detectors was applied to the full data set (see Appendix C.1). Second, a subset (1–5 %) of acoustic data were selected for manual analysis of marine mammal acoustic occurrence. The subset was selected based on automated detector results via our Automatic Data Selection for Validation (ADSV) algorithm (Kowarski et al. 2021) (see Appendix B.2). Third, manual analysis results were compared to automated detector results to determine automated detector performance (see Appendix B.3). Finally, hourly marine mammal occurrence plots that incorporated manual and automated detections were created (see Section 3.1), and automated detector performance metrics were provided (see Appendix C.3) to give a reliable representation of marine mammal presence in the acoustic data. These marine mammal analysis steps are summarised here and detailed in Appendix B. Where automated detector results were unreliable or did not add additional information to species occurrence, only the validated results from manual analysis are presented. While all marine mammal species and signal types (e.g. tonal sounds and echolocation clicks) were targeted during the analysis of the data, this report focuses on the detections of blue whales.

2.2.1. Automated Tonal Signal Detection

Tonal signals are narrowband, often frequency-modulated, signals produced by many species across a range of taxa (e.g., baleen whale moans, delphinids whistles), including blue whales. They range predominantly between 15 Hz and 4 kHz (Berchok et al. 2006, Risch et al. 2007), thus automated detectors for these species were applied to the 32 kHz data (audio bandwidth up to 16 kHz for ~15 min every 16 min). The automated tonal signal detector identified continuous contours of elevated energy and classified them against a library of marine mammal signals (see Appendix B.1 for details). JASCO's suite of tonal automated detectors includes species/signal-specific detectors and those that are more generic, recording signals from potentially more than one species that overlap in spectral characteristics.

2.2.2. Automated Detector Validation

JASCO's suite of automated detectors are developed, trained, and tested to be as reliable and broadly applicable as possible. However, the performance of marine mammal automated detectors varies across acoustic environments (e.g., Hodge et al. 2015, Širović et al. 2015, Erbs et al. 2017, Delarue et al. 2018). Therefore, automated detector results must always be supplemented by some level of manual review to evaluate automated detector performance. Here, we manually analysed a subset of acoustic files for the presence/absence of marine mammal acoustic signals via spectrogram review in JASCO's PAMlab software. A subset (1–5 %) of acoustic data were selected via ADSV for manual review (see Appendix B.2).

To determine the performance of the automated detectors per file, the automated and manual results (excluding files where an analyst indicated uncertainty in species occurrence) were plotted as time series and critically reviewed to determine if automated detections should be excluded. If manual detections of a given species were absent during a prolonged period, an exclusion period was defined and all potential automated detections for that species during that period were deemed false and excluded from further processing (See Appendix B.3 for details). The remaining automated and manual detections fed into an algorithm that calculates precision (P), recall (R), and Matthew's Correlation Coefficient (MCC) (see Appendix B.3 for formulas). P represents the proportion of files with detections that are true positives. A P value of 0.90 means that 90 % of the files with automated detections truly contain the targeted signal, but it does not indicate whether all files containing acoustic signals from the species were identified. *R* represents the proportion of files containing the signal of interest that were identified by the automated detector. An *R* value of 0.90 means that 90 % of files known to contain a target signal had automated detections, but it says nothing about how many files with automated detections were incorrect. An MCC provides an overall measure of performance, and has been argued as the standard metric for assessing binary automated detection (Chicco and Jurman 2023). MCC values can range between -1.0 and 1.0. An MCC of 1.0 indicates perfect performance, i.e., all events were correctly automatically detected, whereas an MCC of -1.0 indicates the detector did not perform better than random chance. The algorithm determines a per-file automated-detector threshold (the number of automated detections per file) that maximises the MCC.

For many species, more than one automated detector targeted their vocalisations. In these instances, the performances of all automated detectors were evaluated, and the highest performing detector was used to represent species/vocalisation-type occurrence in Section 3.1. Only automated detections associated with a *P* greater than or equal to 0.75, an *R* greater than or equal to 0.5, and an MCC greater than or equal to 0.4 (well above the midrange value of 0.0), were considered. When performance metrics fell below minimum requirements, only the validated results were used to describe the acoustic occurrence of a species.

JASCO’s Ark software was used to plot the occurrence of each species (both validated and automated, or validated only where appropriate) as time series showing the hourly presence/absence over each day of the recording period. Automated detector performance metrics associated with the results (included in Section 3.1 and detailed in Appendix C.3) should be considered when interpreting results.

A post-automated detector validation ‘spot check’ was performed for periods where automated detections of pygmy blue whale song and non-song calls occurred without or with few manual validations, as evidenced by the presence/absence plots in Section 3.1.1. This spot check involved manual analysis of a selection of files representative of the period in question. Depending on both duration of the period and number of files with automated detections occurring in that period, between five and 30 files per period were spot checked.

2.3. Detection Range Modelling

Detection Range Modelling (DRM) was conducted to estimate the detectability of vocalisations for the baleen whale species detected at all three stations and to provide a comparison of detection ranges between the stations. The DRM considered the following data inputs to estimate species-specific detection distances:

- Ambient decidecade sound pressure level (SPL) percentiles measured at each station (see Section 2.1).
- Local bathymetry, geology, and sound speed profile (see Appendix C.1)
- Published marine mammal vocalisation source level and bandwidth characteristics, as well as vocalisation depth (see Appendix C.4).

The detection range is defined as the range at which the expected sound level of a mammal vocalisation is *X* dB above the expected background level, where *X* is the detection threshold of the relevant detector for a given species (Table B-1). Modelled signal-to-noise ratios (SNRs) were calculated at discrete locations within a three-dimensional (3-D) volume (easting, northing, and depth) to predict a detection range. The detection range, therefore, represents the maximum range at which a signal of a given source level can be identified by a detector in given background noise conditions. This underestimates the range to which vocalisations could be detected by experienced human analysts conducting a fine-scale analysis.

To compute the detection range, an estimate of the sound's propagation loss between the vocalising animal and the recorder is required. To perform the propagation loss calculations in a computationally efficient manner, we applied the reciprocity principle, which states that an identical signal will be received between a source and receiver pair if their coordinates are inter-changed (Jensen et al. 2011). So rather than performing individual propagation loss calculations for a source at many locations (e.g., an animal) to the receiver to estimate SNR and detectability, the loss between source and receiver is computed by setting the source location for the propagation model to be the location of the seafloor recorder. The propagation loss from this position was then calculated to all locations within the ocean interior in a single execution of the model, thereby reducing the number of individual propagation loss computations that would be required otherwise.

JASCO's Marine Operations Noise Model (MOMN; see Appendix C.2), a range-dependent parabolic equation model for frequencies up to 2 kHz, was used to predict the loss between animal and recorder. Appendix C contains additional information on the propagation models used for detection range estimation.

Propagation loss was calculated for April, June, September, and November 2023 and April and June 2024 to a distance of 100 km from each recorder location. A horizontal separation of 50 m between receiver points along the modelled radials was used. The propagation loss fields were modelled with a horizontal angular resolution of 5° for a total of 72 radial planes. Receiver depths were chosen to span the entire water column over the modelled areas, with step sizes that increased with depth, from 1 m to the maximum water depth in the modelled region.

Ambient decidecade SPL percentile information was derived from acoustic measurements performed on the data recorded at each station (see Section 2.1). The modelling was aimed at assessing the detection ranges of two types of sounds produced by pygmy blue whales (see Appendix C.4). Geological profiles are provided in Appendix C.1.

To evaluate the detection ranges, the received level, $\mathrm{RL}(r)$, measured at the distance r from the source, is modelled as:

$$\mathrm{RL}(r) = \mathrm{SL} - \mathrm{PL}(r)\,, \tag{1}$$

where SL is the source level of the vocalisation and $\mathrm{PL}(r)$ is the range-dependent propagation loss that is a non-random parameter computed with MONM. The source level of each call type is defined as a Gaussian distribution with a specified mean and standard deviation (see Appendix C.4).

The detection of a given marine mammal vocalisation is assumed to occur if the received level is greater than the local noise level in the frequency band of the vocalisation (NL), by a constant threshold c:

$$\mathrm{RL}(r) \geq \mathrm{NL} + c\,. \tag{2}$$

The threshold c must be chosen such that there is little chance of detecting a false alarm due to *ambient sound*, and such that the automated algorithms will have a 50 % chance of detecting a signal when present. Depending on the species of interest, JASCO's detectors use thresholds between 1 and 14 dB, which satisfy the constraints.

Equations 1 and 2 include two independent random variables, NL and SL. The distribution of the noise level is determined empirically from actual data recorded at the project site for the same time period that was used to select the sound speed profile. Thus, NL has discrete values, and the final probability of detecting a call as a function of range is:

$$\mathrm{P_d}(r) = 1 - \sum_{\mathrm{NL}_i} \mathrm{P}(\mathrm{NL}_i)\ \mathrm{CDF_{SL}}\big(\mathrm{NL}_i + c + \mathrm{PL}(r)\big)\,, \tag{3}$$

where $\mathrm{CDF}_{\mathrm{SL}}\big(\mathrm{NL} + c + \mathrm{PL}(r)\big)$ is the cumulative probability of the source level exceeding $\mathrm{NL}_i + c + \mathrm{PL}(r)$.

To further constrain the modelling so that the predicted detection ranges do not become unreasonably long, the maximum source level considered is the 90th percentile of the distribution, and the minimum noise level is the 10th percentile of the noise distribution. We then discretise the signal model into 0.5 dB bins (SL_j) and compute $\mathrm{P_d}(r)$ for all combinations of NL_i and SL_j. We extract the 10th, 50th, and 90th percentiles of this distribution for generating plots and tables of detection performance.

2.4. Directional Analyses

2.4.1. Bearing and Absolute Minimum Number Estimation

Data from the four hydrophones on each ALTO lander were processed to determine the direction of arrival of sounds. The analysis was performed using a maximum likelihood estimation (MLE) beamformer (Urazghildiiev and Hannay 2017). This beamformer estimates the sound level assuming the sounds are arriving from azimuthal bins that are 20 degrees wide (total of 360/20 = 24 bins), and for each azimuth it evaluates 3 elevation angles 30 degrees wide (from horizontal to vertical, assuming a bottom-mounted recorder; 90/30 = 3), for a total of 24 × 3=72 'look directions' or beams. The beam with the greatest received sound level is selected as the most likely direction of arrival for each time-frequency bin. The bearing values for each beam are weighted by the energy in the corresponding time-frequency bin and averaged over all bins of the contours such that the bearing assigned to a call is an energy-weighted direction. This process is applied to marine mammal detections in the frequency range of 0–264 Hz (see Appendix D.1.2). A visual representation of this processing is shown by the directogram (directional spectrogram) in Figure 13.

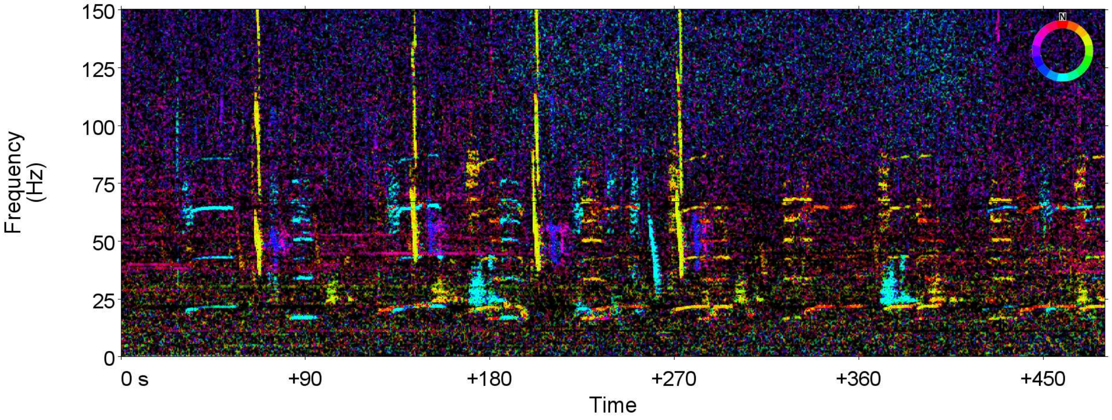


Figure 13. Example of a directogram showing blue whale vocalisations where colour indicates bearing (1 Hz discrete Fourier Transform (DFT) frequency step, 1 s DFT temporal observation window (TOW), 0.125 s DFT time advance, and Hann window resulting in a 75 % overlap and DFT size (NDFT) of 32, normalised across time). The spectrogram is 480 s long.

In this study, detailed directional analyses were restricted to pygmy blue whale vocalisations with relatively low bearing errors and high occurrence (song Unit 2 and downswept non-song vocalisations such as D-calls and EIO1 calls). The absolute minimum number (AMN) of marine mammals present can be determined by counting the number of distinct directions of origin of a target signal over a brief period of time. Here, 10 min was employed. The bearing errors from the beamformer are inversely proportional to the frequency and signal to noise ratios (SNR), i.e., the errors are greater at low frequency and low SNR; therefore, low SNR calls are not considered for counting the minimum number of animals present. Once the low SNR calls are removed (see Appendix D.1.4), the bearing accuracy for pygmy blue whale calls ranges from 20 to 60 degrees. For the 63–65 Hz harmonic of unit 2 of the EIO PBW song, 20 degrees is considered an appropriate error while we used 30 deg as the error for non-song vocalisations (Appendix D.1). The error estimate defines the size of the angle bins within which all calls are assumed to be from the same animal. The maximum number of bins with detections among the 144 10-min windows per day is the daily AMN.

The AMN is an index of occurrence and not an absolute number of animals in the area. It is a conservative index because of the short integration period over which distinct bearing clusters are counted. The choice of a 10-min window was made to avoid counting a whale that may be transiting past the recorder at close range in more than one bin. AMN of whales are shown as time series for each recorder and deployment. Appendix D.1 provides details of the beamforming and AMN analysis.

2.4.2. Acoustic Location Estimation and Motion Representation

The following analyses are applied to the same automated detections for which bearings were estimated (see Section 2.4.1) and are therefore applied to the same call types. One objective was to display the location of vocalising blue whales around the Scott Reef recorders. Based on the results of the detection range modelling (see Section 3.2.1.3), these spatial displays were restricted to a 50-km radius around each recorder.

Following bearing estimation, the range of each automated detection was estimated using its received level and propagation loss modelling (Section 2.4.2.1). The 50-km area around the recorders was broken into sixteen 22.5° sectors and six range bins for a total of 96 bins. Range and bearing estimates were then used to create polar plots showing the proportion of the total number of hours with detection occurring in each bin (Figure 14) in order to assess the relative use of waters surrounding Scott Reef by pygmy blue whales.

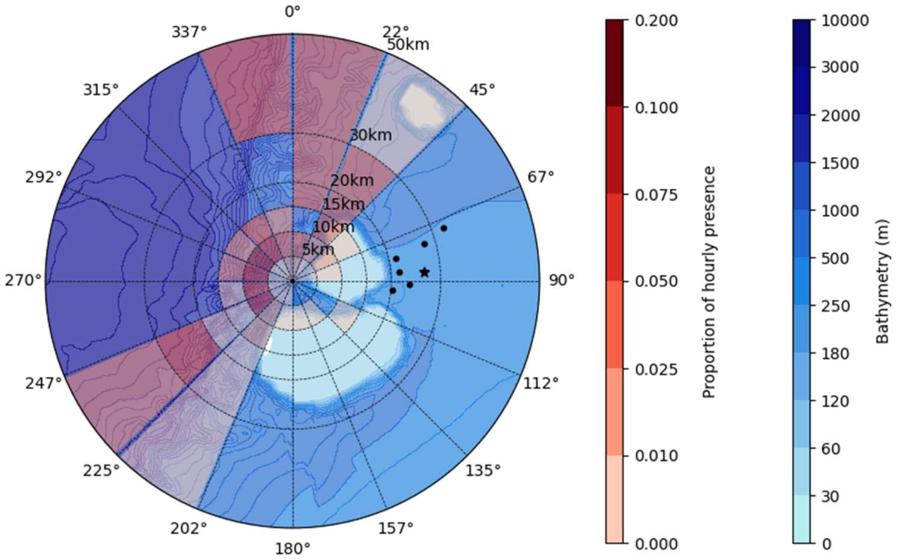


Figure 14. Example of a radar plot showing the monthly proportion of hours with automated detections of pygmy blue whale vocalisations as a function of the range and bearing from West Scott Reef. The area around the recorder was divided into 16 angular wedges 22.5 degrees wide and six range bins between 0 and 50 km from the recorder. The plot is centred on the location of the recorder.

2.4.2.1. Estimation of Call Received Levels and Distance to Sources

The spectrogram data were stored in units of power spectral density (PSD). The received level of the calls of interest were computed by summing the PSD of all time-frequency bins in the automatically detected contours then dividing by the total duration of the contour and converting to decibels re 1 µPa².

The received SPL (RL) of the detected sounds can be represented using the basic passive sonar equation as:

$$RL = SL - PL, \tag{4}$$

where SL is the mean-square source level of sounds and PL is the propagation loss. Appendix C.4 provides details for the calls targeted in this study.

In the simplest form corresponding to the spreading in an ideal media, the PL is represented as:

$$PL = A \log R \,, \tag{5}$$

where R is the distance to the source, and A is the coefficient that equals $A = 10$ for cylindrical spreading and A$= 20$ for spherical spreading. In reality, the PL is a random variable that also depends on absorption, refraction, multipath effects, and other unpredictable factors. In the low-frequency bands occupied by baleen whale sounds, the main factors affecting PL are the distance to the source and surface and bottom reflections. The influence of these factors was assessed using PL modelling carried out using JASCO's MONM algorithm (Zykov et al. 2015), which for low frequencies employs a version of the Range dependent Model (RAM) parabolic equation solution to the acoustic wave equation (Collins 1993).

The propagation loss curves determined during detection range modelling (Section 2.3) were used, with the curve for the closest azimuth to the received signal being interpolated at a fixed depth (22 m for pygmy blue whale song and non-song calls).

3. Results

3.1. Soniferous Marine Life

The acoustic presence of marine mammals was identified automatically by JASCO's detectors (see Section 2.2) and validated via the manual review of 1 to 5 % of data selected as per Kowarski et al. (2021; see Appendix B.2 and Table B-3; 5463 acoustic files totalling over 1013 h analysed). Automated detectors and analysts found acoustic signals of EIO pygmy and Antarctic blue whales, fin whales, humpback whales, dwarf and Antarctic minke whales, Omura's whales, delphinids, sperm whales, an unknown beaked whale, dwarf and/or pygmy sperm whales, and fish, along with presumed Bryde's whales, and possible sei whales. Appendix B.4 provides automated detector performance for each blue whale signal type, by monitoring period, and station.

A summary of blue whale occurrence at each of the recording stations is provided in Table 5 based on the monthly proportion of days with acoustic detections. Blue whale presence is reported in detail in the sections following this table.

Table 5. Species occurrence summary per station for the full recording period. Presence per month is indicated quantitatively (in percentage of days, colour scale) for automated detections and qualitatively (grey/black scale) for manual detections (including spot checks). Manual review of automated detections is indicated, with only the percentage of valid detections included. PBW: pygmy blue whale; BW: blue whale.

Species	Daily presence per month (% days)																	
	2023									2024								
	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
West Scott Reef Station																		
PBW, song	92	100	100	97	77	3[†]	<80	100	97	55	0[†]	0[†]	50*	100	100	100	100	94
PBW, non-song	50	52	77	35	16	0[†]	10	53	32	6	0[†]	0[†]	30*	58	87	65	35	22
Antarctic BW	⬛	▒	▒	▒	▒	▒	16	0	0	0	0	0	⬛	⬛	⬛	▒	▒	⬛
East Scott Reef Station																		
PBW, song	85	100	100	94	81	0[†]	<55	100	90	35	0[†]	0[†]	83*	100	100	100	100	94
PBW, non-song	▒	▒	▒	▒	▒	0[†]	55	73	55	39	0[†]	0[†]	7*	48	80	45	13	6
Antarctic BW	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	▒	⬛
North West Cape Station																		
PBW, song	57	100	100	42	35	0[†]	<80	100	100	71	72	54	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
PBW, non-song	0	65	50	0[†]	0[†]	0[†]	48	87	61	10	0[†]	0[†]	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
Antarctic BW	43	90	43	13	10	30	6	0	0	0	0	0	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
South Scott Reef Station																		
PBW, song	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	0[†]	70*	100	100	100	100	94
PBW, non-song	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	0[†]	3*	61	70	52	10	0
Antarctic BW	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	⬛	⬛	⬛	▒	⬛	▒	⬛

Legend
0
0.1-20.0
20.1-40.0
40.1-60.0
60.1-80.0
80.1-100
▒ Present
⬛ Absent

* Temporal restricted detection statistics based upon detector operational periods of after 15 April at West Scott Reef, after 31 March at East Scott Reef, and after 10 April for South Scott Reef.

[†] Based on manual review / spot checks of automated detections.

3.1.1. EIO Pygmy Blue Whales

3.1.1.1. Songs

EIO pygmy blue whale songs (see examples in Figures 15 to 19) were detected at all stations (Figure 20). Pygmy blue whale song is comprised of ‘units’ I, II and III that are produced in varying combinations or ‘phrases’. A single phrase is one repetition of a unit sequence, and where more than one phrase is repeated in succession, the song is referred to by the phrase name. Both the units present and the spacing between phrases is used to delineate a song (Jolliffe et al. 2019). Several song types, such as the examples in Figures 15 to 19, were identified during manual review. Detailed song analysis was beyond the scope of the present analysis.

Songs identified include Phrase 3 (P3; units I, II, and III; Figure 15) and Phrase 2 (P2, only units II and III; Figure 16). Both P3 and P2 songs were observed during the same period (Figure 17). The target of analysis was the 63–65 Hz harmonic of unit II because this signal is included in all song types and can often be detected even when other units are faint. Though the unit II tonal is often contiguous (for example, see Figure 15), it can also have ‘breaks’ where there is a pause longer than 4 s in the middle of the unit where the signal ‘dips’ in frequency after the break, and ‘split’, where there is a pause of less than 4 s in the middle of the unit where frequency remains constant across the unit (e.g. Figure 18) (Jolliffe et al. 2019). Songs co-occurred with signals from other species and with blue whale non-song calls.

The estimated automated detector performance for pygmy blue whale unit II song notes was high (see Appendix B.4), indicating that the results in Figures 20–23 correctly represent the overall occurrence of this signal in the data, though manual results remain the most reliable indicator of presence. EIO pygmy blue whale song occurrence was similar at both Scott Reef stations. Pygmy blue whale songs were manually confirmed around Scott Reef in all months of the 2023 recording year except February and March (Table 5; Figures 20 to 23). Songs were detected in at least 50% of days per month in all months except February, March, September and October at West Scott Reef while East Scott Reef saw reduced acoustic occurrence in September and in January, with the first confirmed detection after this on 13 April 2024. South Scott Reef had no song detections in March, but saw sustained acoustic presence (>70% detection-positive days) from April to September 2024. Song detections occurred almost year-round at the North West Cape station, however there was a notable absence in September, and vessel presence influenced detections at times. There was seemingly no diel trend in pygmy blue whale song occurrence, with songs present throughout all hours of the day (Figure 20 and 21).

During the most recent deployment (March to September 2024), the data captured the onset of the northbound migration in the Scott Reef region. The West Scott Reef recorder may have also captured the end of the migration on that side of the reef, but detections were sustained south and east of the reef until the end of the recording period (Figure 22 and 23). Interestingly, the August peak in detections noted at stations West Scott Reef and East Scott Reef in 2023 was also observed to some degree in 2024, although more significantly west than east of the reef. In 2024, the August peaks were not preceded by a near-complete cessation of detections as seen in 2023 (Figure 23), demonstrating inter-annual variability.

A combined panel plot showing song and non-song detections over the three monitoring periods is provided in Figure 33. Section 3.2.1 provides further directional analysis of these signals. Automated detections within the blue highlighted periods in Figures 20, 23 and 33 have been spot checked (as described in Section 2.2.2). and no blue whale song was manually confirmed. The autodetections within these periods are typically due to faint vessel tonals at the same frequencies as the EIO pygmy blue whale song units.

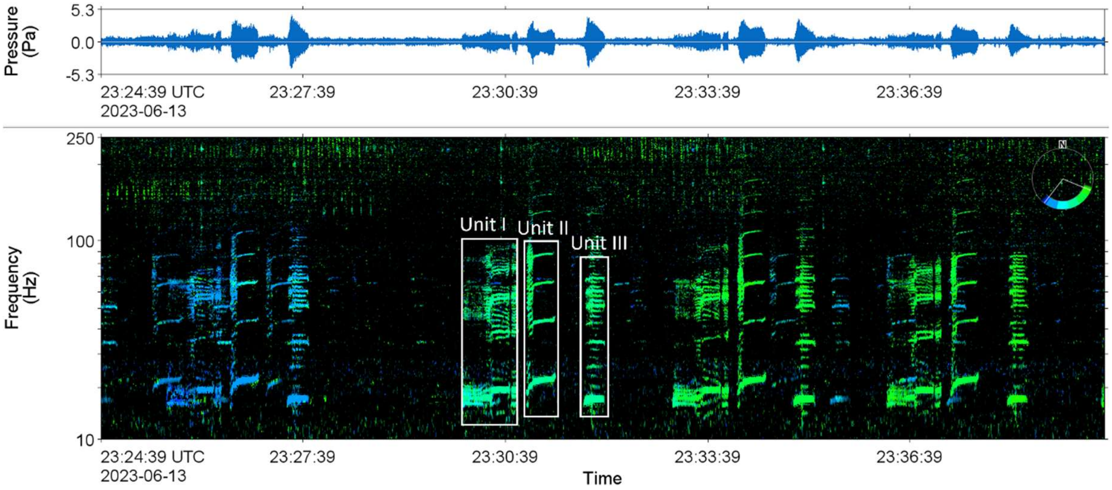


Figure 15. Pygmy blue whale song, Phrase 3 (P3; units I to III): (Top) Waveform and (bottom) directogram of song units recorded moving from north to northeast of North West Cape on 13 Jun 2023 (0.4 Hz discrete Fourier Transform (DFT) frequency step, 2 s DFT temporal observation window (TOW), 0.5 s DFT time advance, and Hann window resulting in a 75 % overlap and DFT size (N_{DFT}) of 131072). The spectrogram is 15 min long. Note that P3 can be further differentiated by the spacing between phrases, and various spacings were present in the data as depicted in the spectrogram.

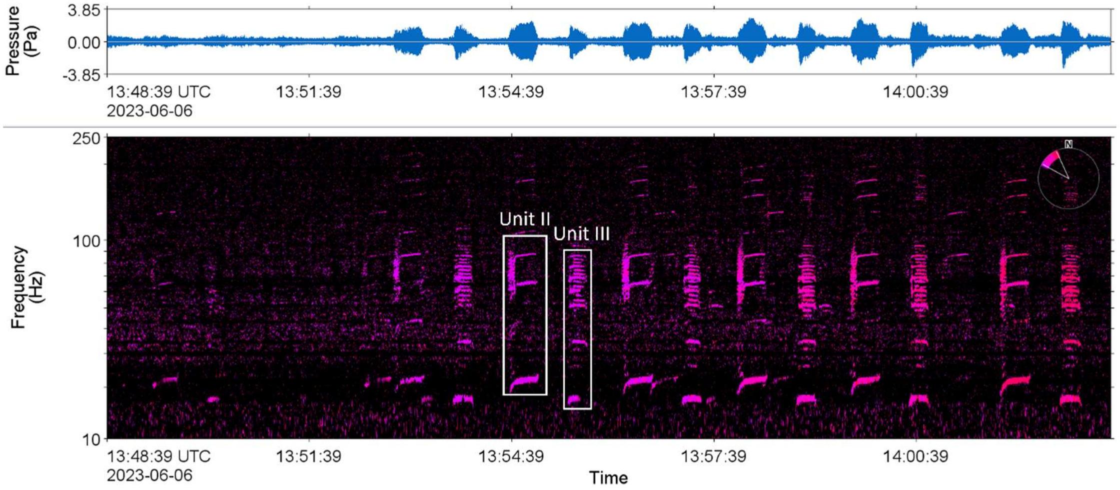


Figure 16. Pygmy blue whale song, Phrase 2 (P2; song units II and III): (Top) Waveform and (bottom) directogram of a P3A song recorded moving from northwest to north of North West Cape on 6 Jun 2023 (0.4 Hz discrete Fourier Transform (DFT) frequency step, 2 s DFT temporal observation window (TOW), 0.5 s DFT time advance, and Hann window resulting in a 75 % overlap and DFT size (N_{DFT}) of 131072). The spectrogram is 15 min long.

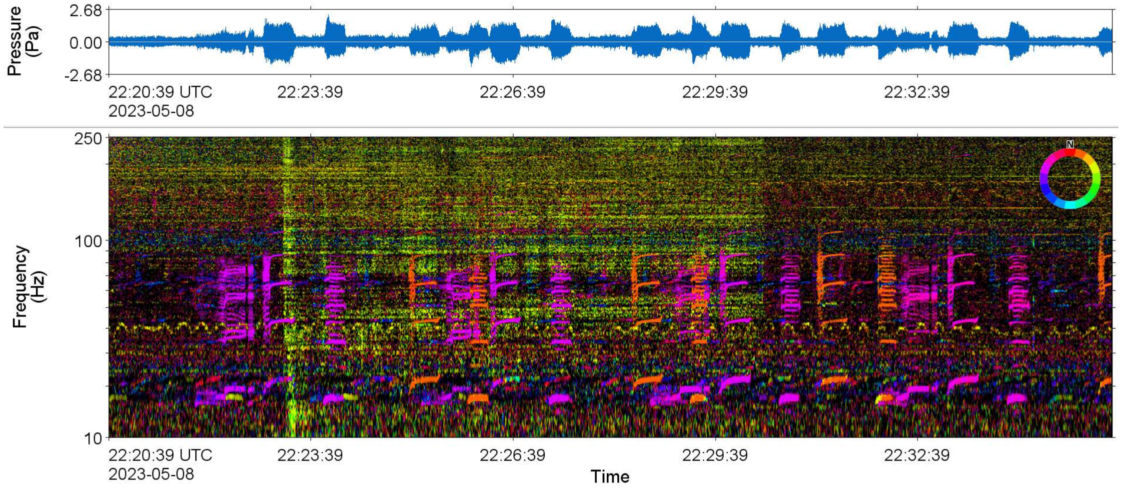


Figure 17. Pygmy blue whale song, Phrase 2 (P2; units II and III) and Phrase 3 (P3; units I to III): (Top) Waveform and (bottom) directogram of two individuals singing. One is singing a P2 song from the north (orange) and the other is singing a P3 song from the northwest (purple). Songs were recorded at North West Cape on 8 May 2023 (0.4 Hz discrete Fourier Transform (DFT) frequency step, 2 s DFT temporal observation window (TOW), 0.5 s DFT time advance, and Hann window resulting in a 75 % overlap and DFT size (N_{DFT}) of 131072). The spectrogram is 15 min long.

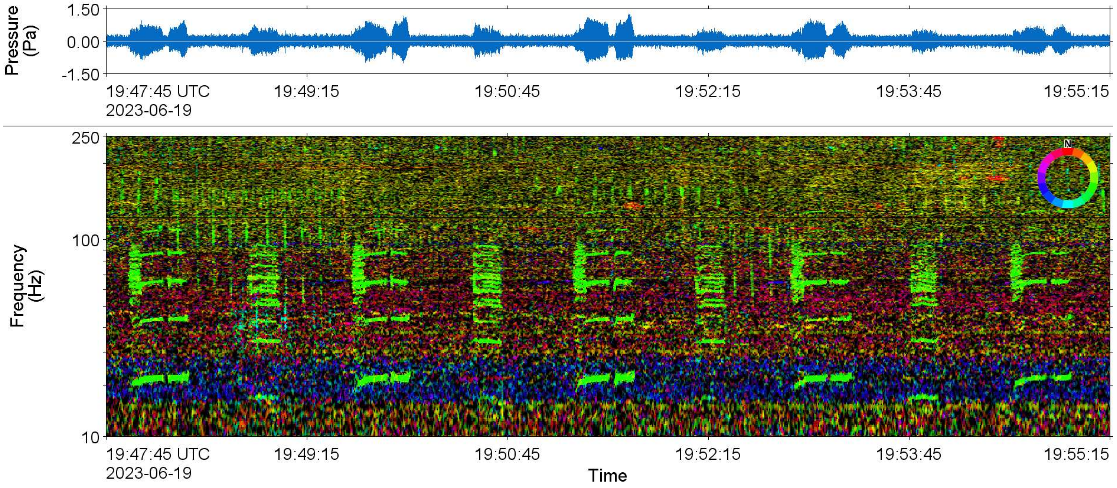


Figure 18. Pygmy blue whale song, Phrase 2 (P2) with unit II split: (Top) Waveform and (bottom) directogram of P2 song with unit II split recorded east of North West Cape on 19 Jun 2023 (0.4 Hz discrete Fourier Transform (DFT) frequency step, 2 s DFT temporal observation window (TOW), 0.5 s DFT time advance, and Hann window resulting in a 75 % overlap and DFT size (N_{DFT}) of 131072). The spectrogram is 450 s long. Humpback whale song is also present in directogram.

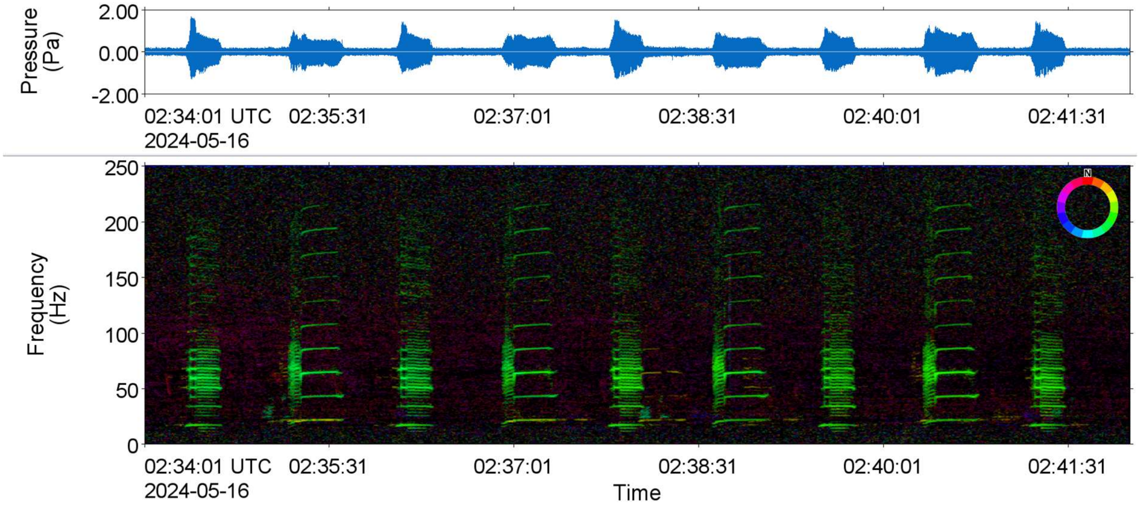


Figure 19. Pygmy blue whale song, Phrase 2 (P2): (Top) Waveform and (bottom) directogram of P2 song, originating from the southeast recorded at East Scott Reef on 16 May 2024 (0.4 Hz discrete Fourier Transform (DFT) frequency step, 2 s DFT temporal observation window (TOW), 0.5 s DFT time advance, and Hann window resulting in a 75 % overlap and DFT size (N_{DFT}) of 16384). The spectrogram is 480 s long.

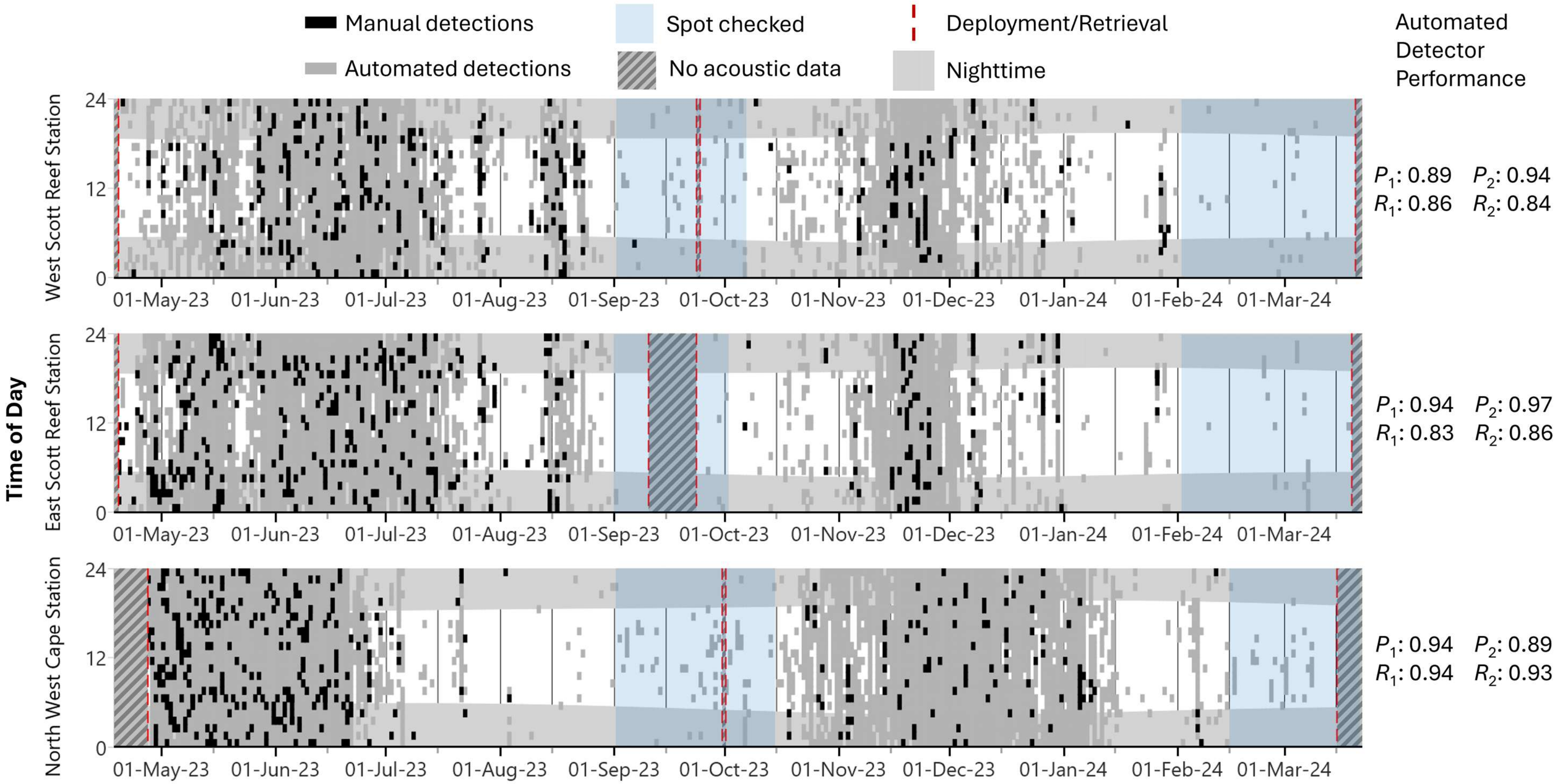


Figure 20. Pygmy blue whale song: Daily and hourly occurrence of song recorded from April 2023 to March 2024 (Monitoring Periods 1 and 2) including automated detector performance metrics (P_1 and R_1: Precision and Recall during Monitoring Period 1; P_2 and R_2: Precision and Recall during Monitoring Period 2). The grey areas indicate hours of darkness (nighttime) from sunset to sunrise (Ocean Time Series Group 2009).

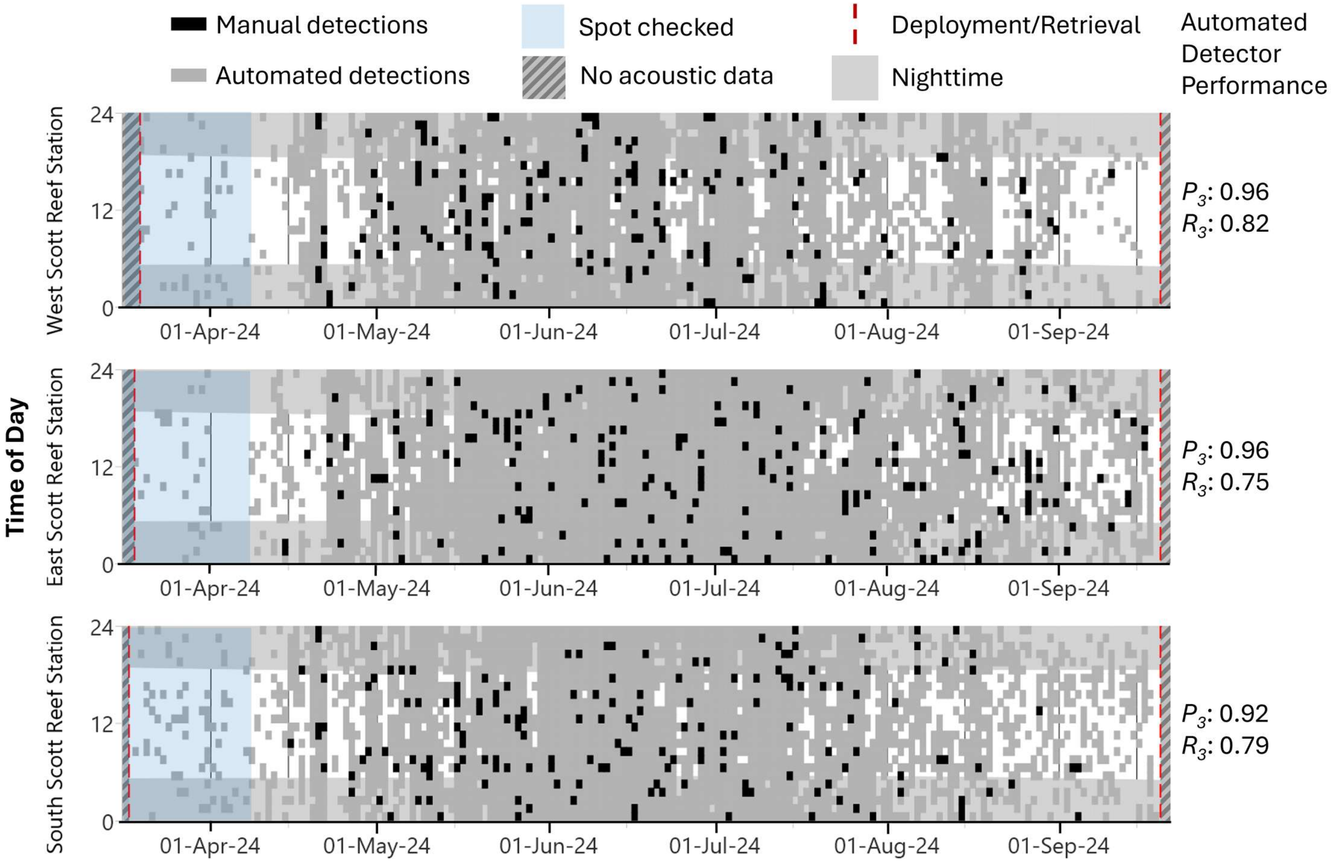


Figure 21. Pygmy blue whale song: Daily and hourly occurrence of song recorded from March to September 2024 (Monitoring Period 3) including automated detector performance metrics (P_3 and R_3: Precision and Recall during Monitoring Period 3). The grey areas indicate hours of darkness (nighttime) from sunset to sunrise (Ocean Time Series Group 2009).

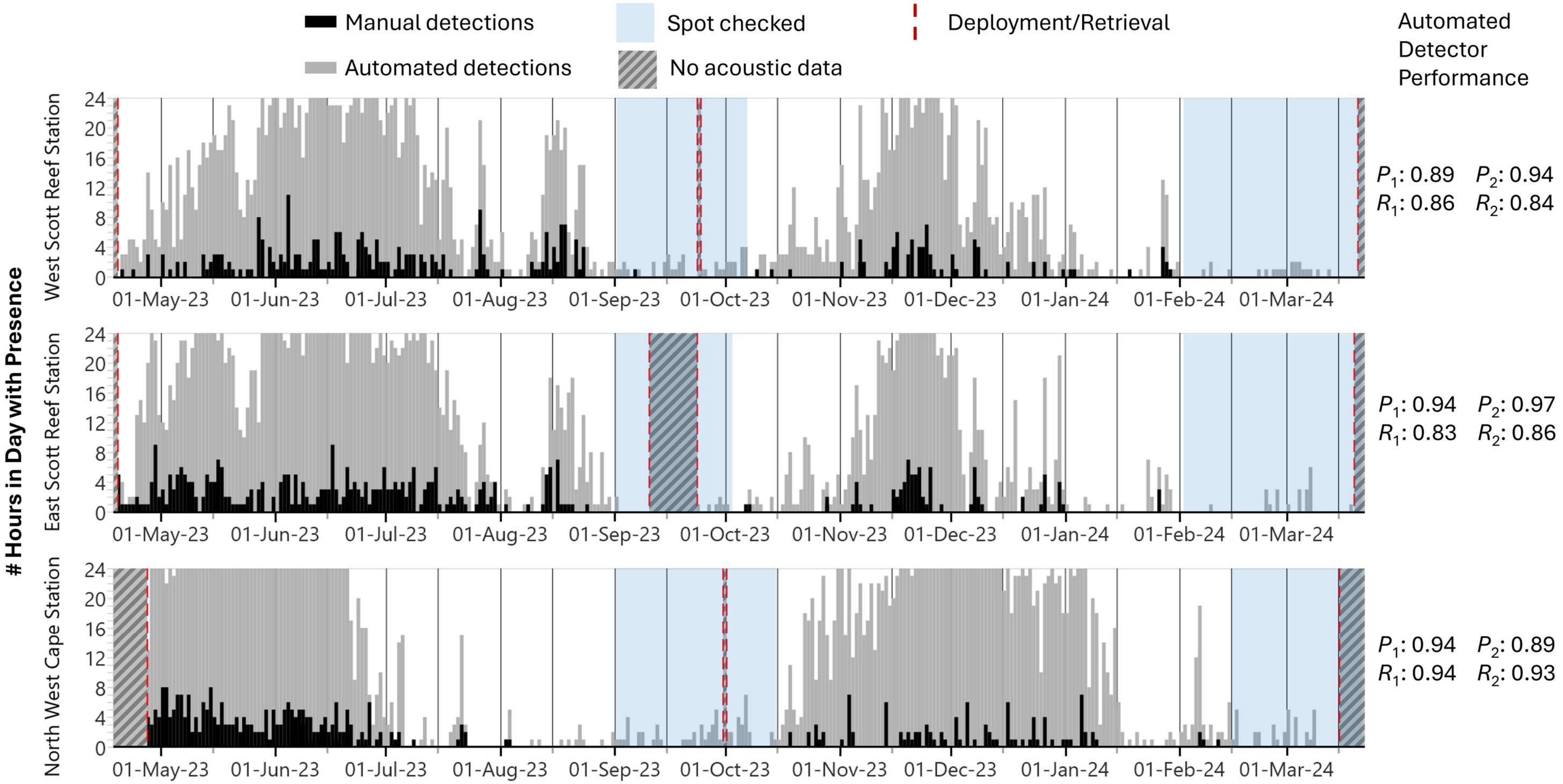


Figure 22. Pygmy blue whale song: Number of hours per day with song recorded from April 2023 to March 2024 (Monitoring Periods 1 and 2) including automated detector performance metrics. (P_1 and R_1: Precision and Recall during Monitoring Period 1; P_2 and R_2: Precision and Recall during Monitoring Period 2).

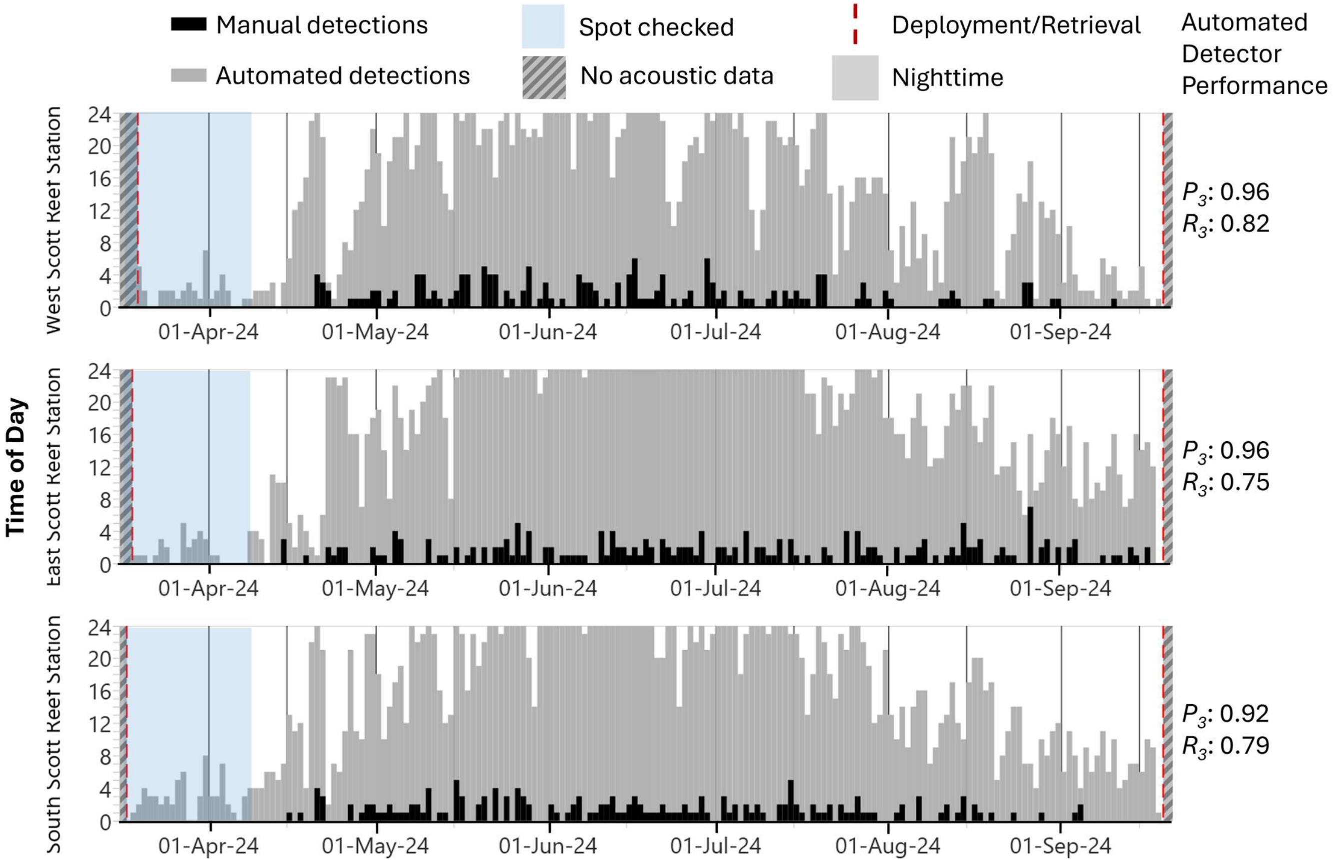


Figure 23. Pygmy blue whale song: Number of hours per day with song recorded from March to September 2024 (Monitoring Period 3) including automated detector performance metrics (P_3 and R_3: Precision and Recall during Monitoring Period 3).

3.1.1.2. Non-song vocalisations

Pygmy blue whale non-song vocalisations vary in frequency, shape, and duration (Oleson et al. 2007a, Recalde-Salas et al. 2014). Figures 24 to 27 provide a sample of the variability observed in the present data set. Though pygmy blue whale non-song vocalisations can overlap in characteristics with calls of Antarctic blue whales and sei whales, most detections were assigned to pygmy blue whales given the notable overlap in occurrence between these signals (Figure 29) and the pygmy blue whale song notes (Figure 20).

Non-song calls were detected at all recording stations (Figure 29 to 32) with estimated automated detector performance varying depending on station and Monitoring Period (Appendix B.4). Automated detector performance results indicate that this is an underestimate of call presence with *R* not exceeding 0.76. The presence of these calls may be underestimated because the automated detector missed faint signals identified during manual review. Further, during periods when humpback whales were singing, the downsweeping moans in the humpback whale songs may have masked or overlapped with the blue whale signals, which makes automated and manual classification challenging.

Pygmy blue whale non-song vocalisations generally followed the same occurrence trends as pygmy blue whale songs. However, the monthly proportion of detection-positive days was consistently lower for non-song calls than songs, with the exception of January and February 2024 at East Scott Reef (Table 5). In addition, non-song calls were systematically detected in fewer hours per day than songs. All Scott reef stations considered, non-song vocalisations were manually confirmed at least once in all months – except East Scott Reef in September 2023. The monthly proportions of detection-positive days showed more inter-month variability than for songs, with the highest detection rates occurring in June and November at all stations. Similar to song, there was no evidence of a diel trend in pygmy blue whale non-song vocalisations' occurrence, with the signals present throughout all hours of the day. One of the most commonly detected non-song vocalisations, the D-call, is commonly associated with foraging and social interactions and produced by male and female animals from all blue whale populations. The non-song detections typically detected the D-call and EIO-1 calls, experienced analysts confirmed the association of these calls to blue whales based upon contextual information within the file, in addition to the individual vocalisation characteristics. This suggests that the use of the monitored areas, Scott Reef in particular, for foraging activities cannot be ruled out for the periods when non-song vocalisations occurred.

A combined panel plot showing song and non-song detections over the three monitoring periods is provided in Figure 33. Section 3.2.1 provides further directional analysis of these signals.

Automated detections within the blue highlighted periods in Figures 29 to 32 have been spot checked (as described in Section 2.2.2). and no blue whale non-song vocalisation was manually confirmed. The autodetections within these periods are typically due to baleen whale downsweeps which have not been attributed to a specific whale species (Figure 28), however the individual calls, and the broader context around them in the recordings, however they are not representative of EIO pygmy blue whale vocalisations.

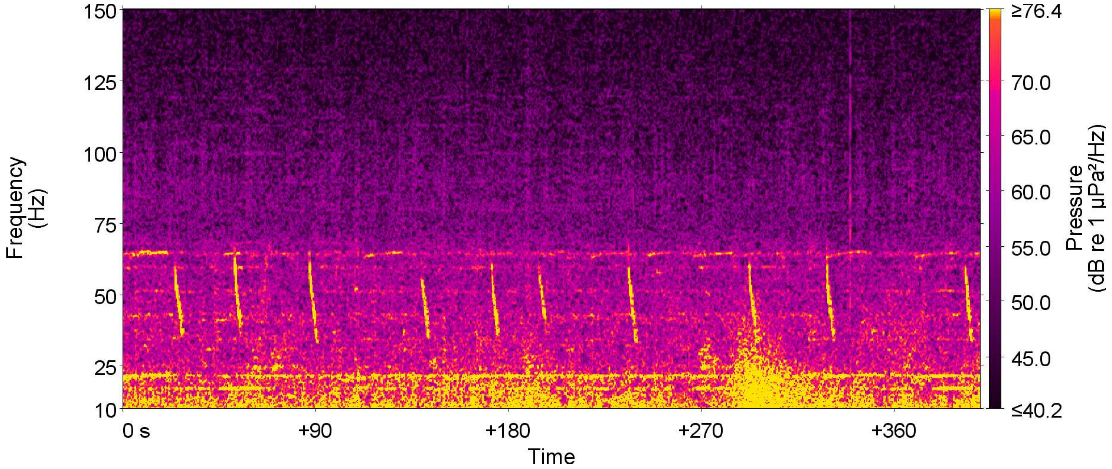


Figure 24. Blue whale D-calls: (Top) (1 Hz discrete Fourier Transform (DFT) frequency step, 0.1 s DFT temporal observation window (TOW), 0.005 s DFT time advance, and Hann window resulting in a 95 % overlap and DFT size (NDFT) of 32768). The spectrogram is 400 s long.

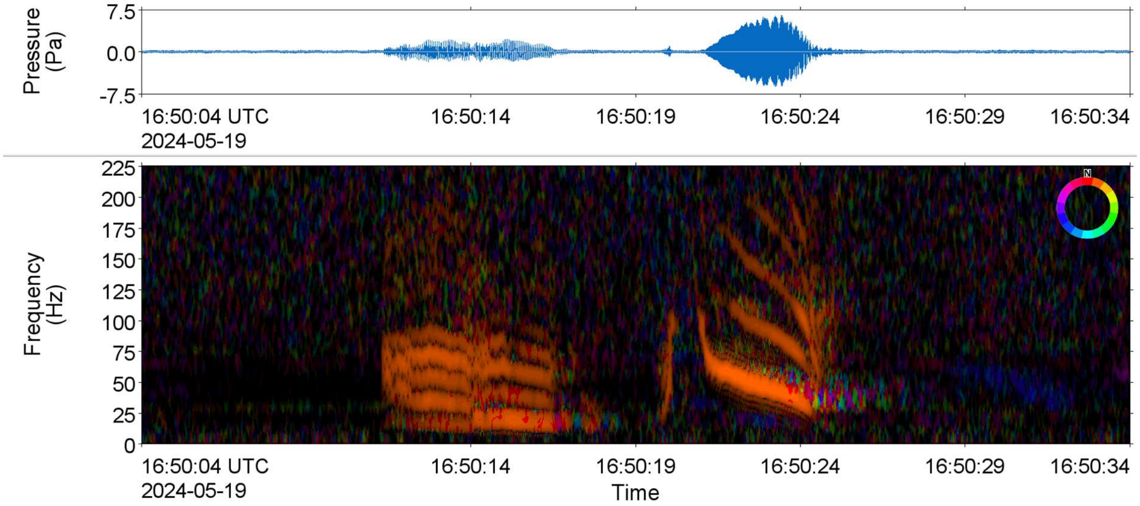


Figure 25. Pygmy blue whale non-song vocalisations: (Top) Waveform and (bottom) directogram of non-song calls recorded west of East Scott Reef on 19 May 2024 (1 Hz discrete Fourier Transform (DFT) frequency step, 0.2 s DFT temporal observation window (TOW), 0.002 s DFT time advance, and Hann window resulting in a 95 % overlap and DFT size (N_{DFT}) of 32768). The spectrogram is 30 s long.

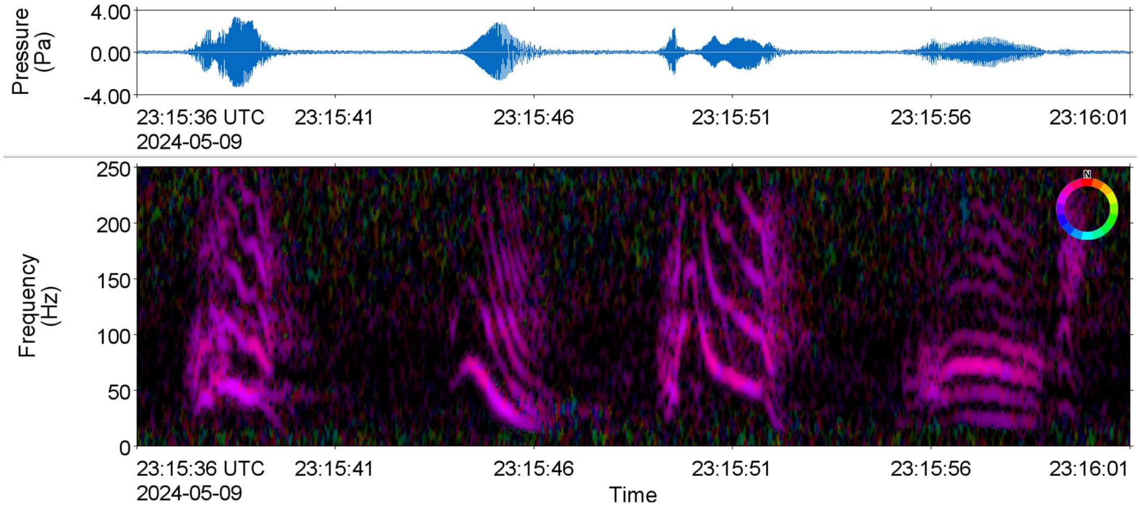


Figure 26. Pygmy blue whale non-song vocalisations: (Top) Waveform and (bottom) directogram of non-song calls recorded west of East Scott Reef on 9 May 2024 (1 Hz discrete Fourier Transform (DFT) frequency step, 0.2 s DFT temporal observation window (TOW), 0.02 s DFT time advance, and Hann window resulting in a 95 % overlap and DFT size (N_{DFT}) of 32768). The spectrogram is 25 s long.

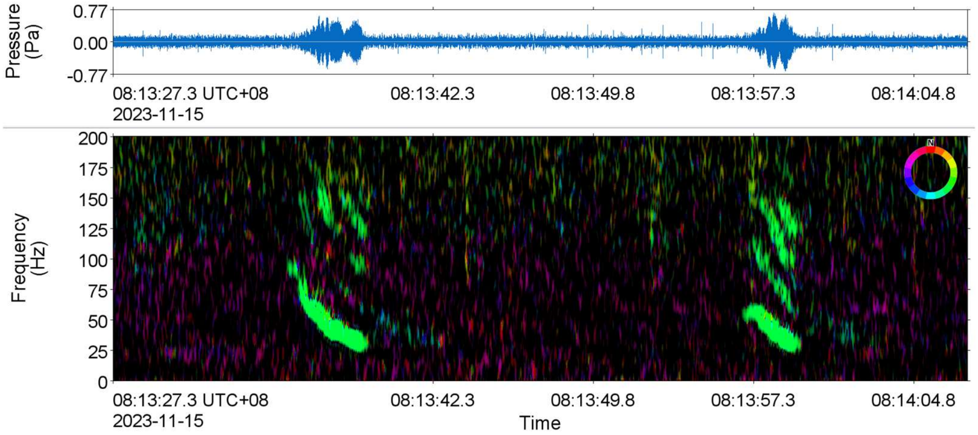


Figure 27. Pygmy blue whale non-song vocalisations: Directogram (bottom) and waveform (top) of two Eastern Indian Ocean (EIO) pygmy blue whale non-song calls, originating from southeast of the recorder, recorded at West Scott Reef on 15 Nov 2023 (1 Hz discrete Fourier Transform (DFT) frequency step, 0.2 s DFT temporal observation window (TOW), 0.02 s DFT time advance, and Hann window resulting in a 75 % overlap and DFT size (N_{DFT}) of 16384). The spectrogram is 40 s long.

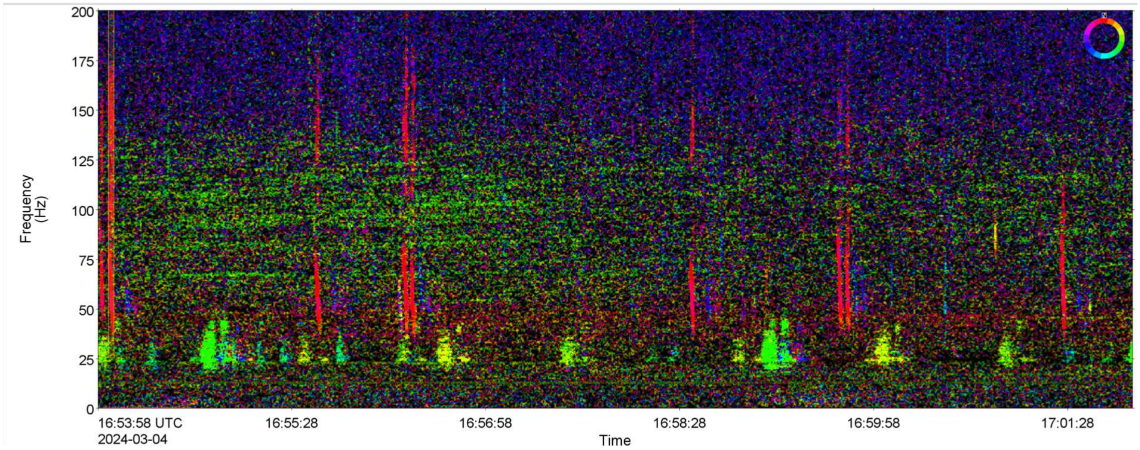


Figure 28. Baleen whale downswept vocalisations: Directogram showing baleen whale downswept vocalisations (red vocalisations) which are yet to be attributed to a particular species, however they are not from Eastern Indian Ocean (EIO) pygmy blue whales , originating from southeast of the recorder, recorded at West Scott Reef on 15 Nov 2023 (0.4 Hz discrete Fourier Transform (DFT) frequency step, 2 s DFT temporal observation window (TOW), 0.5 s DFT time advance, and Hann window resulting in a 75 % overlap and DFT size (N_{DFT}) of 64000).

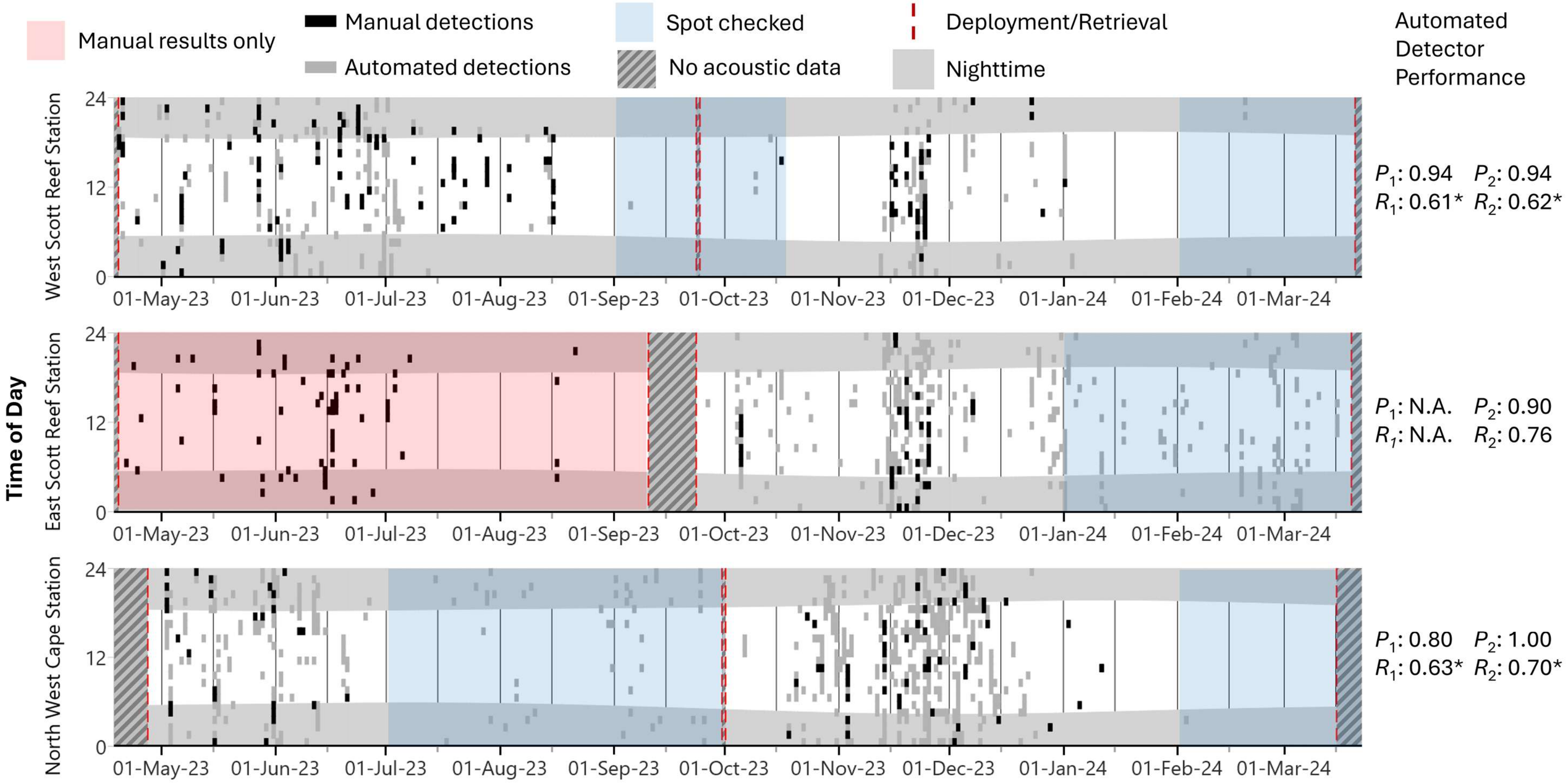


Figure 29. Pygmy blue whale non-song: Daily and hourly occurrence of non-song calls recorded from April 2023 to March 2024 (Monitoring Periods 1 and2) including automated detector performance metrics (P_1 and R_1: Precision and Recall during Monitoring Period 1; P_2 and R_2: Precision and Recall during Monitoring Period 2). * Note that automated detector performance evaluation indicated high uncertainty for these metrics, so they should be considered rough estimates (Appendix C.3). Where automated detector performance was poor, only manual results are provided and should be considered an underestimate of true occurrence. The grey areas indicate hours of darkness (nighttime) from sunset to sunrise (Ocean Time Series Group 2009).

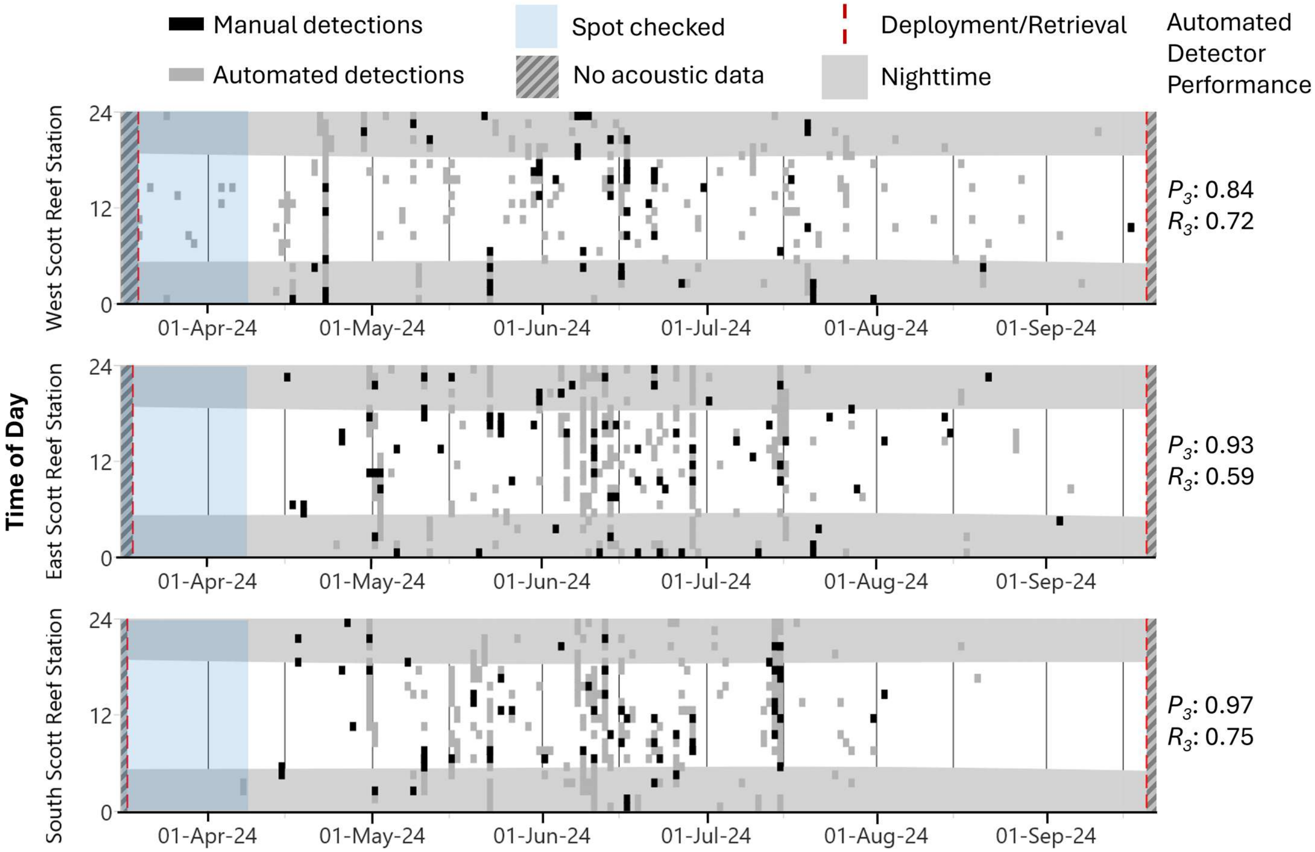


Figure 30. Pygmy blue whale non-song: Daily and hourly occurrence of non-song calls recorded from March to September 2024 (Monitoring Period 3) including automated detector performance metrics (P_3 and R_3: Precision and Recall during Monitoring Period 3). The grey areas indicate hours of darkness (nighttime) from sunset to sunrise (Ocean Time Series Group 2009).

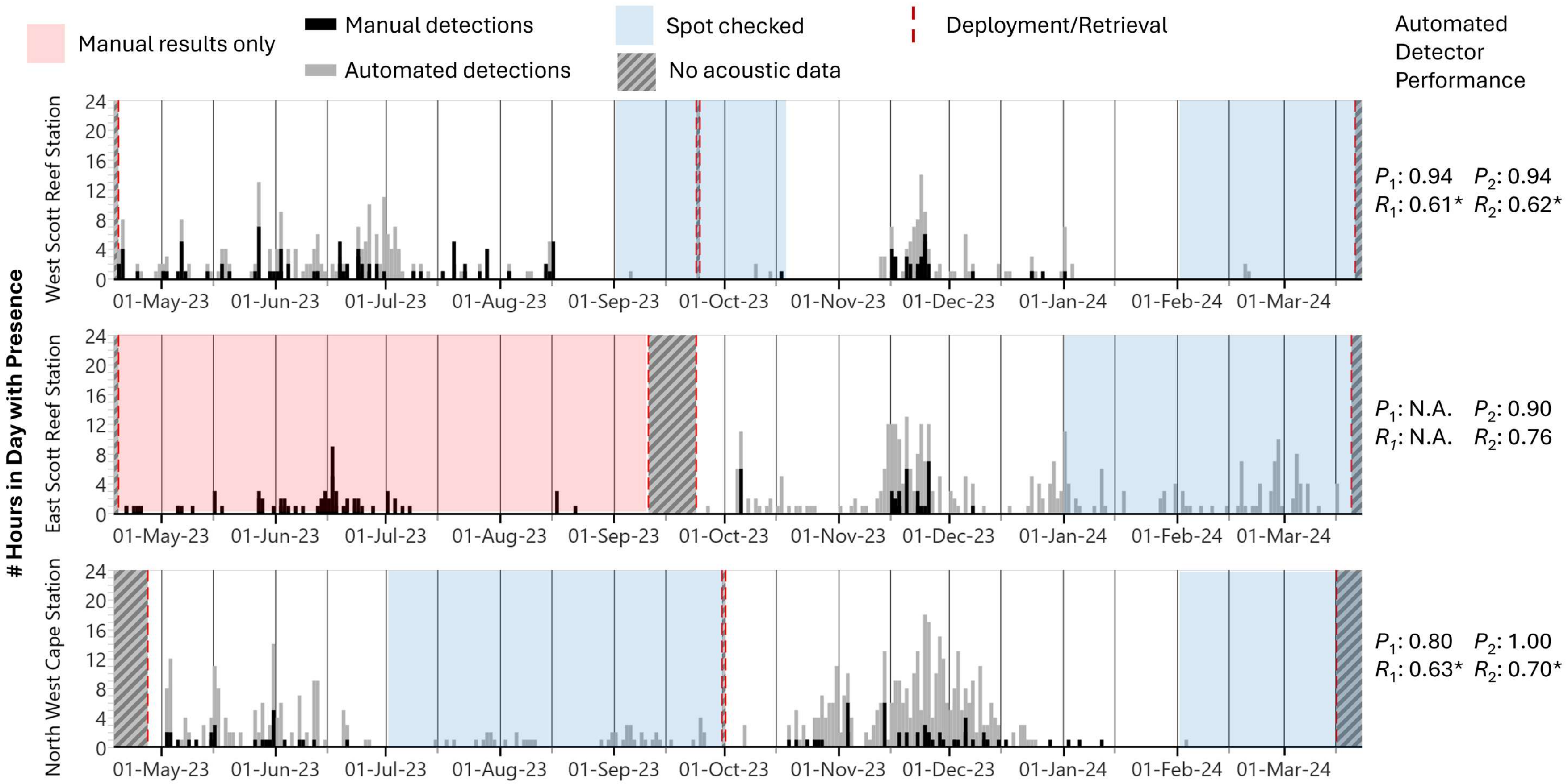


Figure 31. Pygmy blue whale non-song: Number of hours per day with non-song calls recorded from April 2023 to March 2024 (Monitoring Periods 1 and 2) including automated detector performance metrics (P_1 and R_1: Precision and Recall during Monitoring Period 1; P_2 and R_2: Precision and Recall during Monitoring Period 2). * Note that automated detector performance evaluation indicated high uncertainty for these metrics, so they should be considered rough estimates (see Appendix C.3). Where automated detector performance was poor, only manual results are provided and should be considered an underestimate of true occurrence.

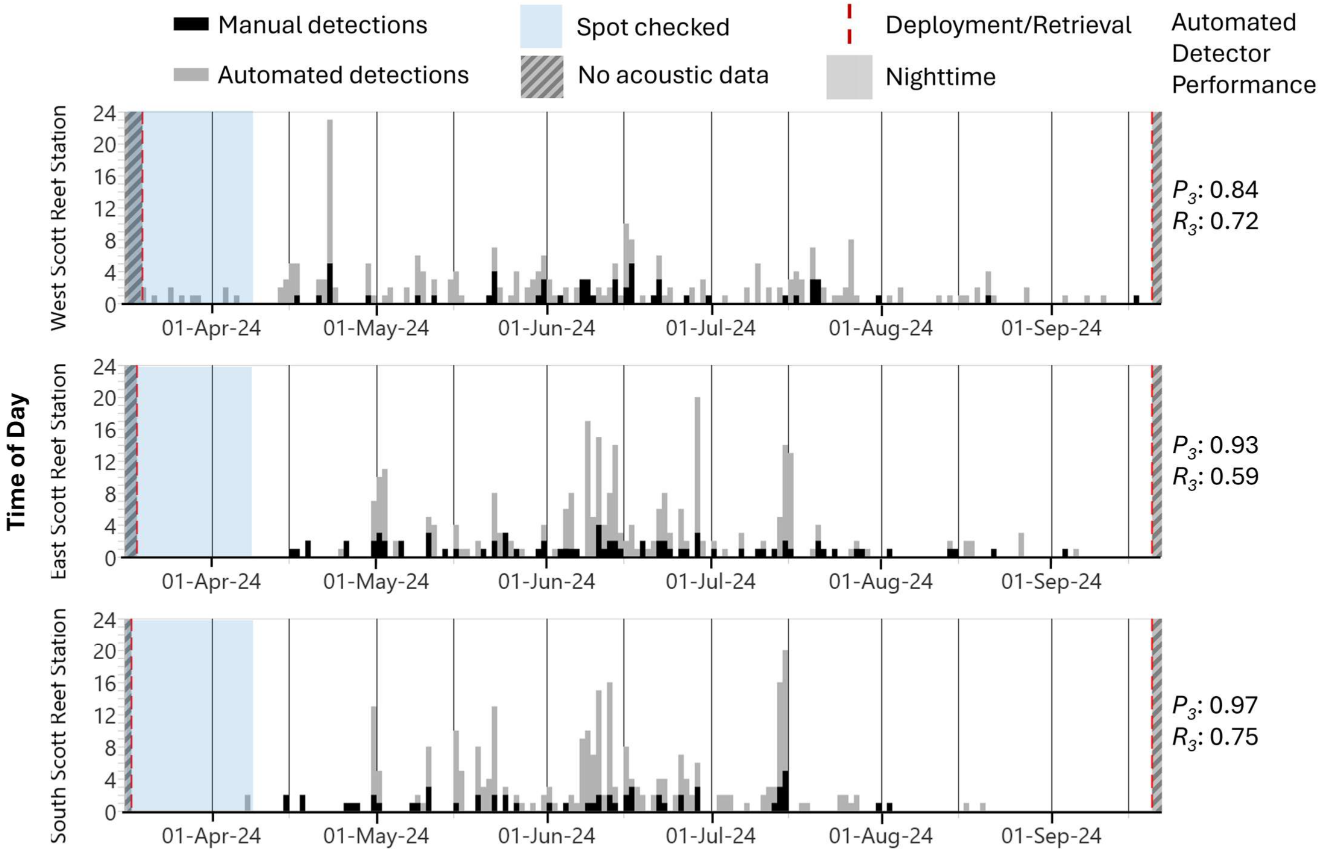


Figure 32. Pygmy blue whale non-song: Number of hours per day with non-song calls recorded from March to September 2024 (Monitoring Period 3) including automated detector performance metrics (P_3 and R_3: Precision and Recall during Monitoring Period 3).

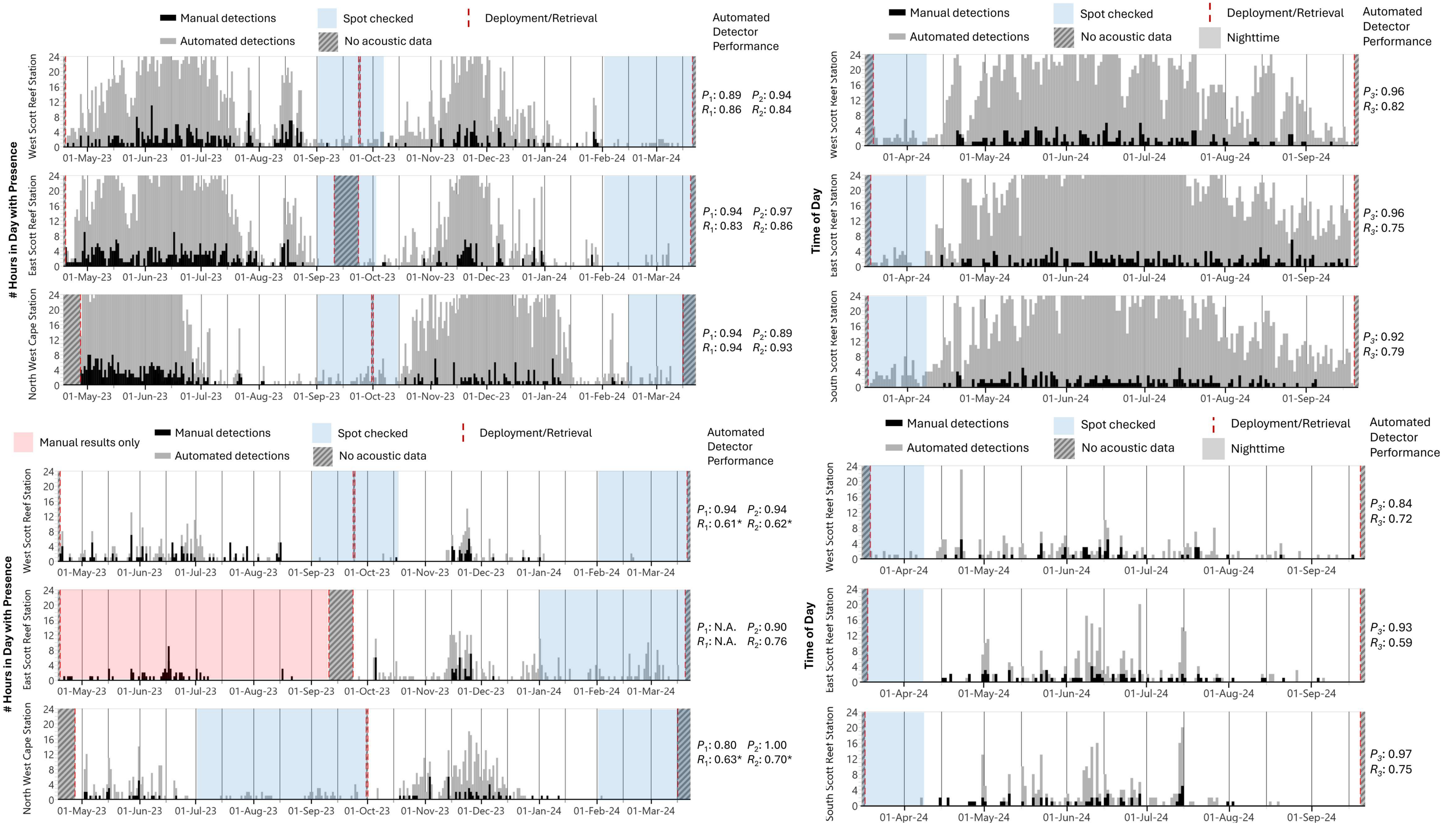


Figure 33. Pygmy blue whale song and non-song: Number of hours per day with (top) song and (bottom) non-song calls recorded from April 2023 to September 2024 (Monitoring Periods 1,2 and 3) including automated detector performance metrics (*P* and *R*: Precision and Recall. * Note that automated detector performance evaluation indicated high uncertainty for these metrics, so they should be considered rough estimates (see Appendix C.3). Where automated detector performance was poor, only manual results are provided and should be considered an underestimate of true occurrence.

3.1.2. Antarctic Blue Whales

Antarctic blue whales produce a song known as the ‘Z’ call (Figure 34), which is composed a single note (Širović et al. 2004) named for its stereotyped shape when visualised as a spectrogram. The ‘Z’ shape starts around 26 Hz and ends at approximately 18 Hz, with a duration of approximately 20 s (Širović et al. 2004, Gavrilov et al. 2012). In this study, signals were often faint, with only the upper ~25 Hz tone of the call present at ~60 s intervals (Figure 35).

Antarctic blue whale Z-calls were primarily detected at station North West Cape from April to June with a peak in May (90% detection-positive days) and a few additional sporadic detection events between July and October. Isolated manual detections occurred between May and September near Scott Reef, primarily at station West Scott Reef (Table 5; Figure 36 to 39). Antarctic blue whale Z-calls were detected manually only once at East Scott Reef and on two occasions at South Scott Reef.

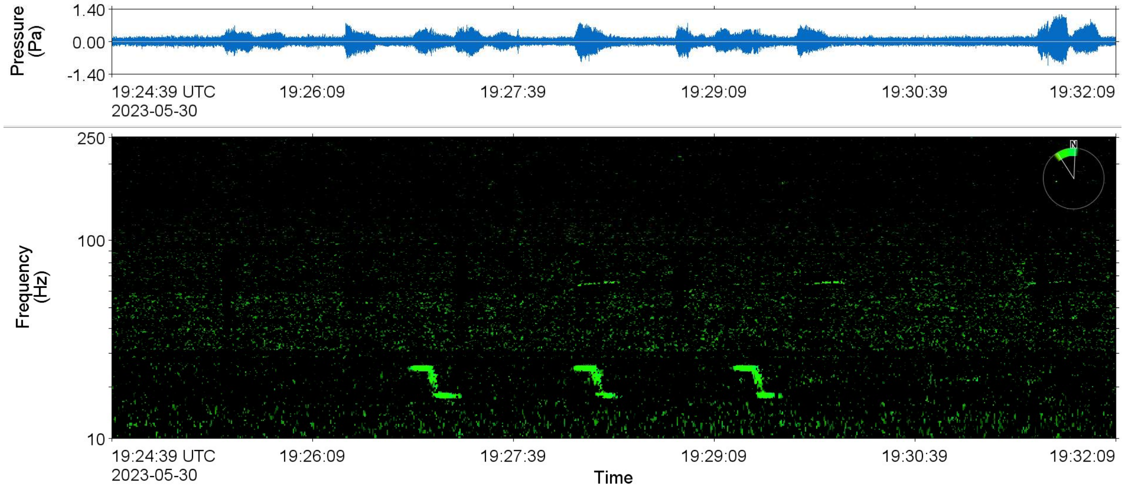


Figure 34. Antarctic blue whale song: Directogram of Z-calls recorded coming from the northwest at North West Cape on 30 May 2023 (0.4 Hz discrete Fourier Transform (DFT) frequency step, 2 ~~m~~s DFT temporal observation window (TOW), 0.5 ~~m~~s DFT time advance, and Hann window resulting in a 75 % overlap and DFT size (N_{DFT}) of 131072). The spectrogram is 450 s long. Faint pygmy blue whale unit II song notes are also present in the directogram.

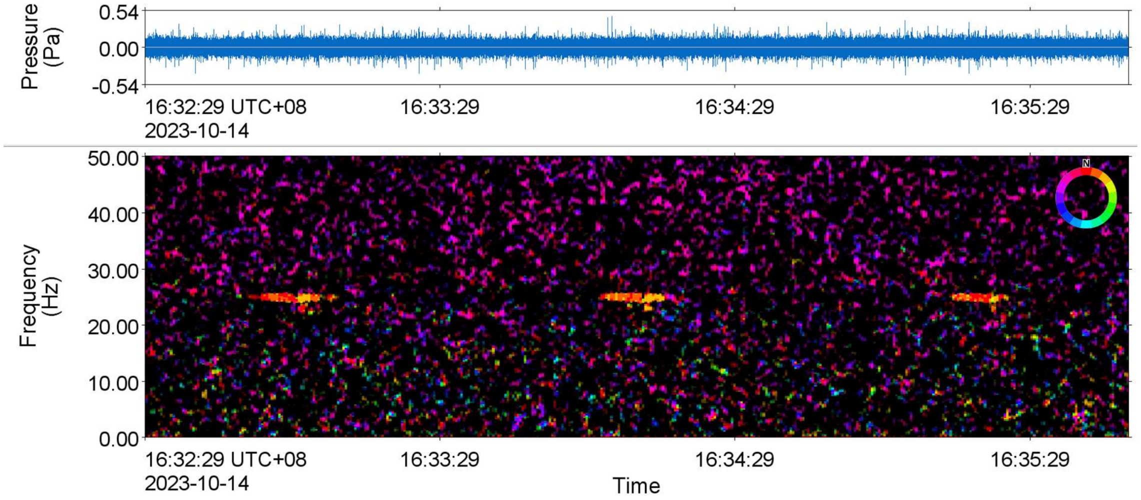


Figure 35. Antarctic blue whale song: Directogram (bottom) and waveform (top) of the upper energy of three Antarctic blue whale Z-calls, originating from north-northeast to the recorder, recorded at West Scott Reef on 14 Oct 2023 (0.4 Hz discrete Fourier Transform (DFT) frequency step, 2 s DFT temporal observation window (TOW), 0.5 s DFT time advance, and Hann window resulting in a 75 % overlap and DFT size (N_{DFT}) of 16384). The spectrogram is 200 s long.

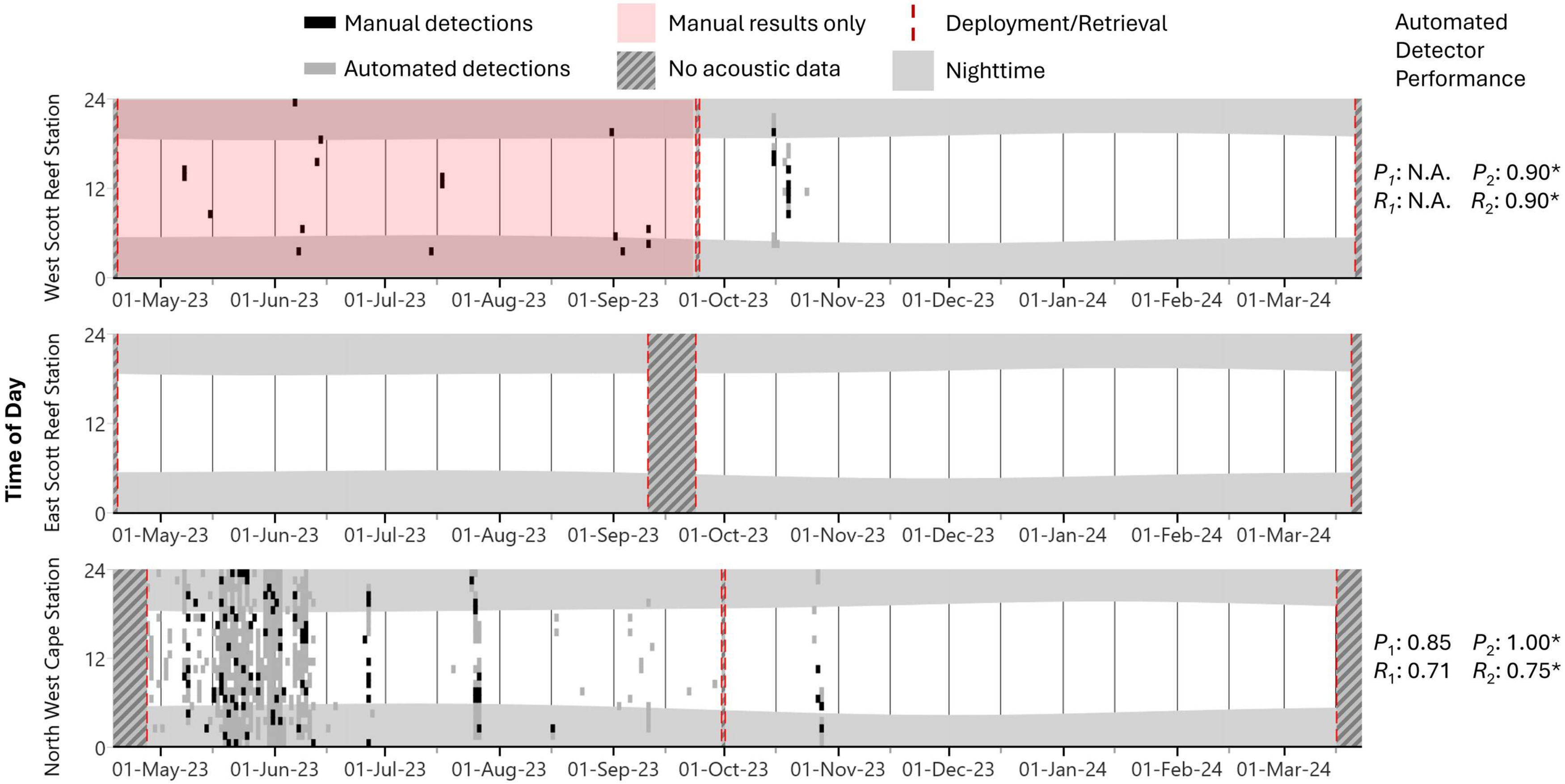


Figure 36. Antarctic blue whale: Daily and hourly occurrence of Z-calls recorded from April 2023 to March 2024 (Monitoring Periods 1 and 2) including automated detector performance metrics (P_1 and R_1: Precision and Recall during Monitoring Period 1; P_2 and R_2: Precision and Recall during Monitoring Period 2). * Note that automated detector performance evaluation indicated high uncertainty for these metrics, so they should be considered rough estimates (Appendix C.3). Where automated detector performance was poor, only manual results are provided and should be considered an underestimate of true occurrence. The grey areas indicate hours of darkness (nighttime) from sunset to sunrise (Ocean Time Series Group 2009).

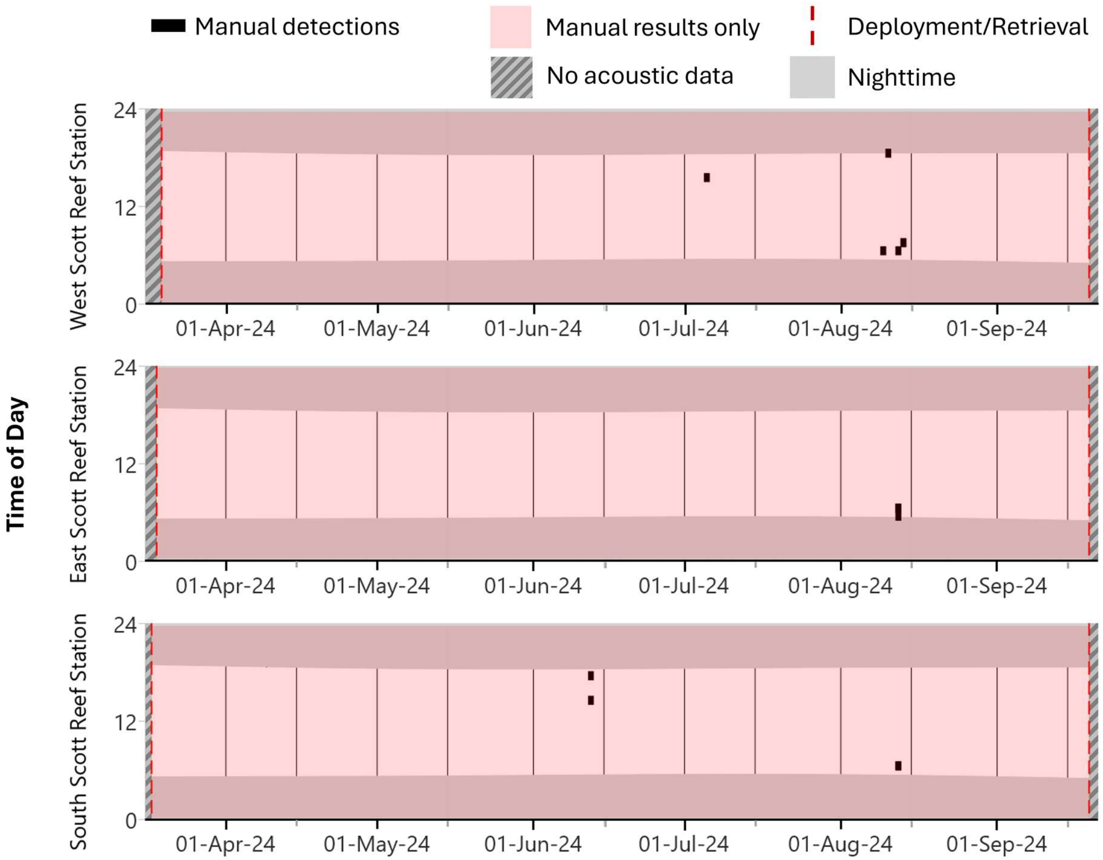


Figure 37. Antarctic blue whale: Daily and hourly occurrence of Z-calls recorded from March to September 2024 (Monitoring Period 3). As automated detector performance was poor, only manual results are provided and should be considered an underestimate of true occurrence. The grey areas indicate hours of darkness (nighttime) from sunset to sunrise (Ocean Time Series Group 2009).

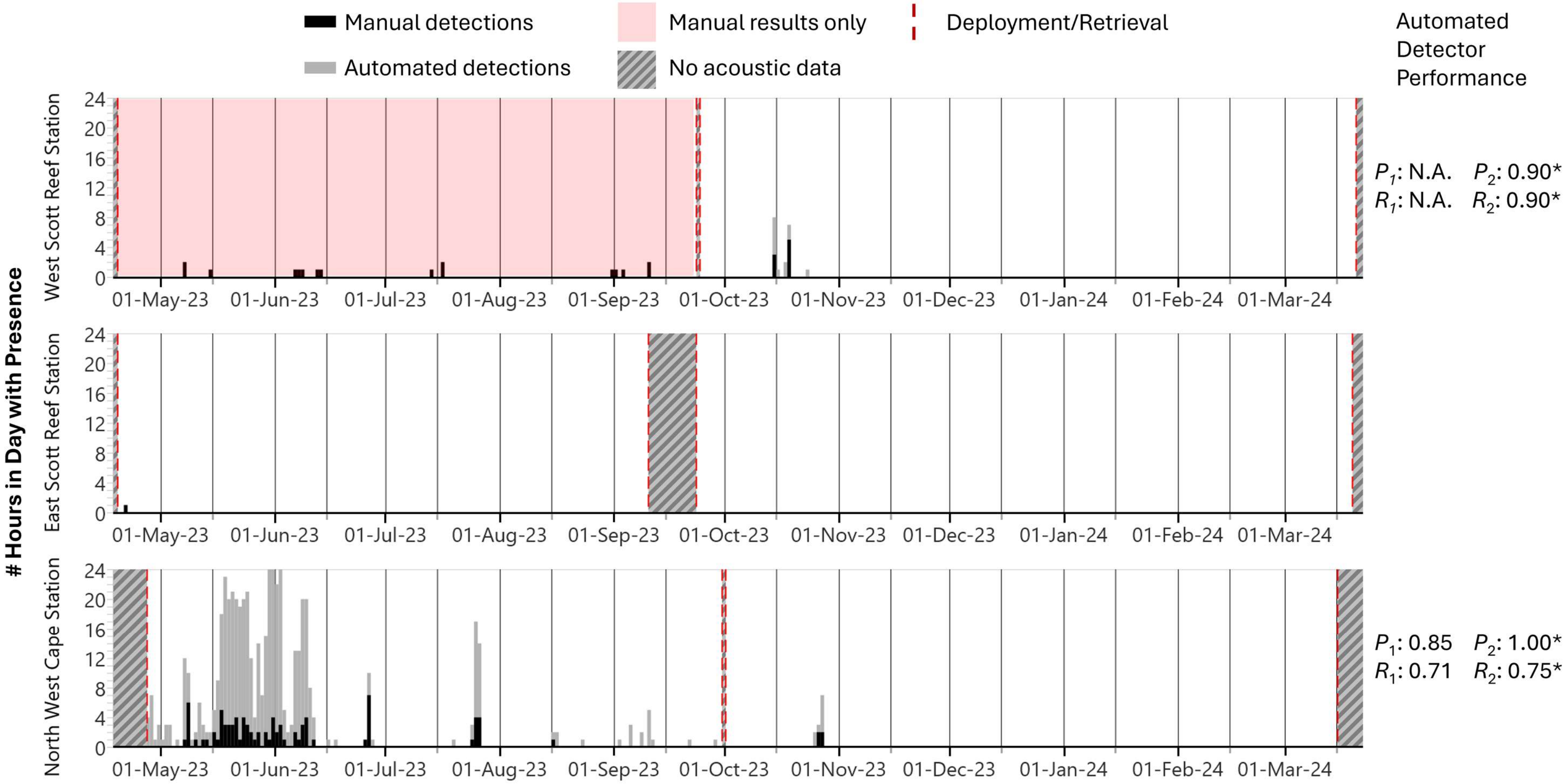


Figure 38. Antarctic blue whale: Number of hours per day with Z-calls recorded from April 2023 to March 2024 (Monitoring Periods 1 and 2) including automated detector performance metrics (P_1 and R_1: Precision and Recall during Monitoring Period 1; P_2 and R_2: Precision and Recall during Monitoring Period 2). * Note that automated detector performance evaluation indicated high uncertainty for these metrics, so they should be considered rough estimates (Appendix C.3). Where automated detector performance was poor, only manual results are provided and should be considered an underestimate of true occurrence.

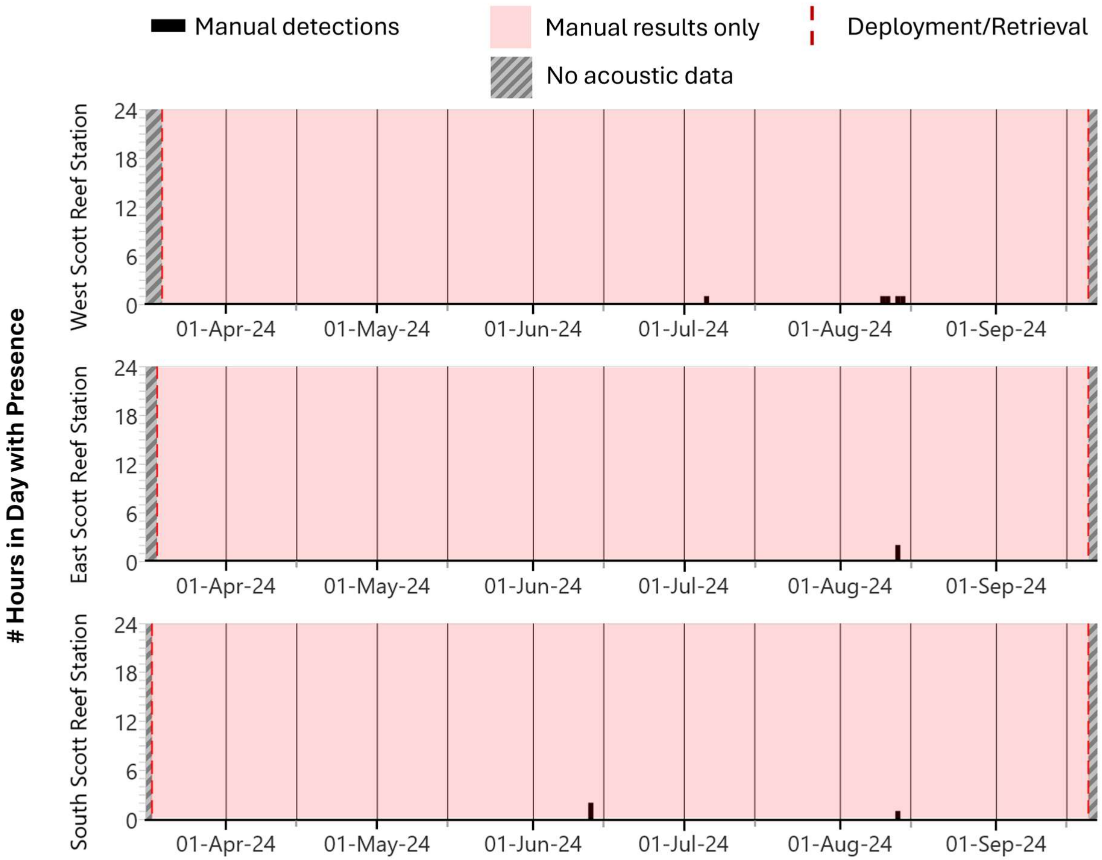


Figure 39. Antarctic blue whale: Number of hours per day with vocalisations recorded from March to September 2024 (Monitoring Period 3). As automated detector performance was poor, only manual results are provided and should be considered an underestimate of true occurrence.

3.2. Directional Characterisation and Detection Ranges of Calling Whales

The following sections report on the directional processing of the multi-channel acoustic data. It provides information on the spatial distribution of pygmy blue whales around the three stations as well as minimum daily counts of vocalising individuals. These results should be viewed and interpreted with the following caveats in mind:

- The minimum daily counts of vocalising individuals (AMN) are conservative index of occurrence primarily because of the short period over which whales are counted (10 min). A longer integration period may result in higher counts as not all whales present would be expected to vocalize at all times and a higher number might be captured over a longer period. The choice of a short window was made to avoid counting transiting whales in more than one bin, because a large proportion of animals are expected to be traveling in this area.
- The error associated with bearing estimates varies as a function of frequency. For a given frequency, it also varies as a function of SNR. Therefore, the actual error associated with bearing estimates of blue whale vocalisations falls within a range of values, e.g., 20–60 degrees for pygmy blue whale vocalisations. For consistency, we applied a bearing error of 20 and 30 degrees when estimating the number of vocalising whales based on detections of songs’ Unit 2 and downswept calls, respectively. These errors, which define the angle bins within which vocalising whales are counted, could result in an underestimate of the number of calling whales in cases where two or more whales are calling close to each other (e.g., bearing offset is 20–30 degrees). In cases of closely spaced callers, received level was not deemed to be a reliable feature to distinguish potentially distinct callers in the same bearing cluster.
- Songs are only produced by males. Therefore, song-based AMN only captures approximately half of the population. Although both male and female pygmy blue whales produce non-song vocalisations, it is likely that not all individuals present in the recorder’s detection area produce social calls at any given time. Therefore, both estimates are minimum numbers of vocalising animals and under-estimate the total number of pygmy blue whales that were present during the migratory periods.
- Some of the directional results (radar plots) rely on determining range from received and source levels. Although source levels are fairly well characterised for pygmy blue whale song notes, there is less confidence in the representativeness of the SL value used for their audible calls (Gavrilov et al. 2011). The accuracy of the radar plots is contingent on the validity of this estimates. However, the bearing estimates are not affected by source level and range estimates.

3.2.1. EIO Pygmy Blue Whales

3.2.1.1. Estimating the Minimum Number of Calling Whales

During the first year of monitoring (April 2023 to March 2024), the daily AMN of singing pygmy blue whales ranged between one and four, with mean values (across all days with at least one detection) of 1.4, 2.3, and 1.7 at West Scott Reef, North West Cape, and East Scott Reef Stations, respectively (Figure 40). The daily AMN of pygmy blue whales producing non-song calls ranged between one and three at all stations, with mean values (across all days with at least one detection) of 1.2 at East and West Scott Reef Stations and 1.4 at North West Cape Station (Figure 42). The periods with the maximum AMN for both call types generally overlapped.

During the last Monitoring Period, the daily AMN of singing pygmy blue whales ranged between one and six, with mean values (across all days with at least one detection) of 2.0, 2.4, and 2.3 at West, East and South Scott Reef Stations, respectively (Figure 41). The daily AMN of pygmy blue whales producing non-song vocalisations ranged between one and three at all stations, with mean values (across all days with at least one detection) of 1.1, 1.4, and 1.1 at West, East, and South Scott Reef Stations, respectively (Figure 43).

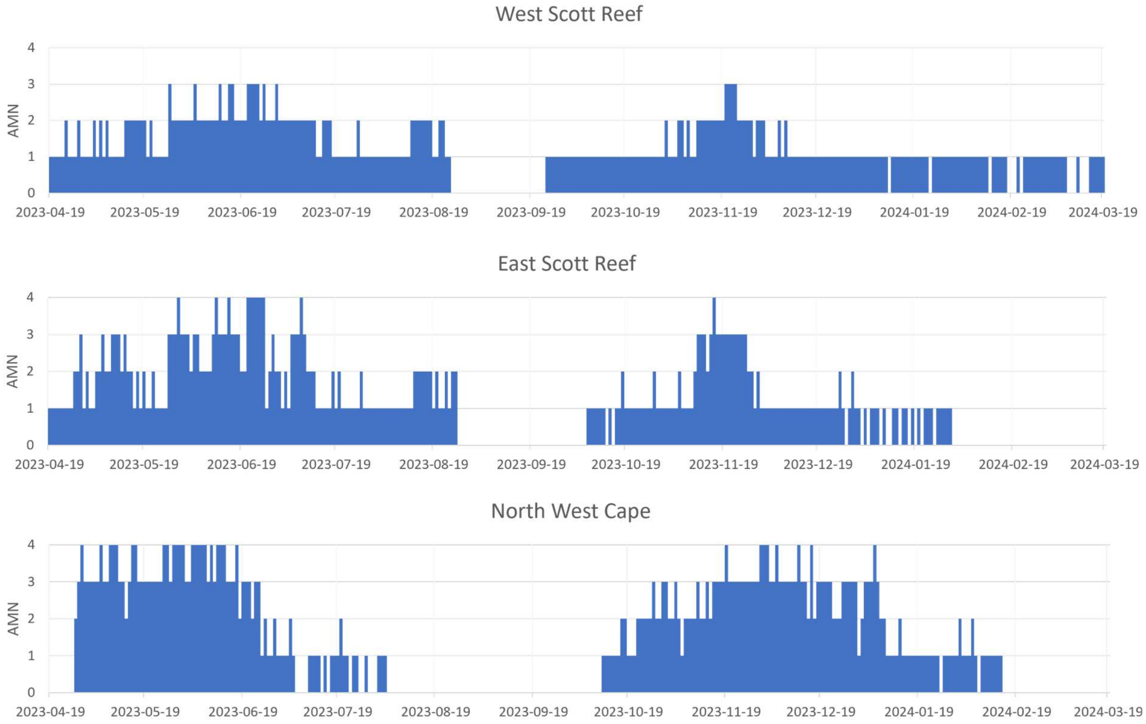


Figure 40. Pygmy blue whale unit II song note: Absolute Minimum Number (AMN) of singing whales detected per day, which is the maximum per day of the AMN per 10-min time block, between April 2023 and March 2024 at the three recording stations.

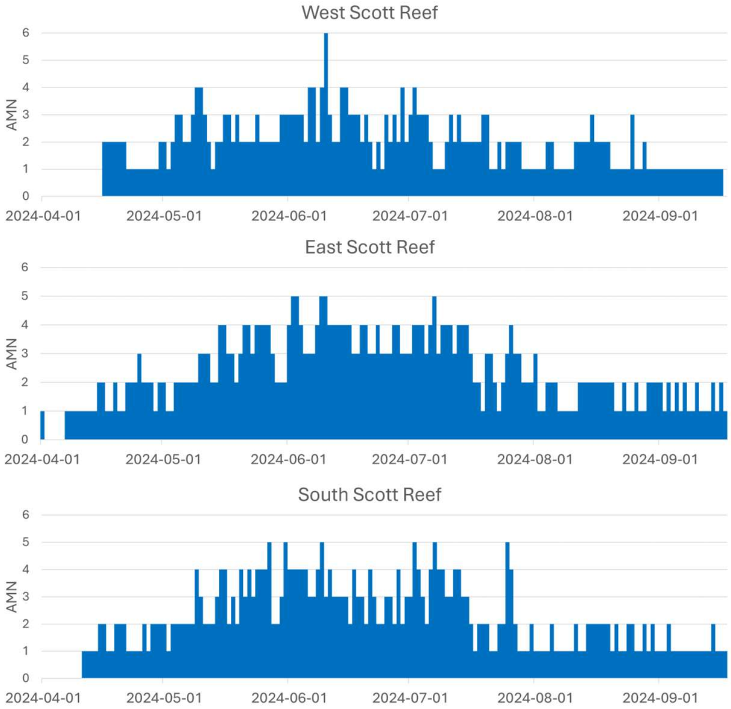


Figure 41. Pygmy blue whale unit II song note: Absolute Minimum Number (AMN) of singing whales detected per day, which is the maximum per day of the AMN per 10-min time block, between March and September 2024 at the three recording stations.

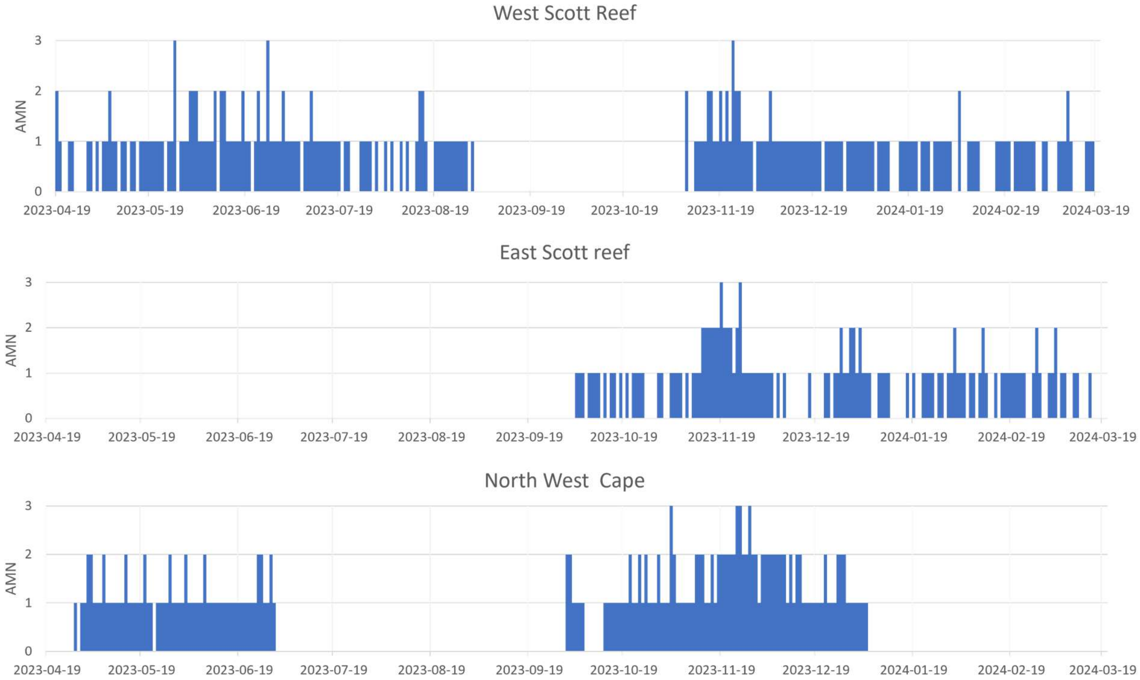


Figure 42. Pygmy blue whale non-song call: Absolute Minimum Number (AMN) of vocalising whales detected per day, which is the maximum per day of the AMN per 10-min time block, between April 2023 and March 2024 at the three recording stations.

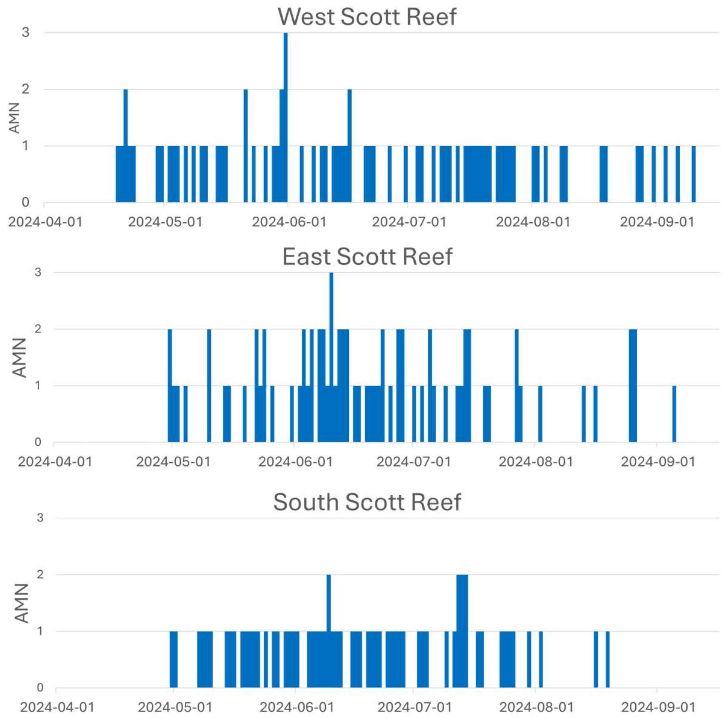


Figure 43. Pygmy blue whale non-song call: Absolute Minimum Number (AMN) of vocalising whales detected per day, which is the maximum per day of the AMN per 10-min time block, between March and September 2024 at the three recording stations.

3.2.1.2. Distribution and Movements of Calling Whales around Scott Reef

The radar plots shown in Figures 44 to 50 present the spatial distribution of song-producing pygmy blue whales around Scott Reef. At station West Scott Reef, singing pygmy blue whales were most often located within 10 km and on the deep-water side (i.e. west) of the recorder (Figures 44 to 46). This was true for northbound and southbound animals. Blue whales were also present in more distant sectors (in the 30–50 km bin), their location coinciding with areas shown to produce longer detection ranges via detection range modelling (see Section 3.2.1.3). In relatively few instances, whales were detected between the recorder and the reef itself. There were no clear changes in distribution between Monitoring Periods, i.e. between the northbound and southbound migrations .

At station East Scott Reef, song detections were generally fairly evenly distributed from the NNW to the south via the eastern side of the reef, although the sectors to the NNW tended to have higher proportions of hours with detections (Figures 47 to 49). A few detections originated from the west side of the recorder, i.e. between the recorder and Scott reef. While the spatial distribution of singing blue whales was comparable during Monitoring Periods 1 and 2, we noted a lower use of the 30-50 km sectors, which may reflect slight differences in habitat use or detection ranges in that period. At station South Scott Reef, song detections occurred relatively evenly around the recorder, except towards the NW where vocalising whales were noticeably closer (Figure 50)

The distribution of blue whales producing non-song vocalisations recorded by the West Scott Reef recorders was generally similar to that derived from songs, but the vocalising whales appeared to be more evenly distributed across sectors than singing individuals. Blue whales producing non-song vocalisations were detected closer to the reef then singing animals, partly due to their lower source levels and thus detection range (Figures 51 to 53). During Monitoring Period 3, despite the distribution of song detections being similar to Monitoring Periods 1 and 2, the distribution of non-song detections was more localised, primarily restricted to within 5km of the station. The restricted detections at station West Scott Reef do not change substantially across the three periods (Section 3.2.1.3). At station East Scott Reef, detections of non-song calls during the northbound migration (Monitoring Period 3) originated more often from the south-southeast of the recorder than during the southbound migration. The apparent greater use of sectors to the NNW of the recorder by singing whales was not observed in the distribution of whales producing non-song vocalisations (Figures 54 to 55).

At station South Scott Reef during Monitoring Period 3, individuals producing non-song vocalisations followed a similar spatial distribution as singing whales, with whales detected to the NW located closer to the recorder (Figure 56).

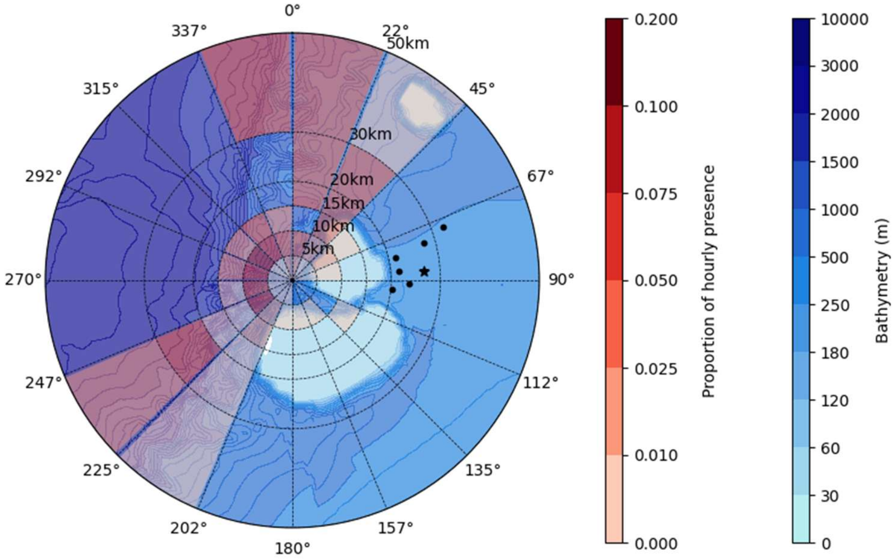


Figure 44. Pygmy blue whale song call, unit 2: Radar plot showing the proportion of hours with automated detections as a function of the range and bearing from West Scott Reef during Deployment 1. The area around the recorder was divided into 16 angular wedges 22.5 degrees wide and six range bins between 0 and 50 km from the recorder. The plot is centred on the location of the recorder. The black star and six black dots indicate the proposed Torosa FPSO and well locations, respectively.

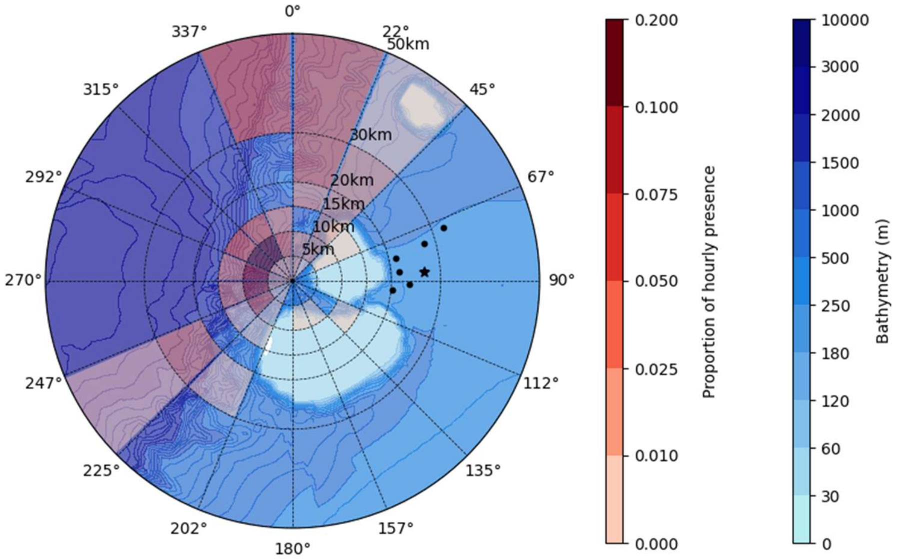


Figure 45. Pygmy blue whale song call, unit 2: Radar plot showing the monthly proportion of hours with automated detections as a function of the range and bearing from West Scott Reef during Deployment 2.

The area around the recorder was divided into 16 angular wedges 22.5 degrees wide and six range bins between 0 and 50 km from the recorder. The plot is centred on the location of the recorder. The black star and six black dots indicate the proposed Torosa FPSO and well locations, respectively.

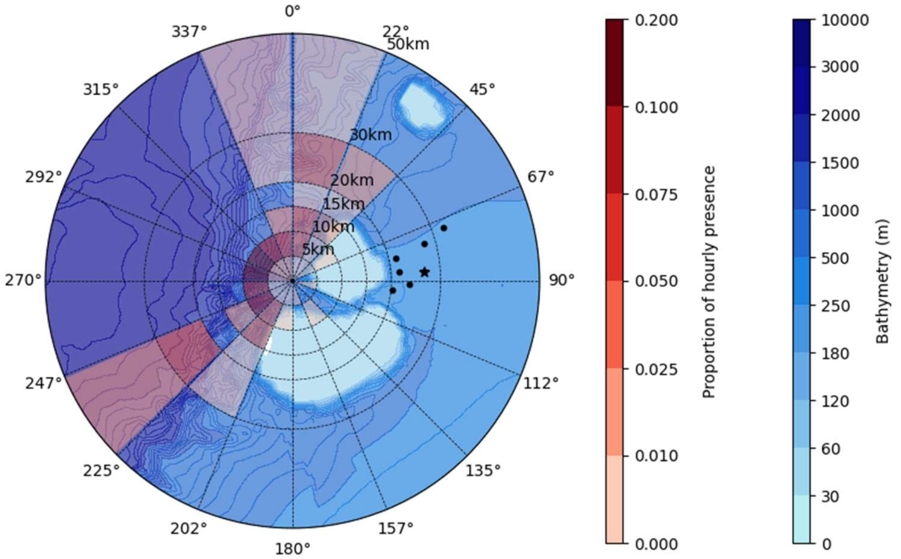


Figure 46. Pygmy blue whale song call, unit 2: Radar plot showing the monthly proportion of hours with automated detections as a function of the range and bearing from West Scott Reef during Deployment 3. The area around the recorder was divided into 16 angular wedges 22.5 degrees wide and six range bins between 0 and 50 km from the recorder. The plot is centred on the location of the recorder. The black star and six black dots indicate the proposed Torosa FPSO and well locations, respectively.

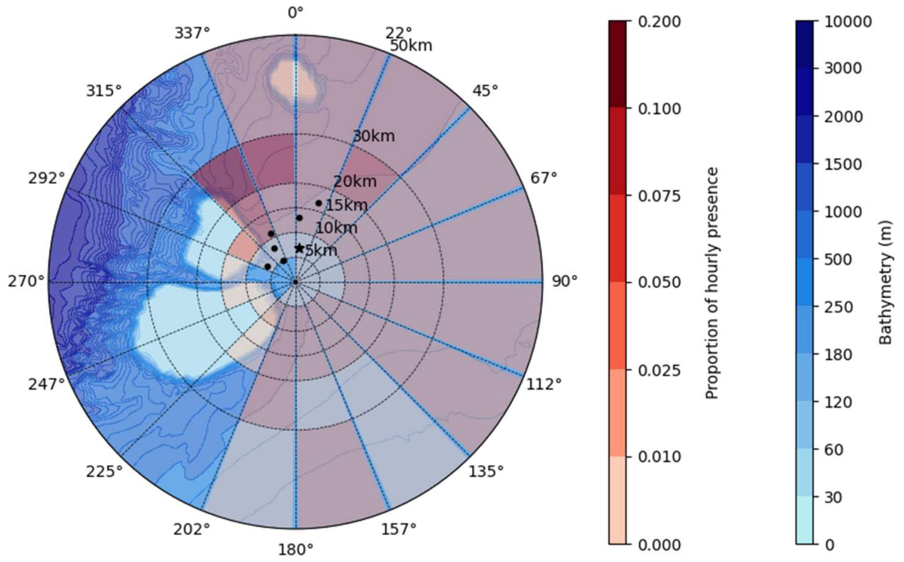


Figure 47. Pygmy blue whale song call, unit 2: Radar plot showing the monthly proportion of hours with automated detections as a function of the range and bearing from East Scott during Deployment 1. The area around the recorder was divided into 16 angular wedges 22.5 degrees wide and six range bins between 0 and 50 km from the recorder. The plot is centred on the location of the recorder. The black star and six black dots indicate the proposed Torosa FPSO and well locations, respectively.

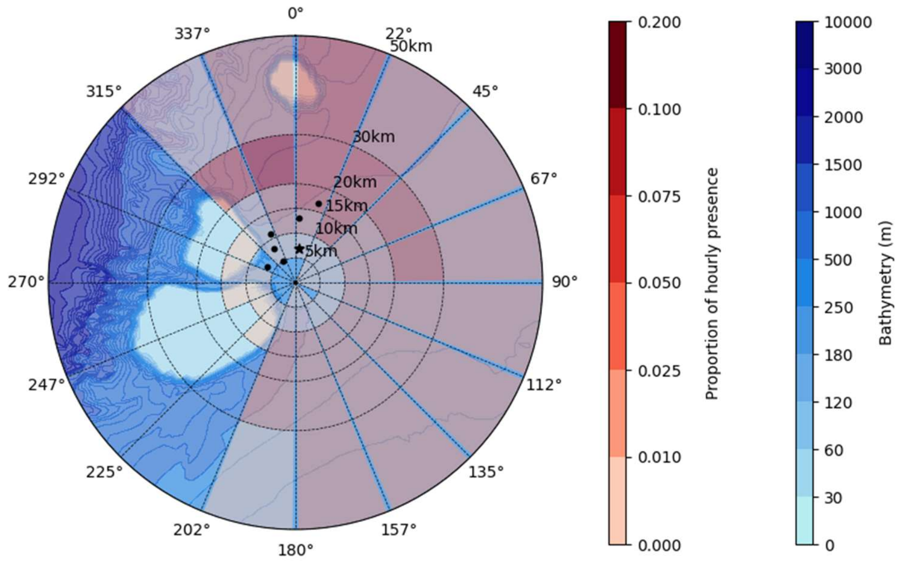


Figure 48. Pygmy blue whale song call, unit 2: Radar plot showing the monthly proportion of hours with automated detections as a function of the range and bearing from East Scott Reef during Deployment 2. The area around the recorder was divided into 16 angular wedges 22.5 degrees wide and six range bins between 0 and 50 km from the recorder. The plot is centred on the location of the recorder. The black star and six black dots indicate the proposed Torosa FPSO and well locations, respectively.

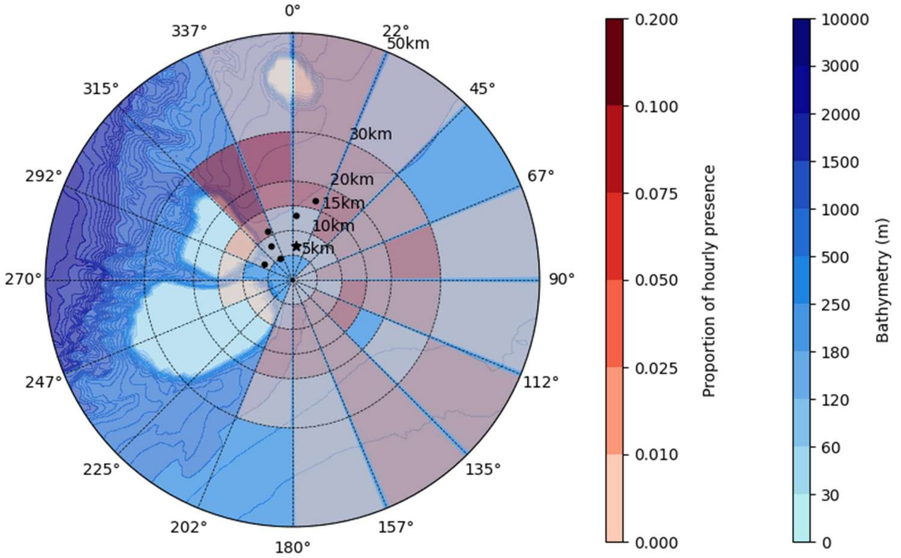


Figure 49. Pygmy blue whale song call, unit 2: Radar plot showing the monthly proportion of hours with automated detections as a function of the range and bearing from East Scott Reef during Deployment 3. The area around the recorder was divided into 16 angular wedges 22.5 degrees wide and six range bins between 0 and 50 km from the recorder. The plot is centred on the location of the recorder. The black star and six black dots indicate the proposed Torosa FPSO and well locations, respectively.

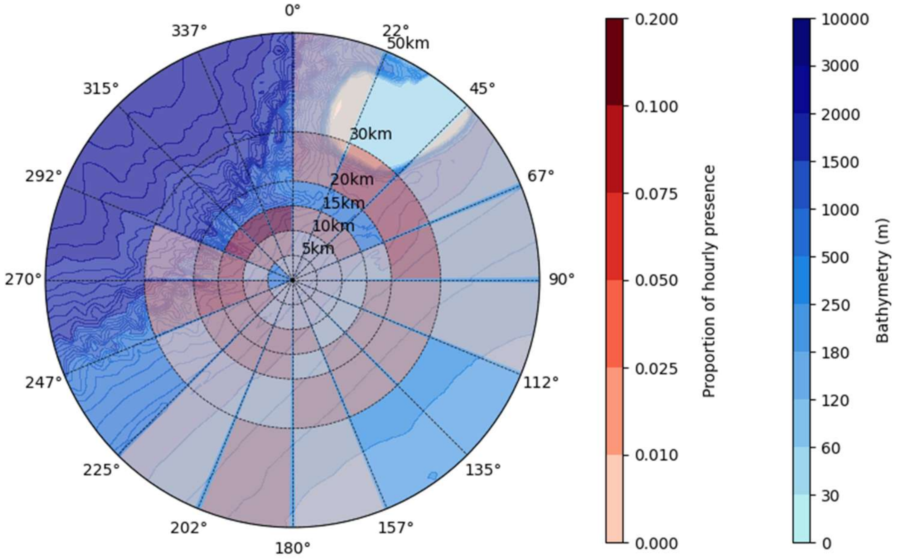


Figure 50. Pygmy blue whale song call, unit 2: Radar plot showing the monthly proportion of hours with automated detections as a function of the range and bearing from South Scott Reef during Deployment 3. The area around the recorder was divided into 16 angular wedges 22.5 degrees wide and six range bins between 0 and 50 km from the recorder. The plot is centred on the location of the recorder. The black star and six black dots indicate the proposed Torosa FPSO and well locations, respectively.

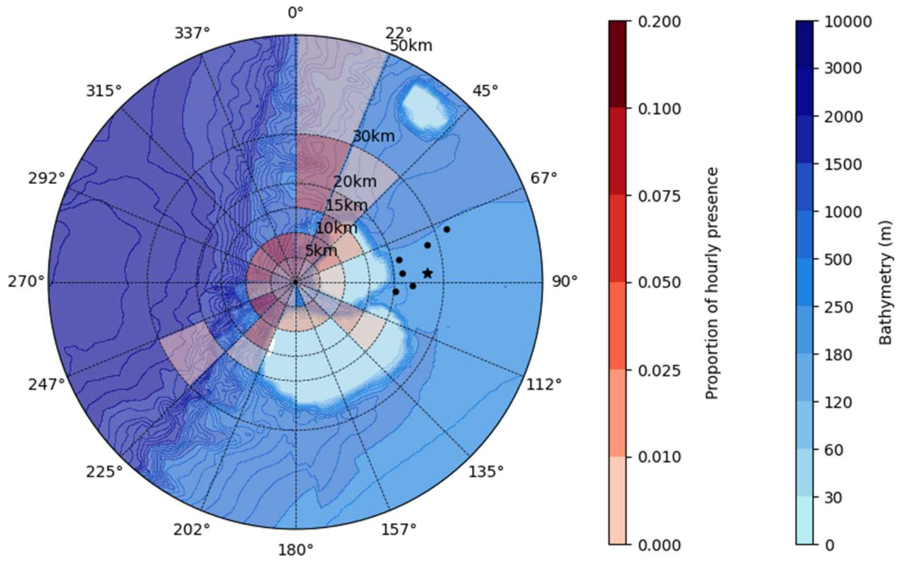


Figure 51. Pygmy blue whale non-song vocalisations: Radar plot showing the monthly proportion of hours with automated detections as a function of the range and bearing from West Scott Reef during Deployment 1. The area around the recorder was divided into 16 angular wedges 22.5 degrees wide and six range bins between 0 and 50 km from the recorder. The plot is centred on the location of the recorder. The black star and six black dots indicate the proposed Torosa FPSO and well locations, respectively.

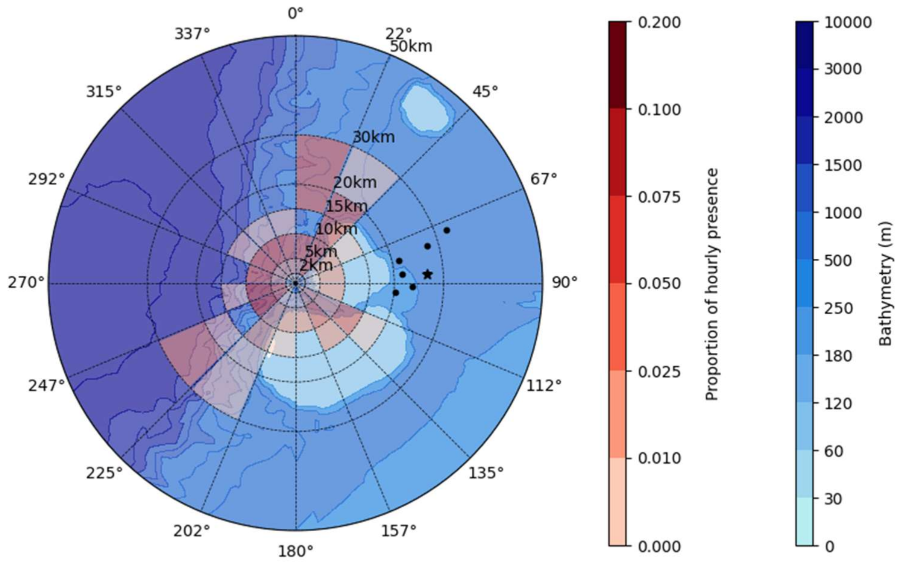


Figure 52. Pygmy blue whale non-song vocalisations: Radar plot showing the monthly proportion of hours with automated detections as a function of the range and bearing from West Scott Reef during Deployment 2. The area around the recorder was divided into 16 angular wedges 22.5 degrees wide and six range bins between 0 and 50 km from the recorder. The plot is centred on the location of the recorder. The black star and six black dots indicate the proposed Torosa FPSO and well locations, respectively.

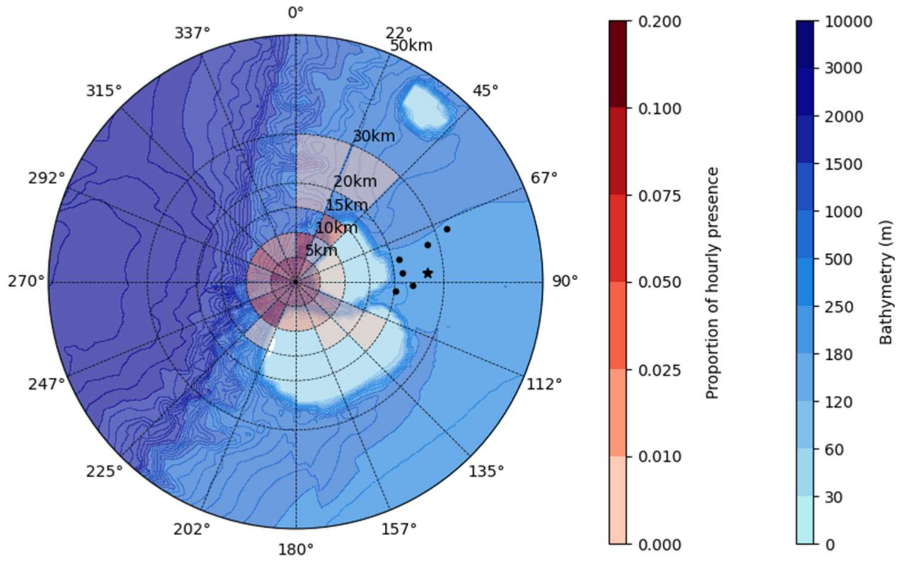


Figure 53. Pygmy blue whale non-song vocalisations: Radar plot showing the monthly proportion of hours with automated detections as a function of the range and bearing from West Scott Reef during Deployment 3. The area around the recorder was divided into 16 angular wedges 22.5 degrees wide and six range bins between 0 and 50 km from the recorder. The plot is centred on the location of the recorder. The black star and six black dots indicate the proposed Torosa FPSO and well locations, respectively.

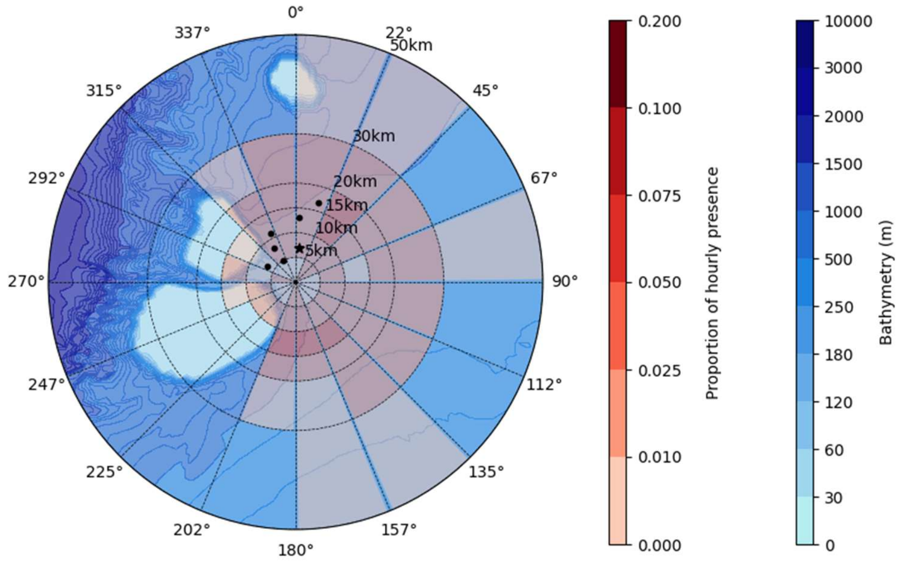


Figure 54. Pygmy blue whale non-song call: Radar plot showing the monthly proportion of hours with automated detections as a function of the range and bearing from East Scott Reef during Deployment 2. The area around the recorder was divided into 16 angular wedges 22.5 degrees wide and six range bins between 0 and 50 km from the recorder. The plot is centred on the location of the recorder. The black star and six black dots indicate the proposed Torosa FPSO and well locations, respectively.

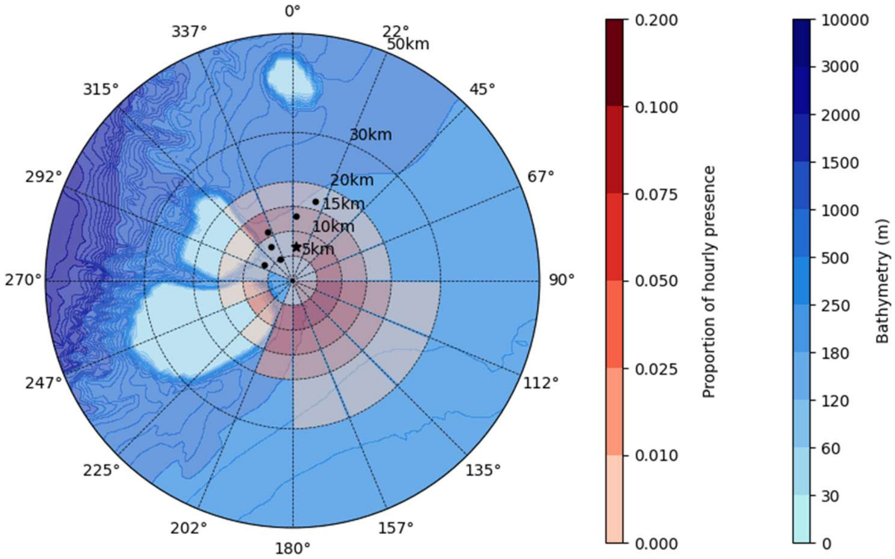


Figure 55. Pygmy blue whale non-song call: Radar plot showing the monthly proportion of hours with automated detections as a function of the range and bearing from East Scott Reef during Deployment 3. The area around the recorder was divided into 16 angular wedges 22.5 degrees wide and six range bins between 0 and 50 km from the recorder. The plot is centred on the location of the recorder. The black star and six black dots indicate the proposed Torosa FPSO and well locations, respectively.

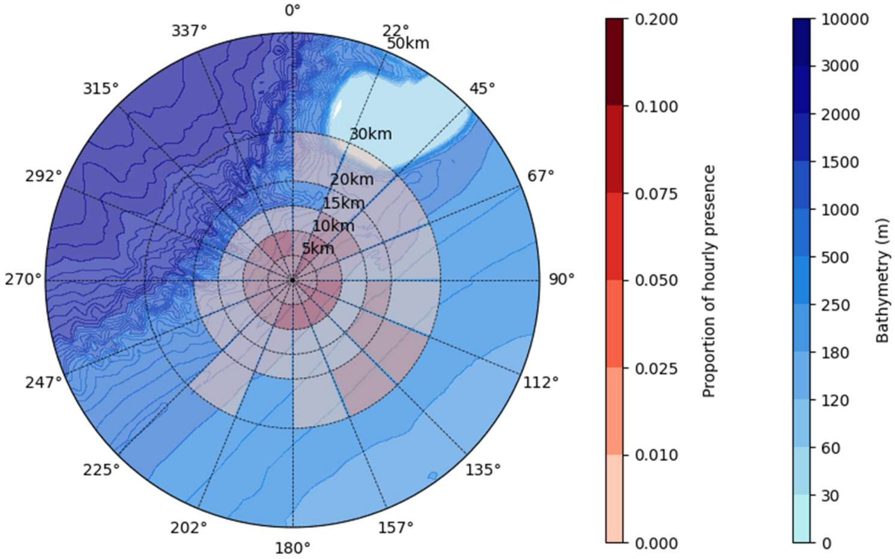


Figure 56. Pygmy blue whale non-song call: Radar plot showing the monthly proportion of hours with automated detections as a function of the range and bearing from South Scott Reef during Deployment 3. The area around the recorder was divided into 16 angular wedges 22.5 degrees wide and six range bins between 0 and 50 km from the recorder. The plot is centred on the location of the recorder. The black star and six black dots indicate the proposed Torosa FPSO and well locations, respectively.

3.2.1.3. Detection Range Modelling

The approximate detection ranges were modelled for pygmy blue whale song and non-song ‘D-calls’ (both targeted by JASCO’s manual and automated analysis techniques) for six months spread out across the full monitoring period: April, June, September and November 2023 and April and June 2024. Figures 57 to 62 show the 25, 50, and 75 % probability of detection ranges for D-calls and 65 Hz song harmonic per modelled month. These estimates are approximate given the assumptions detailed in Appendix C, including estimated vocalisation source levels and vocalising depth.

Song unit II had larger detection areas than D-calls at all stations across all months. Detection areas were generally circular at North West Cape Station but were impacted by Scott Reef and the shelf edge at the Scott Reef stations. On average, East and South Scott had the largest detection areas followed by North West Cape and West Scott Reef.

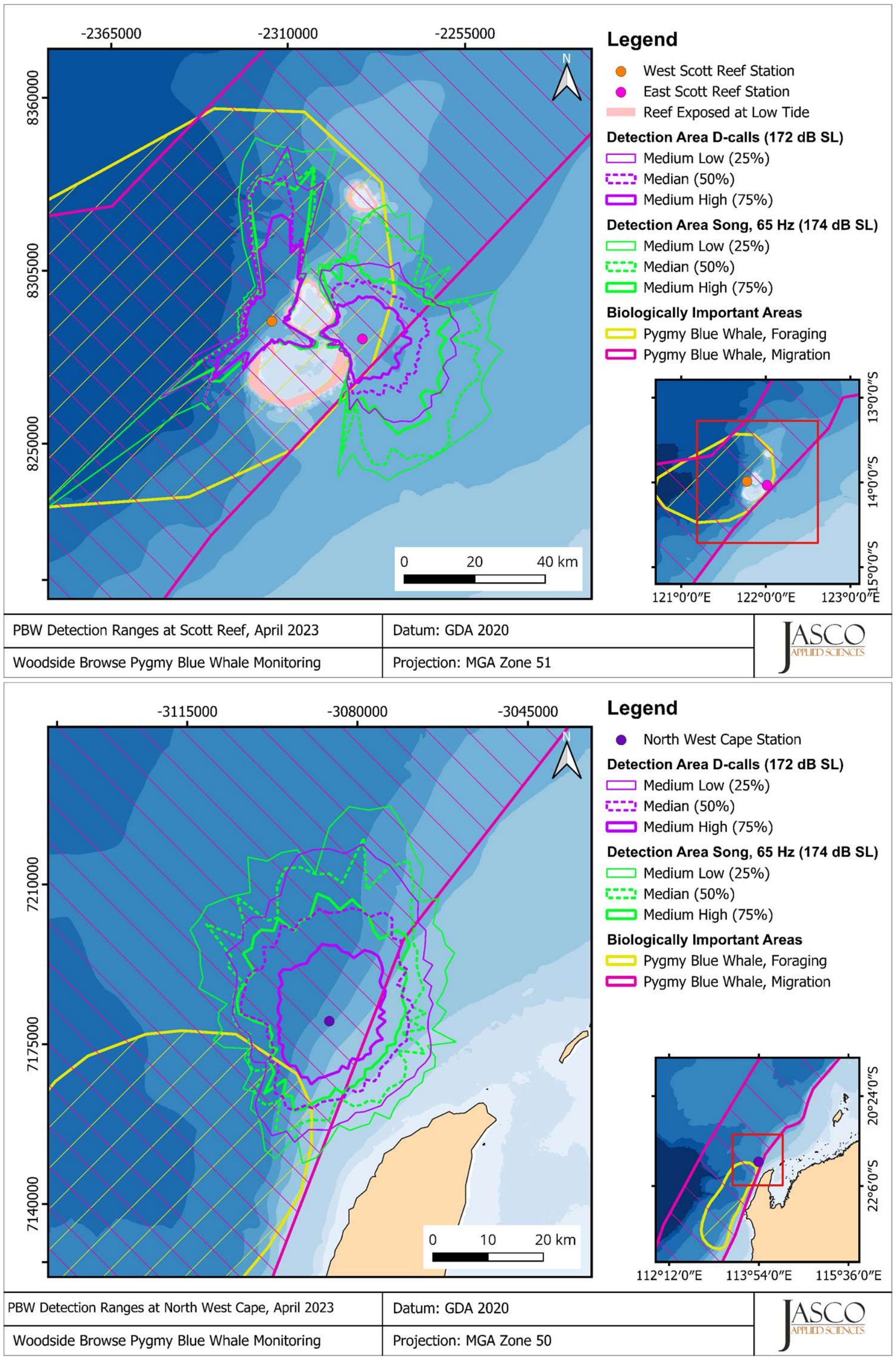


Figure 57. Pygmy blue whales: Median (50 %) detection ranges for all call types modelled for April 2023 at (top) the two Scott Reef stations and (bottom) North West Cape. Non-song vocalisations are labelled as ‘D-calls.’

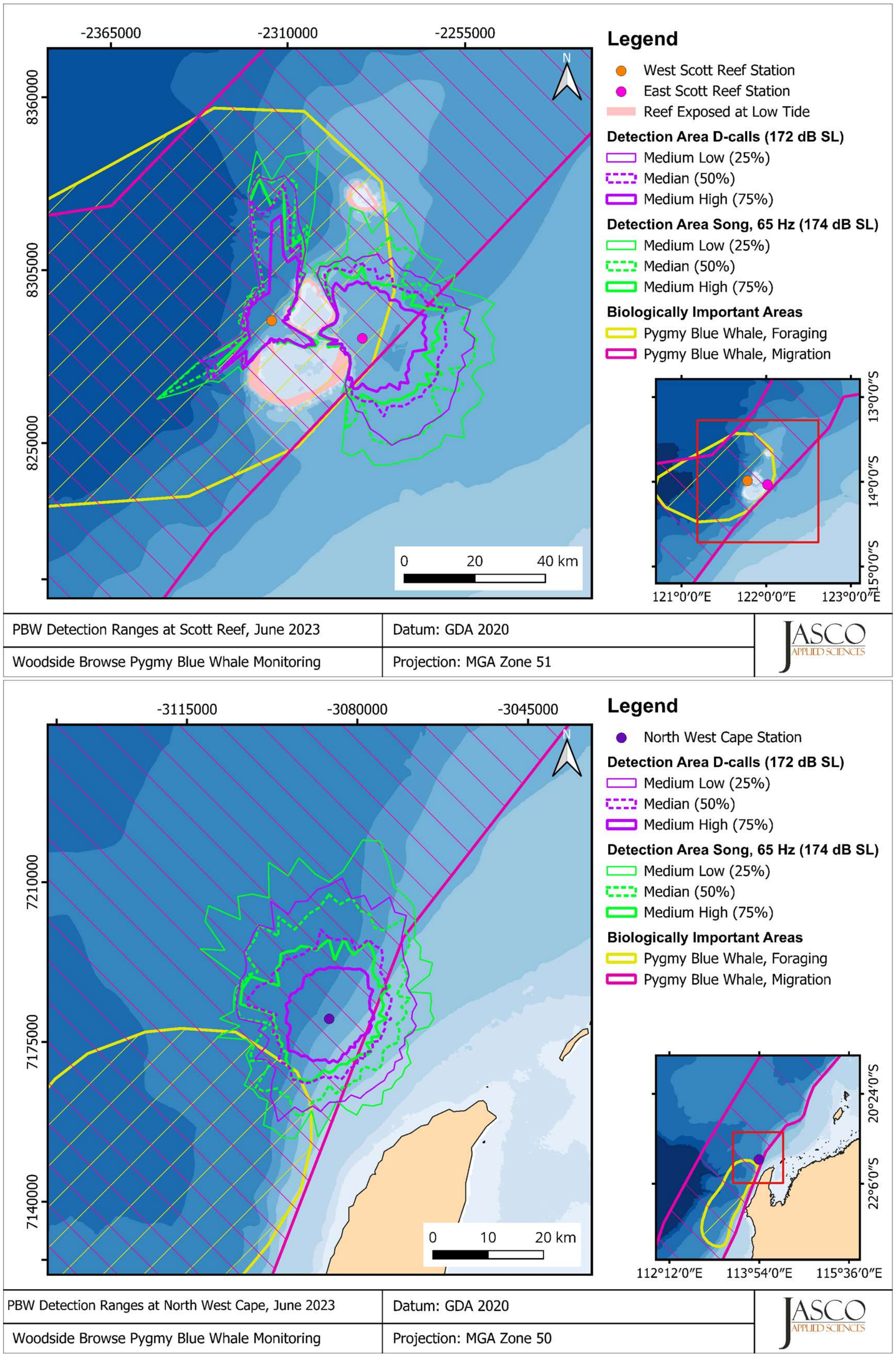


Figure 58. Pygmy blue whales: Median (50 %) detection ranges for all call types modelled for June 2023 at (top) the two Scott Reef stations and (bottom) North West Cape. Non-song vocalisations are labelled as 'D-calls.'

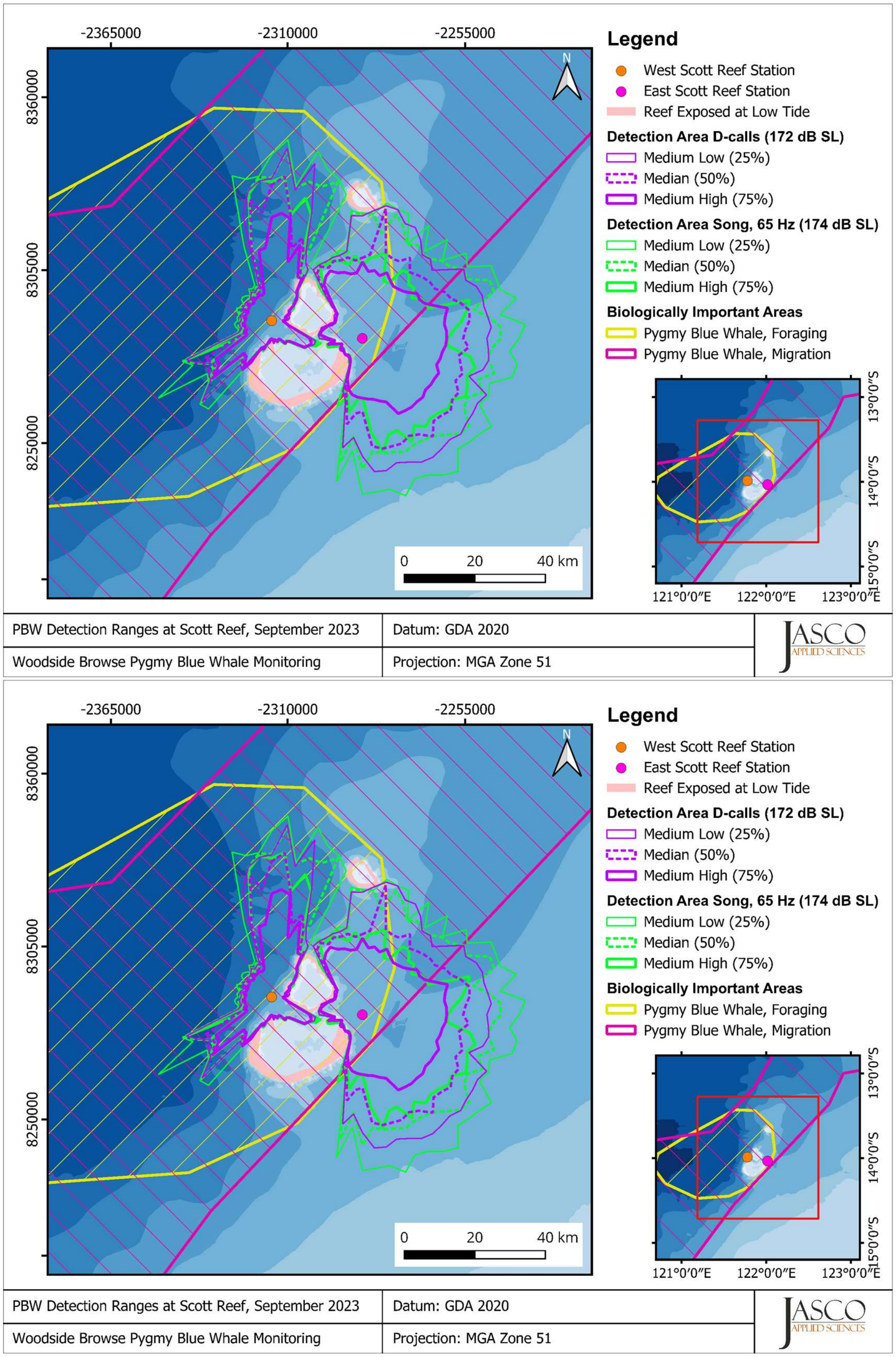
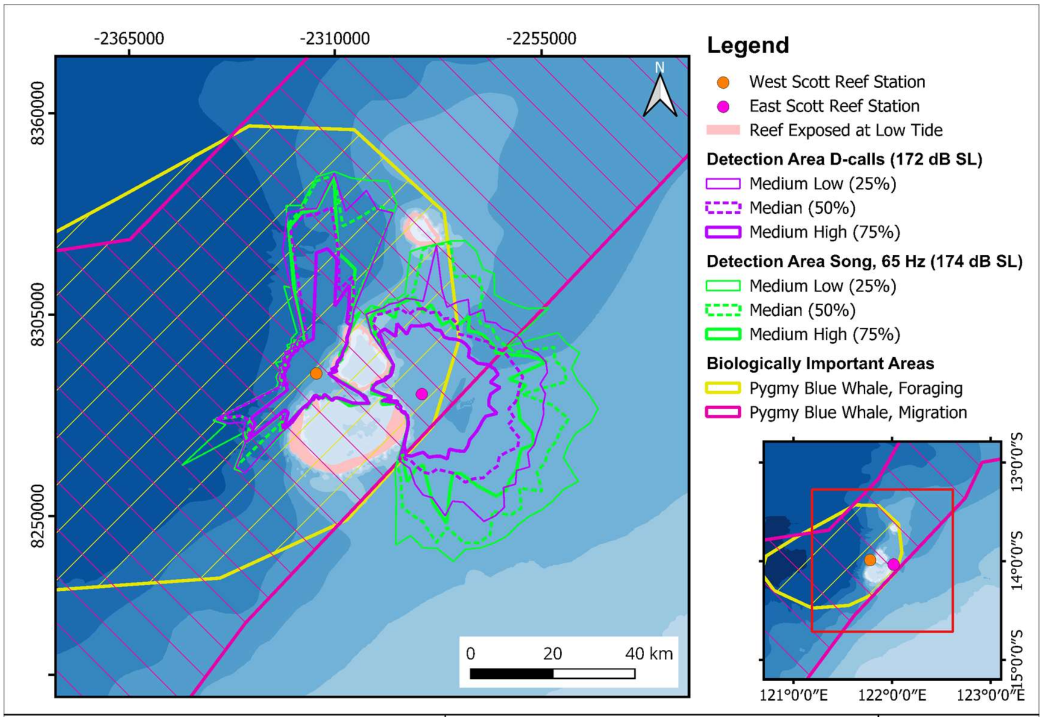
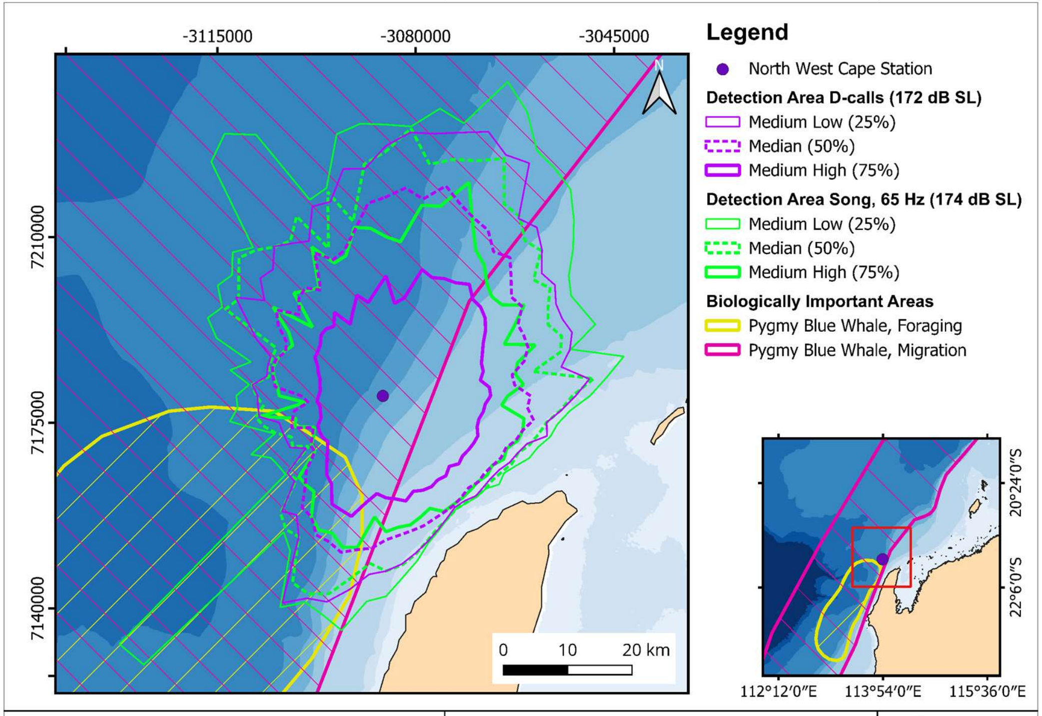


Figure 59. Pygmy blue whales: Median (50 %) detection ranges for all call types modelled for September 2023 at (top) the two Scott Reef stations and (bottom) North West Cape. Non-song vocalisations are labelled as 'D-calls.'



PBW Detection Ranges at Scott Reef, November 2023	Datum: GDA 2020
Woodside Browse Pygmy Blue Whale Monitoring	Projection: MGA Zone 51



PBW Detection Ranges at North West Cape, November 2023	Datum: GDA 2020
Woodside Browse Pygmy Blue Whale Monitoring	Projection: MGA Zone 50

Figure 60. Pygmy blue whales: Median (50 %) detection ranges for all call types modelled for November 2023 at (top) the two Scott Reef stations and (bottom) North West Cape. Non-song vocalisations are labelled as 'D-calls.'

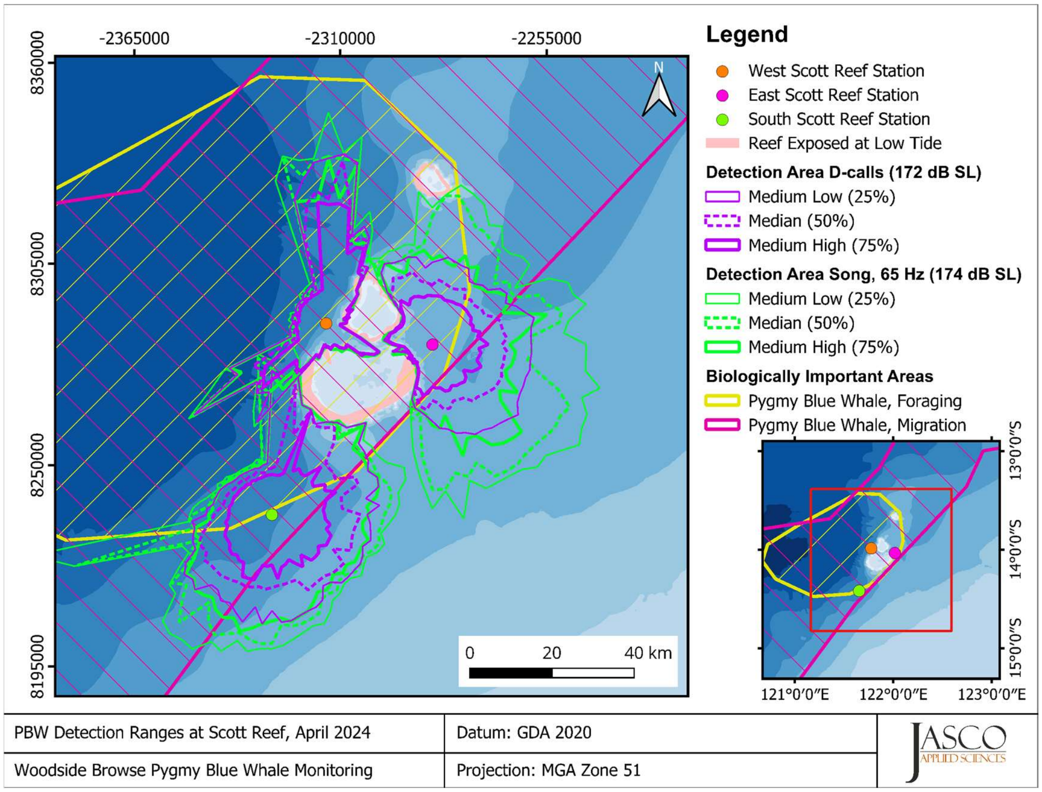


Figure 61. Pygmy blue whales: Detection ranges for non-song vocalisations (labelled ‘D-calls’) and the 65 Hz harmonic of unit II song calls for April 2024 at (top) the three Scott Reef stations.

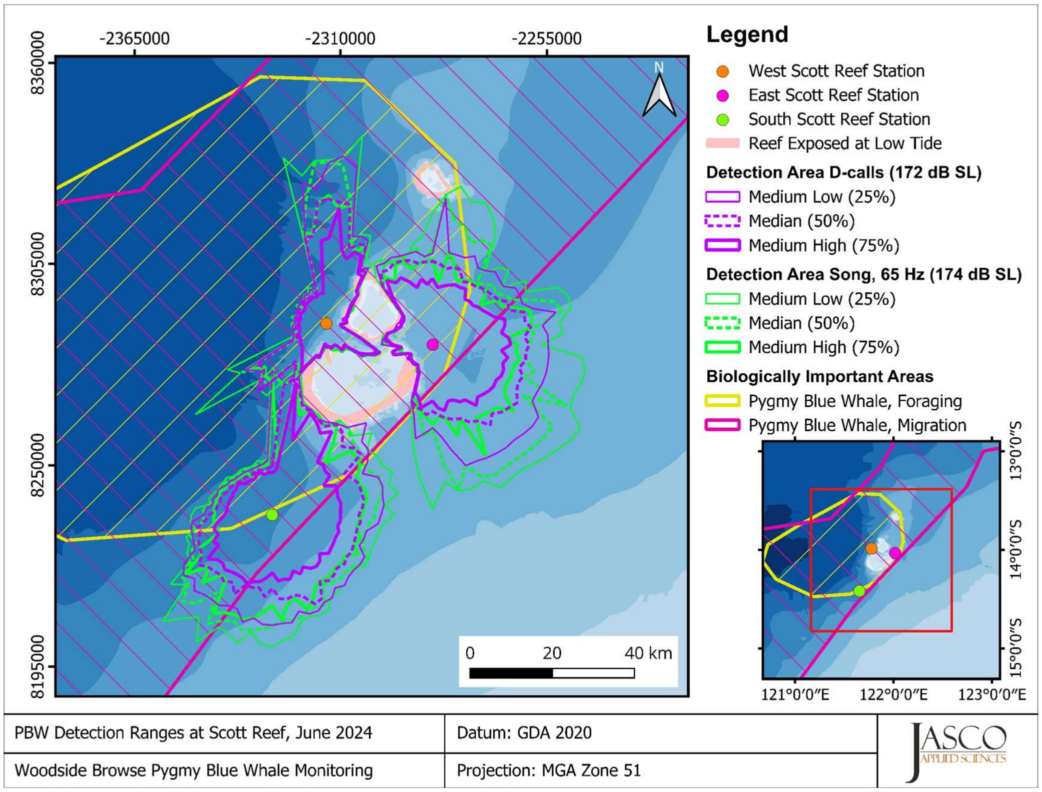


Figure 62. Pygmy blue whales: Detection ranges for non-song vocalisations (labelled ‘D-calls’) and the 65 Hz harmonic of unit II song calls for June 2024 at (top) the three Scott Reef stations.

4. Discussion and Conclusion

The aims of the monitoring program were to improve understanding of the migration of EIO pygmy blue whales and spatio-temporal use of the Scott Reef region, learn more about the seasonality and distribution of other marine mammal species in the area, and enhance the understanding of the marine soundscape in this environment. This report focuses on the acoustic occurrence of blue whales.

The acoustic detection results herein provide an index of acoustic occurrence of pygmy and Antarctic blue whales. Although they can be used to describe the relative abundance of a species across the study area, several factors influence the detectability of the targeted signals. Although an acoustic detection does indicate presence, an absence of detections does not necessarily indicate absence of animals. An animal may be present but not detected if no individuals were vocalising near the recorder, their signals were masked by environmental and/or anthropogenic noise sources, or a combination of these factors. Different sound propagation environments and different seasonal effects will impact the detection range of a given signal over time and, therefore, influence the number of detectable signals. Seasonal variations in vocalising behaviour may falsely suggest changes in occurrence. Therefore, environmental, anthropogenic, and biological factors that influence the detectability of the targeted acoustic signals must be considered when interpreting these results.

4.1. EIO Pygmy Blue Whales

The acoustic data collection in this monitoring program spanned 18 months and therefore the full migratory cycle of EIO pygmy blue whales, which migrate between their summer feeding grounds in the subtropical frontal zone off southern and south-western Australia and their winter breeding grounds in Indonesia. East and West Scott Reef stations both lie in the migration and foraging BIA, whilst South Scott Reef station lies just outside the foraging BIA and only within the migratory BIA. The North West Cape station lies in the migration BIA and about 10 km north of a foraging BIA. The heading of migrating whales is reflected in the bearing time series for all stations (see Section 3.2.1.2).

While the passage of migrating pygmy blue whales seemed to be well underway when the recordings started at North West Cape, the Scott Reef recordings appear to have captured the onset of the transit of pygmy blue whales in this area. Detections associated with the northbound migration stopped earlier at North West Cape, which is consistent with the location of this station further upstream along the migratory path. During the southbound migration, detections started generally around the same time at all three stations, but the duration of the peak detection period was substantially longer off North West Cape. This may indicate that a smaller proportion of pygmy blue whales migrate past Scott Reef on their way to the feeding grounds and that the various migratory paths may coalesce near North West Cape. The concept that migratory paths coalesce approximately between Exmouth and Dampier aligns with historic acoustic monitoring programs (i.e. Gavrilov and McCauley 2013, Gavrilov et al. 2018), current research (Jolliffe et al. In Prep), and north-bound tagging data (Double et al. 2014, Thums et al. 2022), including recent unpublished tracks[1]. This concept is supported by comparing the acoustic detections to recent satellite tagging work in Indonesia (Mustika et al. 2024). Limited studies have been done on the east-west distribution of blue whales between Scott Reef and Indonesia, and approximations about the proportional distribution are not able to be made given the available data.

Acoustic detections of D calls, a social sound commonly associated with foraging and social interactions and produced by male and female animals from all blue whale populations, and other

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[1] https://my.wildlifecomputers.com/data/map/?id=68304aa647df02bf430cbd13&fbclid=IwY2xjawLtLuVleHRuA2FlbQlxMABicmlkETFDc1dBNkJnQVVjcDMxWTJ4AR48fbmseXitZwPzEfAdNylCcjblH6p1EfZ_RP6COEsjBzXZKpouTE92_KqSqA_aem_ZmFrZWR1bW15MTZieXRlcw

social sounds, were found to match the timings of songs closely. D-calls and other social calls were not found to be produced more commonly at any station, which may have indicated foraging activities, as has been previously observed in the Scott Reef region (Sutton et al. 2019).

4.2. Antarctic Blue Whales

Antarctic blue whales were primarily detected from late April to early June at station North West Cape, with a few additional sporadic detection events in July and October. Isolated detections occurred during the same time frame at station West Scott Reef, but were not recorded at East Scott Reef. This observation, combined with the generally low received levels of the calls, suggests that the detected individuals were located in deep waters off the continental slope.

Antarctic blue whales are also a migratory species, with summer feeding grounds around the Antarctic continent and winter breeding grounds in warmer waters at lower latitudes (Branch et al. 2007). Antarctic blue whale songs have been detected off Western Australia from May to October, although primarily off southwestern and southern Australia (Stafford et al. 2004, Tripovich et al. 2015, McCauley et al. 2018). There are only sporadic records of Antarctic blue whale acoustic detections off northwest Australia (JASCO, unpublished data; McCauley et al. 2011). It has been established that not all Antarctic blue whales migrate every year (Leroy et al. 2016, Thomisch et al. 2016) and there is the possibility of their presence in Australian waters outside of this seasonal window. The detections presented here support the current understanding of Antarctic blue whales' occurrence in western Australian waters.

Acknowledgements

The authors would like the acknowledge the assistance of the JASCO field team, Robert Mills, James Tanner, and Dion Stroot, along with Terrafirma Offshore team (including Daemon Bass, Brad Tasker, Sarah Irvin, and Corey Ogg) who provided exceptional support, and their professionalism from vessel planning and HAZID process through to implementation in the field was greatly appreciated. Thank you to JASCO’s manual analysts that contributed to this work including Brodie Elsdon, Emily Evans, Emily Maxner, and Kiersten Runte. Also, we acknowledge Briand Gaudet, who provided support with the Ark software, and Dion Stroot, who contributed to data collection, storage, and transfer.

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Appendix A. Recorder Calibration

Each AMAR was calibrated before deployment and upon retrieval (battery life permitting) with a pistonphone type 42AC precision sound source (G.R.A.S. Sound & Vibration A/S; Figure A-1). The pistonphone calibrator produces a constant tone at 250 Hz at a fixed distance from the hydrophone sensor in an airtight space of known volume. The recorded level of the reference tone on the AMAR yields the system gain for the AMAR and hydrophone. To determine absolute sound pressure levels, this gain was applied during data analysis. Typical calibration variance using this method is less than 0.7 dB absolute pressure.

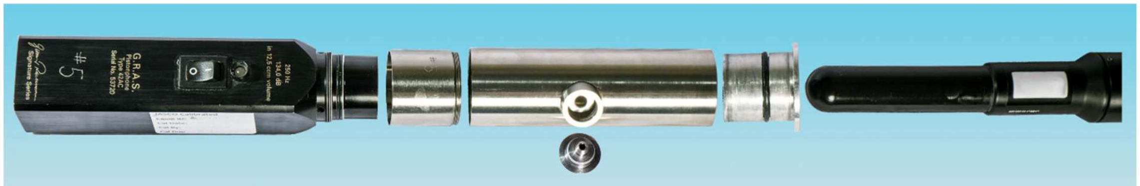


Figure A-1. Split view of a G.R.A.S. 42AC pistonphone calibrator with an M36 hydrophone.

Appendix B. Marine Mammal Detection Methodology

B.1. Automated Tonal Signal Detection

Marine mammal tonal acoustic signals are automatically detected using the contour detection and following algorithm depicted in Figure B-1. The algorithm has the following steps:

1. Create spectrograms of the appropriate resolution for each mammal vocalisation type that were normalised by the median value in each frequency bin for each detection window (Table B-1).
2. Join adjacent bins and create contours via a contour-following algorithm (Figure B-2).
3. Apply a sorting algorithm to determine if the contours match the definition of a marine mammal vocalisation (Table B-2).

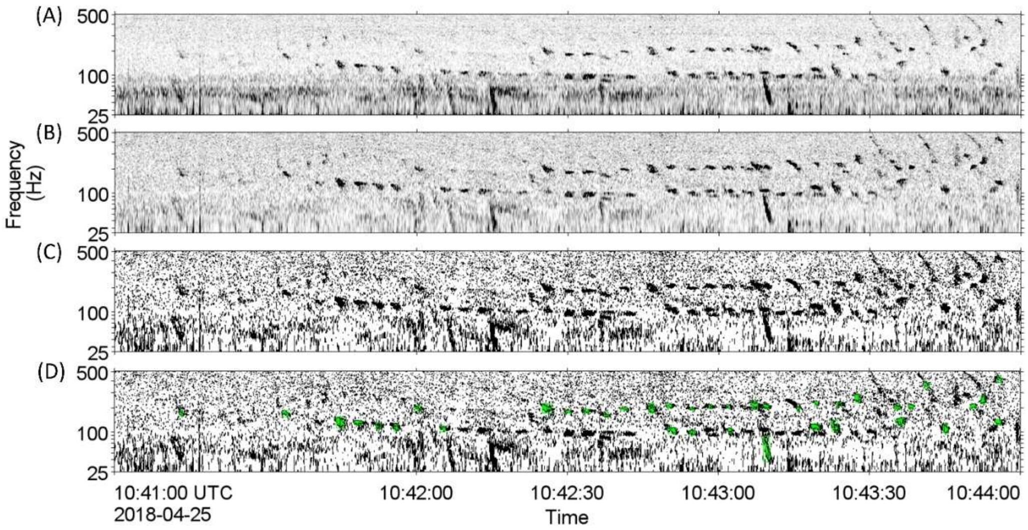


Figure B-1. Illustration of the contour detection process. (A) A spectrogram is generated at the frequency and time resolutions appropriate for the tonal calls of interest. (B) A median normaliser is applied at each frequency. (C) The data are turned into a binary representation by setting all normalised values less than the threshold to 0 and all values greater than the threshold to 1. (D) The regions that are ‘1’ in the binary spectrogram are connected to create contours, which are then sorted to detect signals of interest, shown here as green overlays.

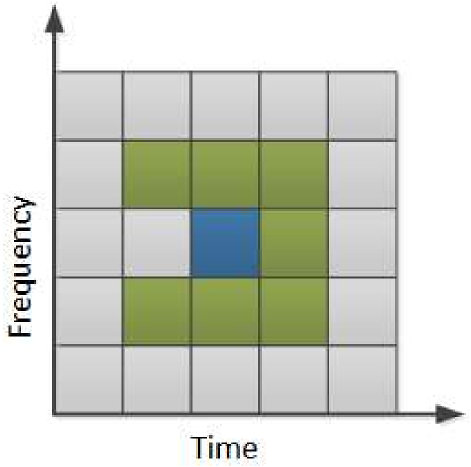


Figure B-2. Illustration of the search area used to connect spectrogram bins. The blue square represents a bin of the binary spectrogram equalling 1, and the green squares represent the potential bins it could be connected to. The algorithm advances from left to right, so grey cells left of the test cell need not be checked.

The tonal signal detector is expanded into a pulse train detector through the following steps:

1. Detect and classify contours as described in Steps 1 and 2 above.
2. A sorting algorithm determines if any series of contours can be assembled into trains that match a pulse train template.

Table B-1. Discrete Fourier Transform (DFT) and detection window settings for all automated contour-based detectors used to detect tonal vocalisations of marine mammal species in the data. Values are based on JASCO's experience and empirical evaluation of various data sets. Due to the overlapping characteristics of some species' signals, automated detectors developed for a particular signal (Primary species (signal) targeted), can also effectively detect the signals of other species (Other species (signal) targeted). For some signals, many automated detectors were applied and after manual validation the best performing detector is determined.

Automated detector	Primary species (signal) targeted	Other species (signal) targeted	Discrete Fourier transform			Detection window (s)	Detection threshold
			Frequency step (Hz)	Temporal observation window (s)	Time advance (s)		
ANT_BW_H25_TH2	Antarctic blue whale (Z call)	NA	0.125	2	0.5	50	2
ANT_BW_H25_TH3			0.125	2	0.5	50	3
ANT_BW_H27			0.125	2	0.5	40	2
AU_BW_H67	Pygmy blue whale (Song note)	NA	0.125	2	0.5	5	3
AUS_BW_AH17 AUS_BW_AH60			0.125	2	0.5	50	2
AUS_BW_AH60–70_TH2			0.4	2	0.5	50	2
AUS_BW_BH20 AUS_BW_BH43 AUS_BW_BH65			0.125	2	0.5	40	2
NZ_BW_H67			0.125	2	0.5	1200	3
NZ_BW_IM			0.125	2	0.5	1200	4

BWBaleen1_Down_TH2 BWBaleen7_NZDown_TH2 BWBaleen11_UpDown_TH2 BWBaleen12_UpDown_HF_TH2	Pygmy blue whale (non-song call)	Sei whale (downsweep), Bryde's whale (non-song call)	2	0.3	0.1	30	2
BWBaleen2_Down_TH3 BWBaleen5_NZDown_TH3 BWBaleen8_EIODown_TH3 BWBaleen13_UpDown_TH3			2	0.3	0.1	30	3
BWBaleen3_Down_TH5 BWBaleen4_AUDown_TH5 BWBaleen10_EIODown_TH5 BWBaleen15_UpDown_TH5			2	0.3	0.1	30	5
BWBaleen6_NZShortDown_TH4 BWBaleen9_EIODown_TH4 BWBaleen14_UpDown_TH4			2	0.3	0.1	30	4

Table B-2. A sample of automated detector classification definitions for the tonal vocalisations of cetacean species expected in the area. Automated detectors are capable of triggering on species and signals beyond those targeted. Some automated detectors share definitions in this table but differ in other parameters provided in Table B-1.

Automated detector	Frequency (Hz)	Duration (s)	Bandwidth (Hz)	Other parameters
ANT_BW_H25_TH2 ANT_BW_H25_TH3	13–30	4.00–13.00	NA	f_{min} <28 Hz, MIB <8 Hz, 23< f_{peak} <26
ANT_BW_H27	10–100	6.00–30.00	>1	f_{min} <100 Hz, MIB <30 Hz, 26< f_{peak} <28
AU_BW_H67	60–70	10.00–30.00	1–10	None
AUS_BW_AH17	10–100	6.00–60.00	>1	f_{min} <100 Hz, MIB <50 Hz, 17< f_{peak} <18.5
AUS_BW_AH60	10–100	6.00–60.00	>1	f_{min} <100 Hz, MIB <50 Hz, 59< f_{peak} <60.5
AUS_BW_AH60–70_TH2	61–72	6.00–30.00	3.75–10	MIB <50 Hz
AUS_BW_BH20	10–100	6.00–30.00	>1	f_{min} <100 Hz, MIB <3 Hz, 21< f_{peak} <22.5
AUS_BW_BH43	10–100	6.00–30.00	>1	f_{min} <100 Hz, MIB <3 Hz, 43< f_{peak} <44.5
AUS_BW_BH65	10–100	6.00–30.00	>1	f_{min} <100 Hz, MIB <3 Hz, 64< f_{peak} <66.5
NZ_BW_H67	60–70	10.00–30.00	1–10	None
NZ_BW_IM	15–24	10.00–30.00	1–4	f_{min} <18 Hz
BWBaleen1_Down_TH2	19–150	1.50–5.00	30–131	f_{min} <40 Hz, MIB <30 Hz, −20<SR<−5 Hz/s
BWBaleen2_Down_TH3	10–100	1.90–5.00	30–80	f_{min} <40 Hz, MIB <30 Hz, −30<SR<−5 Hz/s
BWBaleen3_Down_TH5	19–150	1.80–5.00	35–180	f_{min} <30 Hz, MIB <30 Hz, −20<SR<−10 Hz/s
BWBaleen4_AUDown_TH5	19–150	1.60–3.50	0.40–131	f_{min} <60 Hz, MIB <40 Hz, −30<SR<−10 Hz/s
BWBaleen5_NZDown_TH3 BWBaleen7_NZDown_TH2	25–80	1.50–4.00	15–60	f_{min} <40 Hz, MIB <20 Hz, −20<SR<−5 Hz/s
BWBaleen6_NZShortDown_TH4	25–60	1.00–2.70	20–30	f_{min} <40 Hz, MIB <20 Hz, −15<SR<−2 Hz/s
BWBaleen8_EIODown_TH3 BWBaleen9_EIODown_TH4 BWBaleen10_EIODown_TH5	10–80	1.30–5.00	30–80	f_{min} <40 Hz, MIB <30 Hz, −20<SR<−5 Hz/s
BWBaleen11_UpDown_TH2	10–90	2.00–7.00	30–80	f_{min} <40 Hz, MIB <30 Hz
BWBaleen12_UpDown_HF_TH2	40–100	1.80–10.00	20–60	f_{min} <60 Hz, MIB <25 Hz
BWBaleen13_UpDown_TH3	10–90	2.00–10.00	30–80	f_{min} <40 Hz, MIB <30 Hz
BWBaleen14_UpDown_TH4	10–90	2.00–7.00	30–80	f_{min} <40 Hz, MIB <30 Hz
BWBaleen15_UpDown_TH5	10–90	2.00–10.00	30–90	f_{min} <40 Hz, MIB <30 Hz
BrWBaleen_HFDown_TH2	50–200	0.70–2.00	40–180	f_{min} <120 Hz, MIB <80 Hz, −70<SR<−20 Hz/s
BrWBaleen_HFDown_TH3	50–200	0.70–2.00	40–110	f_{min} <200 Hz, MIB <70 Hz, −70<SR<−20 Hz/s
BrWBaleen_HFDown_TH5	50–200	0.70–2.00	40–110	f_{min} <120 Hz, MIB <70 Hz, −70<SR<−20 Hz/s

B.2. Automatic Data Selection for Validation (ADSV)

To standardise the file selection process for the selection of data for manual analysis, we applied our Automated Data Selection for Validation (ADSV) algorithm. Kowarski et al. (2021) details the ADSV algorithm, and Figure B-3 shows a schematic of the process. ADSV computes the distribution of three descriptors that describe the automated detections in the full data set: Diversity (number of automated detectors triggered per file), Counts (number of automated detections per file for each automated detector), and Temporal Distribution (spread of detections for each automated detector across the recording period). The aim of ADSV is to select a subset of sound files with as little variation in the distribution of these descriptors compared to those of the full data set as possible. The algorithm progressively removes files from a temporary data set such that this variation is minimised (Figure B-3). Files are removed until a predetermined sample size (*N*) is reached, at which point the temporary data set becomes the subset to be manually reviewed.

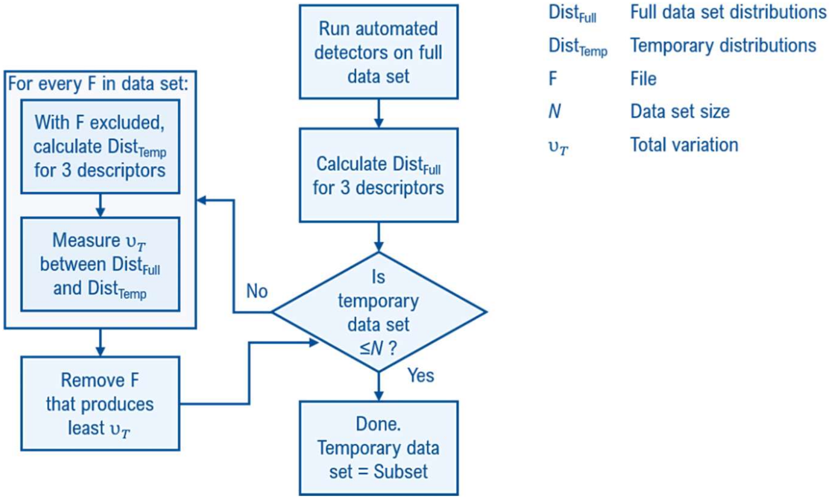


Figure B-3. The Automated Data Selection for Validation (ADSV) process. (source: based on Figure 1 in Kowarski et al. (2021)).

For the present work, an *N* of 1 to 5 % was applied (Table B-3). Even with limited manual review, the results presented here can be considered reliable, but some caveats should be considered. It is important to note that with such limited data manually reviewed, exceedingly rare species may have been missed or their occurrence underestimated.

Table B-3. Amount of data manually reviewed for each monitoring period and sampling rate.

Monitoring period	Sampling rate (kHz)	Percent manually reviewed (%)	# files manually reviewed
1	256	1	371
	32	5	1864
2	256	1	510
	32	2	1030
3	256	1	629
	32	2	1059
		Total	**5463**

B.3. Automated Detector Performance Calculation and Optimisation

All files selected for manual validation were reviewed by one of two experienced analysts using JASCO's PAMlab software to determine the presence or absence of every species, regardless of whether a species was automatically detected in a file. Although the automated detectors classify specific signals, we validated the presence/absence of species at the file level, not the detection level. Acoustic signals were only assigned to a species if the analyst was confident in their assessment. When unsure, analysts would consult one another, internal JASCO guides, peer reviewed literature, and other experts in the field. If certainty could not be reached, the file of concern would be classified as possibly containing the species in question or containing an unknown acoustic signal. Next, the validated results were compared to the automated detector results in three phases to refine the results and ensure they accurately represent the occurrence of each species in the study area.

In Phase 1, the human validated versus automated detector results were plotted as time series and critically reviewed to determine when and where automated detections should be excluded. If manual detections of a given species were absent during a prolonged period (dependent on deployment duration, duty cycle and proportion of data reviewed; usually no less than 1 month) within a data set, an exclusion period was defined and all potential automated detections for that species during that period were deemed false positives (FP) and excluded from further processing. The start and end days of an exclusion period were defined as the dates following and preceding the manual detections bounding the period of absence. Exclusion periods ensure that automated detection results are only used when there is sufficient overlap between manual and automated detections and detector performance can be reliably estimated. Because of the generally low manual review effort, exclusion periods may be overly restrictive but ensure conservative results.

In Phase 2, the performance of the automated detectors was calculated and optimised for each species using a threshold, defined as the number of automated detections per file at and above which detections of species were considered valid.

To determine the performance of each automated detector and any necessary thresholds, the automated and validated results (excluding files where an analyst indicated uncertainty in species occurrence) were fed to a maximum likelihood estimation algorithm that maximises the probability of detection and minimises the number of false alarms using the Matthews Correlation Coefficient (MCC)

$$\mathrm{MCC} = \frac{\mathrm{TP} \cdot \mathrm{TN} - \mathrm{FP} \cdot \mathrm{FN}}{\sqrt{(\mathrm{TP}+\mathrm{FP})(\mathrm{TP}+\mathrm{FN})(\mathrm{TN}+\mathrm{FP})(\mathrm{TN}+\mathrm{FN})}}$$

(minimum and worst value: -1; maximum and best value: 1)

and calculates the resulting Precision (*P*) and Recall (*R*)

$$P = \frac{\mathrm{TP}}{\mathrm{TP}+\mathrm{FP}}; \quad R = \frac{\mathrm{TP}}{\mathrm{TP}+\mathrm{FN}}$$

(minimum and worst value: 0; maximum and best value: 1)

where *TP* (true positive) is the number of files in the subset with both manual and automated detections, *FP* (false positive) is the number of files in the subset with automated detections but no manual detections, *FN* (false negatives) is the number of files in the subset with manual detections but no automated detections, and *TN* (true negatives) is the number of files in the subset with neither automated nor manual detections. For each automated detector performance metric (*P*, *R*, and *MCC*), the metric uncertainty was calculated using methods from Tötsch and Hoffmann (2021) to understand the likelihood that the metric calculated from the subset of data manually reviewed reflects that of the full data set. Metric uncertainty is provided as the credible interval (CI) where there is 95 % likelihood the metric is within the CI. Automated detector performance was calculated for each species and station.

In Phase 3, detections were further restricted to include only those where *P* was greater than or equal to 0.75, *R* was greater than or equal to 0.50, and *MCC* was greater than or equal to 0.40. When performance metrics fell below minimum requirements, only validated results were used to describe the acoustic occurrence of a species. The occurrence of each species was plotted using JASCO's Ark software as time series showing presence/absence by hour over each day.

B.4. Marine Mammal Automated Detector Performance

Of the suite of automated detector-classifiers applied to the entire dataset, those with highest per-file detector performance for each signal type, monitoring period, and station, are provided in Table B-4 along with any optimisation to results (exclusion periods and per-file thresholds). Table B-5 provides the final automated detector performance estimates and indicates whether performance was sufficient to include in presence/absence figures presented in Section 3.1 ($P \geq 0.75$, $R \geq 0.50$, and $MCC \geq 0.40$). Monitoring Period 1 spanned from April to September 2023, Monitoring Period 2 spanned from September 2023 to March 2024 and Monitoring Period 3 spanned from March to September 2024 (see Table 4 for exact recording start and stop dates).

Table B-4. Automated detector performance optimisation implemented including any timeframe(s) where automated detections were deemed false and removed (exclusion period) and the per-file threshold implemented (minimum number of automated detections per file for species to be considered present) for each signal type, station, and Monitoring Period. Results are provided for the highest performing automated detector-classifier for each signal type for the acoustic data that best captured the frequency range of the signal (data sampled at 32 or 256 kHz). Monitoring Periods and stations where no signals were confirmed during manual analysis are excluded.

Species signal	Acoustic data sampling rate (kHz)	File duration (min)	Station	Period	Automated detector	Exclusion period	Per-file threshold
Pygmy blue whale song	32	15	West Scott Reef	1	AUS_BW_BH65	None	Min: 2
				2	AUS_BW_BH65	None	Min: 2
				3	Pygmy_BW_UnitII_65_TH2	None	Min: 1
			East Scott Reef	1	AUS_BW_BH65	1 to 9 Sep	Min: 1
				2	AUS_BW_BH65	None	Min: 2
				3	Pygmy_BW_UnitII_65_TH2	None	Min: 1
			North West Cape	1	AUS_BW_BH65	None	Min: 1
				2	AUS_BW_BH65	None	Min: 2
			South Scott Reef	3	Pygmy_BW_UnitII_65_TH2	None	Min: 1
Blue whale non-song	32	15	West Scott Reef	1	SWBaleen5_ShortDown_TH3	None	Min: 1
				2	SWBaleen5_ShortDown_TH3	None	Min: 1
				3	SWBaleen1_ShortDown_TH3.5	None	Min: 1
			East Scott Reef	1	BWBaleen2_Down_TH3	None	Min: 2
				2	SWBaleen5_ShortDown_TH3	None	Min: 1
				3	BWBaleen16_Down_TH2	None	Min: 2
			North West Cape	1	BWBaleen7_NZDown_TH2	None	Min: 2
				2	BWBaleen5_NZDown_TH3	None	Min: 1
			South Scott Reef	3	BWBaleen16_Down_TH2	None	Min: 2
Antarctic blue whale song	32	15	West Scott Reef	1	ANT_BlueWhale_H25_TH3	None	Min: 7
				2	ANT_BlueWhale_H25_TH3	1 Nov 2023 to 19 Mar 2024	Min: 4
				3	NA[1]	NA[1]	NA[1]
			East Scott Reef	3	NA[1]	NA[1]	NA[1]
			North West Cape	1	ANT_BlueWhale_H25_TH3	None	Min: 2
				2	ANT_BlueWhale_H25_TH3	1 Nov 2023 to 14 Mar 2024	Min: 3 Max: 7
			South Scott Reef	3	NA[1]	NA[1]	NA[1]

Table B-5. Final automated detector performance estimates including detector precision (*P*), recall (*R*), Matthew's Correlation Coefficient (MCC), number of true positives (TP), false positives (FP), false negatives (FN), and true negatives (TN) for each signal type, station, and monitoring period (Period). The final automated detector performance values represent the metric estimates after applying any timeframe and/or threshold restrictions. The unit of time the automated detector performance was calculated over is provided where '15 min' refers to data sampled at 32 kHz and '1 min' to data sampled at 256 kHz and is based on a subset of files manually analysed (see Table B-3). There is a 95 % likelihood that the true *P*, *R*, and MCC falls within the 95 % credible interval (95 %CI) (Tötsch and Hoffmann 2021). Automated detector results were considered acceptable (Detector accepted) and applied to presence/absence figures when *P* ≥ 0.75, *R* ≥ 0.50, and MCC ≥ 0.40. Results are provided for the highest performing automated detector-classifier for each signal type. Monitoring Periods and stations where no signals were confirmed during manual analysis are excluded.

Species signal	Station	Period	Final automated detector performance (per file)								Detector accepted
			File length (min)	*P* (95 %CI)	*R* (95 %CI)	MCC (95 %CI)	TP	FP	FN	TN	
Pygmy blue whale song	West Scott Reef	1	15	0.89 (0.85–0.92)	0.86 (0.82–0.90)	0.79 (0.73–0.83)	239	29	38	331	Yes
		2	15	0.94 (0.88–0.98)	0.84 (0.77–0.90)	0.84 (0.77–0.89)	92	6	17	218	Yes
		3	15	0.96 (0.94–0.99)	0.82 (0.76–0.87)	0.77 (0.71–0.83)	162	4	36	138	Yes
	East Scott Reef	1	15	0.94 (0.91–0.96)	0.83 (0.79–0.87)	0.70 (0.63–0.75)	296	18	59	153	Yes
		2	15	0.97 (0.92–0.97)	0.86 (0.78–0.92)	0.88 (0.81–0.92)	84	3	14	246	Yes
		3	15	0.96 (0.93–0.98)	0.75 (0.68–0.80)	0.67 (0.59–0.73)	167	7	57	125	Yes
	North West Cape	1	15	0.94 (0.91–0.97)	0.94 (0.91–0.96)	0.88 (0.84–0.91)	283	17	19	288	Yes
		2	15	0.89 (0.84–0.94)	0.93 (0.88–0.97)	0.85 (0.78–0.90)	116	14	9	190	Yes
	South Scott Reef	3	15	0.92 (0.88–0.96)	0.79 (0.73–0.84)	0.70 (0.64–0.78)	153	12	41	147	Yes
Blue whale Non-song	West Scott Reef	1	15	0.94 (0.87–0.98)	0.61 (0.52–0.69)	0.72 (0.65–0.78)	74	5	47	572	Yes
		1	15	0.94 (0.83–0.99)	0.62 (0.48–0.74)	0.73 (0.61–0.81)	32	2	20	285	Yes
		3	15	0.84 (0.77–0.94)	0.72 (0.62–0.82)	0.72 (0.64–0.82)	52	8	19	256	Yes
	East Scott Reef	1	15	0.87 (0.73–0.95)	0.42 (0.32–0.54)	0.57 (0.46–0.66)	33	5	45	447	No [1]
		2	15	0.90 (0.81–0.97)	0.76 (0.64–0.86)	0.80 (0.69–0.87)	45	5	14	290	Yes
		3	15	0.93 (0.85–0.98)	0.59 (0.48–0.69)	0.68 (0.58–0.76)	50	4	35	264	Yes
	North West Cape	1	15	0.80 (0.62–0.92)	0.63 (0.46–0.77)	0.69 (0.54–0.80)	20	5	12	575	Yes
		2	15	1.00 (0.95–1.00)	0.70 (0.59–0.81)	0.81 (0.72–0.87)	45	0	19	266	Yes
	South Scott Reef	3	15	0.97 (0.87–0.99)	0.75 (0.64–0.83)	0.82 (0.71–0.86)	55	3	19	267	Yes
Antarctic blue whale song	West Scott Reef	1	15	0.50 (0.26–0.73)	0.39 (0.20–0.61)	0.43 (0.23–0.62)	7	7	11	664	No
		2	15	0.90 (0.61–0.99)	0.90 (0.63–0.99)	0.90 (0.64–0.96)	9	1	1	329	Yes [2]
		3	15	NA [3]							No
	East Scott Reef	3	15	NA [3]							No
	North West Cape	1	15	0.85 (0.76–0.91)	0.71 (0.61–0.79)	0.74 (0.66–0.81)	69	12	28	496	Yes

Species signal	Station	Period	Final automated detector performance (per file)								Detector accepted
			File length (min)	*P* (95 %CI)	*R* (95 %CI)	MCC (95 %CI)	TP	FP	FN	TN	
		2	15	1.00 (0.42–1.00)	0.75 (0.34–0.98)	0.86 (0.42–0.97)	3	0	1	329	Yes [2]
	South Scott Reef	3	15	NA [3]							No

Appendix C. Detection Range Modelling Methods and Input Data

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 energy source level (ESL), expressed in dB re 1 $\mu Pa^2 \cdot s\ m^2$, and propagation loss (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 $\mu Pa^2 \cdot s$ by:

$$\mathrm{RL} = \mathrm{SL} - \mathrm{PL}\,. \tag{C-1}$$

C.2. MONM

Long-range sound fields were computed using JASCO's Marine Operations Noise Model (MONM). Compared to wavenumber integration methods, 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 matching whale vocalisations via a wide-angle parabolic equation solution to the acoustic wave equation (Collins 1993) based on a version of the US Naval Research Laboratory's Range-dependent Acoustic Model (RAM), which has been modified to account for a solid seabed (Zhang and Tindle 1995).

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 meaningful 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 propagation 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).

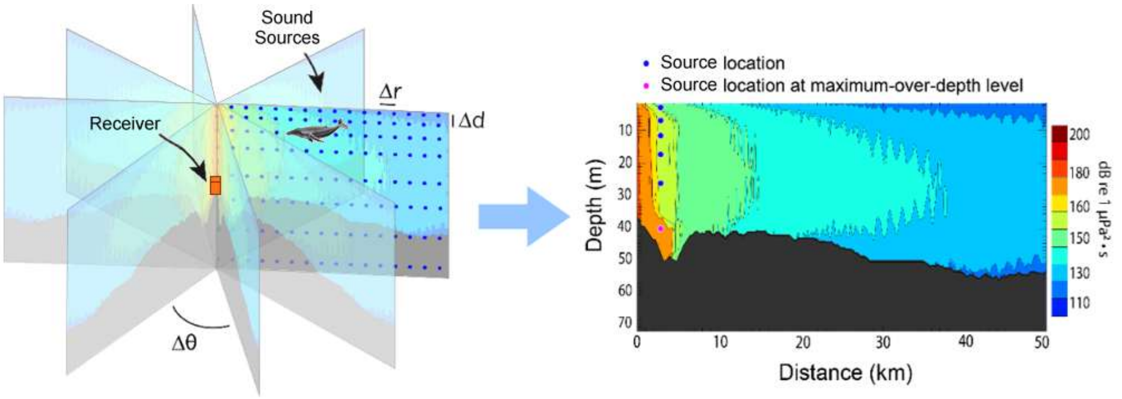


Figure C-1. The N×2-D and maximum-over-depth modelling approach used by MONM.

MONM treats frequency dependence by computing acoustic propagation loss at the centre frequencies of decidecade bands. Sufficiently many decidecade bands, are modelled to include most of the acoustic energy emitted by the source (i.e., see the blue whale call parameters shown in Table C-3). At each centre frequency, the propagation loss is modelled within each of the N vertical planes as a function of depth and range from the recorder. This propagation loss is equivalent to the transmission loss from a whale call detected by the hydrophone due to the reciprocity of wave propagation. The decidecade band received per 1 s, for impulsive and non-impulsive noise sources respectively, SEL are computed by subtracting the band propagation loss values from the directional source level in that frequency band. Composite broadband received per-pulse SEL are then computed by summing the received decidecade band levels.

The received per 1 s 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 maximum received per 1 s SEL at many sampling depths are taken over all samples within the water column, i.e., the maximum-over-depth received per-pulse SEL. These maximum-over-depth per 1 s SEL are presented as contours around the source.

C.3. Environmental Input Data

Bathymetry throughout the modelled area extracted from the Australian Bathymetry and Topography Grid, a 9 arc-second grid rendered for Australian waters (Whiteway 2009). Bathymetry data were re-gridded onto a Map Grid of Australia (MGA) coordinate projection (Zone 51 and 49) with a regular grid spacing of 250 × 250 m.

The sound speed profiles for the modelled sites were 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 US Navy’s Master Oceanographic Observational Data Set (MOODS). The climatology profiles include 78 fixed depth points to a maximum depth of 6800 m (where the ocean is that deep). The GDEM temperature-salinity profiles were converted to sound speed profiles according to Coppens (1981).

The propagation model used in this study considered a two geoacoustic profiles, one for Scott Reef East and West Stations and one for the North West Cape Station. These profiles determine how sound is reflected from the seabed, as well as how it is transmitted, reflected, and absorbed into the sediment layers.

In previous acoustic studies near Scott Reef (Duncan 2014, McPherson et al. 2019), the modelling area was divided into three seabed types, with a silt seabed typical of the continental slope considered for most of the modelling area, and coarser gravel and limestone in the areas in and around the reefs. Due to the type of propagation modelling used in this study, however, the silt seabed was used near Scott Reef, detailed in Table C-1.

Table C-1. Scott Reef geoacoustic profile. Within each depth range, each parameter varies linearly within the stated range. For modelling using MONM, only the surficial S-wave properties are considered. The compressional wave is the primary wave, and the shear wave is the secondary wave.

Depth below seafloor (m)	Material	Density (g/cm^3)	Compressional wave		Shear wave	
			Speed (m/s)	Attenuation (dB/λ)	Speed (m/s)	Attenuation (dB/λ)
0–50	Silt	1.70–1.75	1566–1627	1.0	210	1.5
50–100		1.75–1.80	1627–1686			
100–150		1.80–1.85	1686–1742			
150–200		1.85–1.90	1742–1795			
>200		1.90	1795			

For the North West Cape profile the information on surficial sediment was determined from Baker et al. (2008), and core information from Gallagher et al. (2017) was used to determine the deeper stratigraphy. The geoacoustic profile shown in Table C-2 was subsequently determined from properties for carbonate sediments and calcarenite from Hamilton (1980) and Duncan et al. (2013).

Table C-2. North West Cape geoacoustic profile. Within each depth range, each parameter varies linearly within the stated range. For modelling using MONM, only the surficial S-wave properties are considered. The compressional wave is the primary wave, and the shear wave is the secondary wave.

Depth below seafloor (m)	Material	Density (g/cm^3)	Compressional wave		Shear wave	
			Speed (m/s)	Attenuation (dB/λ)	Speed (m/s)	Attenuation (dB/λ)
0–10	Silty Sand	1.70–1.72	1619.0–1636.1	0.59–0.69	200	3.65
10–50	Increasingly consolidated sand-silt-clay	1.62–1.69	1636.1–1659.7	0.20–0.55		
50–100		1.69–1.76	1659.7–1742.6	0.55–0.96		
100–300		1.76–1.95	1742.6–2055.2	0.96–1.03		
300–850	Semi-cemented sand/calcarenite	1.95–2.20	2100–2600	0.12–0.20		
>850	Well-cemented sand/calcarenite	2.20	2600	0.20		

C.4. Marine Mammal Call Input Parameters

Table C-3 summarises the marine mammal signal parameters used as inputs to the detection range modelling. The maximum extent of the modelled area was set at 100 km.

Table C-3. Marine mammal input parameters. The detection threshold refers to the threshold of the relevant detectors.

Call type	Frequency range (Hz)	Source level (dB)		Source depth (m)	Detection threshold	Reference
		Mean	Standard deviation			
Pygmy blue whale song (63 Hz)	63	174	2	10–30	4	Gavrilov and McCauley (2013)
Blue whale non-song calls	32–80	172	4	10–30	4	Gavrilov et al. (2011)

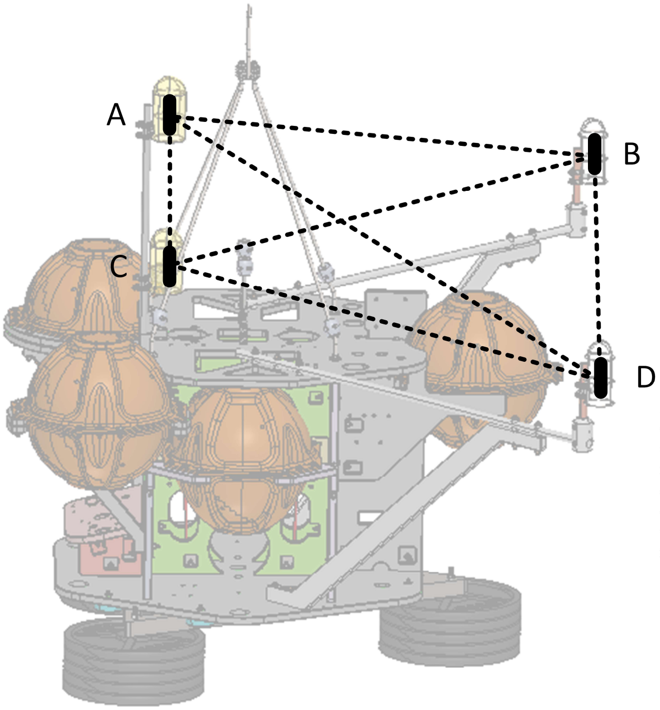
Appendix D. Directional Data Analysis Methods

This appendix describes how the ALTO lander data were analysed to determine the direction of arrival of sounds.

D.1. Bearing and Absolute Minimum Number Estimation

D.1.1. Hydrophone Locations

The hydrophones were arranged in an orthogonal array, with a spacing of approximately 200 cm between them (Figure D-1). The relative locations of the hydrophones must be known exactly as part of the beamforming process described in Appendix D.1.2. The distances between hydrophones are measured on deployment and retrieval and kept in the deployment log file. These values are used in an optimisation script to then determine the positions of hydrophones A, B, and D relative to C. This process generally corrects the positions by several millimetres. The final hydrophone positions are stored in the 'ChannelAssociations.xml' file that is associated with the data.



Hydrophone Pair	Length (mm)
AB	2017
AC	480
AD	2017
BC	1960
BD	2870
CD	1960

Figure D-1. Hydrophone geometry on the ALTO lander with example table of the distances between hydrophones (in mm) where each station will have slightly different values when measures in the field.

D.1.2. Maximum Likelihood Estimation Beamformer

The analysis was performed using a maximum likelihood estimation (MLE) beamformer (Urazghildiiev and Hannay 2017). This beamformer estimates the sound level assuming the sounds are arriving from azimuthal bins that are 20 degrees wide (total of 360/20 = 24 bins), and for each azimuth it evaluates three elevation angles 30 degrees wide (from horizontal to vertical, assuming a bottom-mounted recorder; 90/30 = 3), for a total of 24 × 3 = 72 'look directions' or beams.

For each beam, the time delay of arrival between hydrophones are computed assuming that plane wave arrives from that direction. The time delay is converted to a phase change as a function of frequency, and the beams are then formed using fast Fourier transforms (FFT). The duration of the FFT is selected based on the type of analysis being performed (i.e., for a particular type of mammal call, or for vessel detection). The beam with the greatest received level per frequency is selected as the most likely direction of arrival. In cases where a detection spans many frequencies, it is applied to each, and the bearing values are weighted by the energy in the frequency bin, so that the direction assigned to the call is the energy weighted direction.

The ability of the MLE beamformer to determine the direction of arrival depends on the time delay between hydrophones. When the delay is greater than the time required for one half of a wavelength to travel between the hydrophones, the results become ambiguous, which sets an upper limit on the frequencies that may be analysed. For a 200 cm spaced array, this value is 250 Hz. If the delay, which equates to a phase change, is not long enough, then there is not information to determine the direction of arrival, which sets a lower limit on the frequencies that can be analysed as a function of the spacing between the hydrophones. This is manifested by an increase in the bearing estimation error that increases as the frequency decreases. It also depends on the signal-to-noise ratio (SNR) between the signal of interest and the background. The error can be reduced by increasing the spacing between hydrophones, however, that also lowers the maximum usable frequency (Figure D-2).

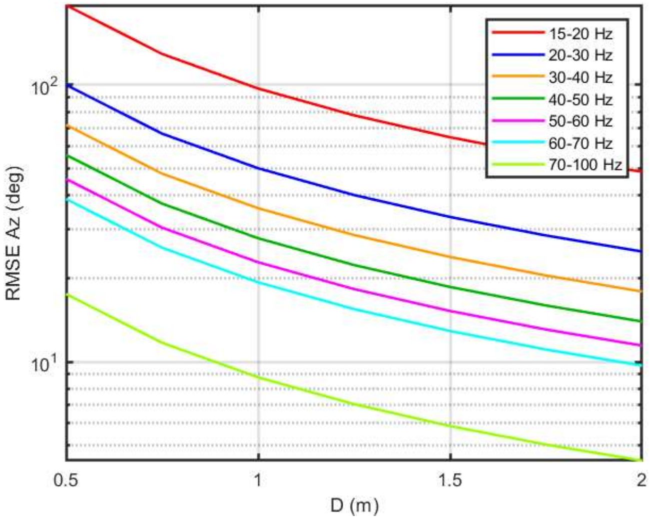


Figure D-2. Root mean square (RMS) azimuthal bearing error for the maximum likelihood estimation (MLE) beamformer processing and orthogonal (cartesian) hydrophone array as a function of frequency band and hydrophone spacing.

D.1.3. Orienting the ALTO Lander

The beamformer provides bearing relative to its ‘x-axis’ (C-B). To orient these values to north, the rotation of the lander on the seabed must be determined. This is achieved by computing the direction of arrival for a sound arriving from known location, typically the deployment vessel. The rotation needed to align the outputs from the beamformer with the known direction is stored in the Channel-Associations.xml file and then used for all future data analysis (Figure D-3).

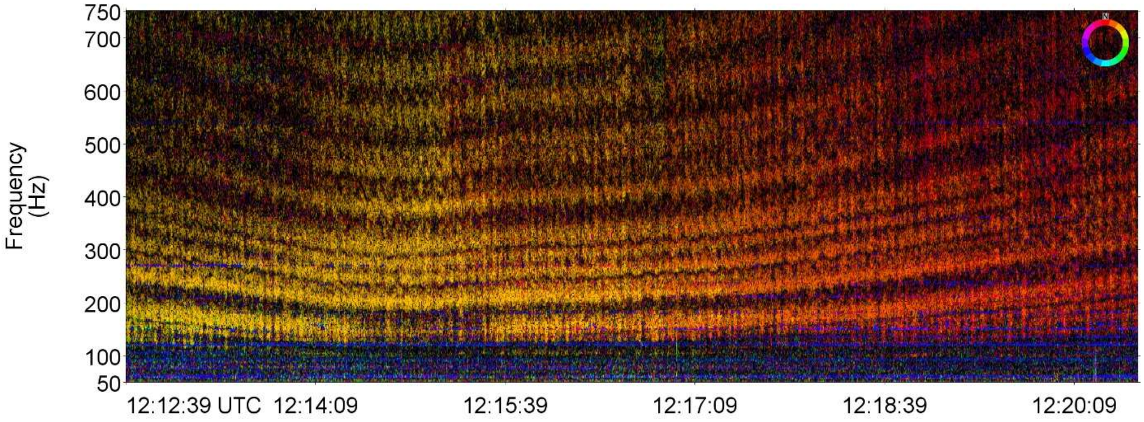


Figure D-3. Example directogram of a vessel passing 650 m from an ALTO lander. At 12:12, the vessel was at 060 degrees, moving to 000 degrees at 12:20. In this data presentation, the colour represents the direction of arrival, as shown by the colour wheel at the top right of the figure. A rotation of 95 degrees was needed to yield the correct results compared to the data without correction. There is a second source to the south-west (blue) that is also present in the sample.

D.1.4. Determining the Absolute Minimum Number of Animals Present

The MLE beamformer is applied to each marine mammal detection below 750 Hz, which generates a data table of the time, duration, minimum and maximum frequencies, SPL, bearing, SNR, and the energy weighted mean frequency of the data in the detection. These detections are filtered to reflect potential restrictions imposed on the output of the relevant detector (see Appendix B.3) and are analysed to find the absolute minimum number (AMN) of animals present. The analysis steps are:

1. Remove species where the manual analysis indicated that the detectors did not have a precision greater than 0.75. This is set as a parameter in the species definition file.
2. Filtering out low SNR data. As discussed in Appendix D.1.2, the bearing errors increase as the frequency and SNR decrease. Therefore, the first stage of analysis is to remove data where the SNR is deemed to be too low:
    a. For detections with a mean weighted frequency below 22 Hz, detections with an SNR below 9 dB are discarded.
    b. For detections with a mean weighted frequency between 22 and 30 Hz, detections with an SNR below 8 dB are discarded.
    c. For detections with a mean weighted frequency between 30 and 40 Hz, detections with an SNR below 7 dB are discarded.
    d. For detections with a mean weighted frequency between 40 and 100 Hz, detections with an SNR below 6 dB are discarded.
    e. For detections above 100 Hz, detections with an SNR below 5 dB are discarded.

3. The data are then grouped in 10-min windows. It is assumed that an individual will not move outside of one bearing sector over this time period. This assumption may be false if the animal is very close to the hydrophone array.
4. Round the bearings to the nearest 5-degrees. This resolution is one quarter of the minimum bearing error (20 degrees, see Appendix D.1.2).
5. For each 10-min block, find the number of calls per species. If this is less than the number of calls required to have a sufficient precision, per the manual analysis, the calls are removed. The number of calls per 5-degree bearing bin is stored to be available for plotting as call densities.
6. For each 10-min block, compute the AMN for each species:
    a. Select the highest SNR call in the 10-min window, then find all calls that are within the bearing error of that call. These are associated with the first animal. The bearing error is defined in a configuration file based on frequency and array shape (see Figure E-2). The selected value is ground-truthed by comparing the AMN outputs with manual counts of bearing clusters.
    b. Repeat the associations for all calls not associated with other calls until the number of unique calling directions is determined. This is the AMN for the 10-min block.
    c. Find the maximum AMN per day and per hour for each species for use in the data presentations. These values are also stored for external review and analysis.