Acoustic Investigation of Bycatch Mitigation Pingers

Submitted by:

Christine Erbe
Craig McPherson
Andrea Craven
JASCO Applied Sciences Australia
Brisbane Technology Park
PO Box 4037
Eight Mile Plains, QLD 4113

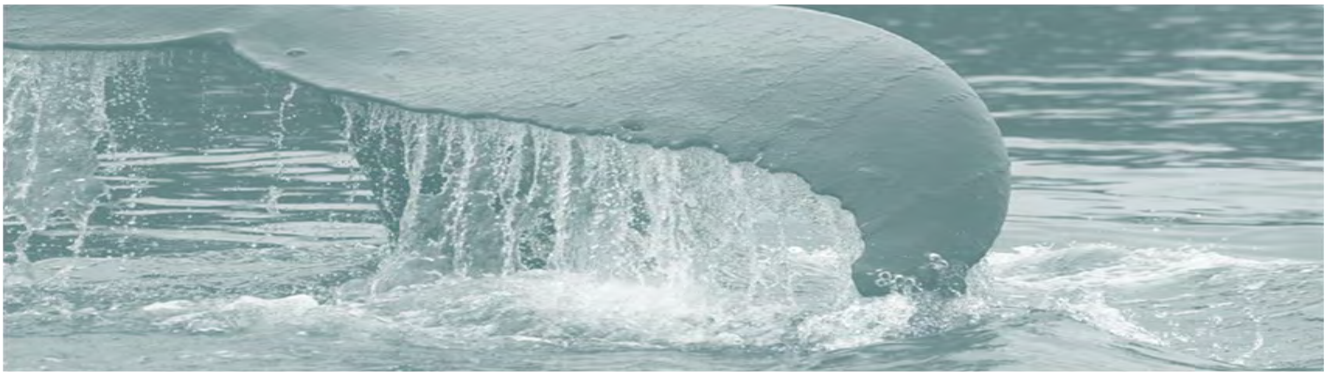
Australia@jasco.com

ABN: 85 134 374 708

Submitted to:

Australian Marine Mammal Centre
Australian Antarctic Division
203 Channel Highway
KINGSTON TAS 7050

ammccoordinator@aad.gov.au



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Contents

Executive Summary

Pingers, or acoustic alarms, were developed to reduce bycatch of marine mammals in fishing gear. A variety of devices exist emitting pure tones, amplitude-modulated tones, frequency sweeps and broadband pulsed sounds, as well as series of multiple sounds. The Queensland Shark Control Program (QSCP) has been using pingers on shark nets along Queensland's beaches to prevent marine mammal entanglement since 1992. An increase in the occurrence of whale entanglements was seen in 2009. As a result, pingers were replaced with new models in July – August 2010. This replacement rendered all previous studies of pinger characteristics obsolete.

The aim of this project was to measure the acoustic characteristics of the new pingers (Fumunda F3 and F10), to model sound propagation in an environment where QSCP pingers are deployed, to estimate over what ranges pingers might be detectable by marine mammals, to monitor ambient noise in an environment where QSCP pingers are deployed, and to make recommendations to QSCP on pinger deployment to optimise pinger efficacy.

Objective 1: Pinger Characterisation

Three Fumunda F3 and three F10 pingers were measured by mounting them in a purpose-built frame that would keep them at a constant distance of 2 m from the recording hydrophones yet allow 180^O rotations in both the vertical and horizontal planes to estimate patterns of sound emission directivity.

F3 Whale Pingers

The F3 pingers emitted a fundamental frequency of on average 2.7 kHz (2.6, 2.7 and 2.8 kHz for the three pingers) with multiple harmonics. The tones were about 400 ms long, occurring once every 6 s. Output levels varied from ping to ping and across pingers. The angular measurements showed some symmetry in the horizontal plane from midpoint to midpoint about the electrode end of the pingers, and in the vertical plane. Patterns were not consistent from pinger to pinger, partly due to the fact that the orientation of the vibrating piezo disk inside the pingers is not consistent but can vary by a few degrees, and partly due to the ping-to-ping variability in output level. The mean source levels over all angles and over five pings at each angle were 98 ± 7, 109 ± 6 and 118 ± 3 dB re 1 µPa^2/Hz @ 1 m for the fundamentals of the three F3 pingers. The first harmonic overtone was 3 – 10 dB stronger for all the pingers tested. The half-power (3 dB) bandwidths were 1-2 Hz for all tones. The broadband levels over all harmonics were 124 ± 3, 125 ± 5 and 128 ± 3 dB re 1 µPa @ 1 m for the three F3s. Fumunda specifies an output level of 135 dB re 1 µPa @ 1 m. This level was measured from one of the three pingers at some angles, however, on average, levels were less.

F10 Dolphin Pingers

The three F10 pingers had fundamental frequencies of 9.4, 9.5 and 9.6 kHz, plus multiple harmonics. The tones were about 400 ms long and occurred once every 4 s. The variations in output level from ping to ping, from pinger to pinger, and as a function of angle were larger than for the F3s. The mean fundamental source levels over five pings at all angles for the three F10s were 106 ± 8, 122 ± 2 and 115 ± 7 dB re 1 µPa^2/Hz @ 1 m in the vertical plane. The mean broadband source levels were 117 ± 3, 127 ± 2 and 123 ± 4 dB re 1 µPa @ 1 m for the three F10s in the vertical plane. Mean levels in the horizontal plane were on average 10 dB less. Fumunda specifies an output level of 132 dB re 1 µPa @ 1 m, which was reached by one of the three pingers at multiple angles, however, at other angles the levels

were less.

Objective 2: Modelling the Pinger Sound Field

JASCO's Marine Operations Noise Model (MONM) was used to predict transmission loss at a site off the Gold Coast where the QSCP has shark nets and pingers installed. Four frequencies were modelled: The F3 fundamental of 2.7 kHz, the first harmonic of 5.4 kHz, the second harmonic of 8.1 kHz, and the nominal F10 fundamental of 10 kHz. Acoustic energy was lost at a rate of 15 – 20 dB/decade in range over the first 10 m, 10 dB/decade from 10 to 100 m, 15 dB/decade from 100 – 1000 m, and > 20 dB/decade to 10 km in range. The effect of tide on transmission loss was < 2 dB from high tide to low tide over the same modelled ranges.

The results of the transmission loss model have to be combined with ambient noise levels and hearing capabilities of the marine mammals involved in order to determine the pingers' effective ranges.

Objective 3: Predicting Pinger Detectability

The literature was searched and reviewed for hearing abilities of marine mammals encountered along the Queensland coast:

- *Humpback whales (Megaptera novaeangliae)*
- *Indo-Pacific bottlenose dolphins (Tursiops aduncus)*
- *Bottlenose dolphins (Tursiops truncatus)*
- *Indo-Pacific humpback dolphins (Sousa chinensis)*
- *Common dolphins (Delphinus delphis)*
- *Snubfin dolphins (Orcaella heinsohni)*
- *Dugongs (Dugong dugon)*

Given the lack of species-specific detail on hearing abilities, the dolphins were grouped together.

There is no audiogram for humpback whales. It is assumed that humpback whales are sensitive at the frequencies of their own vocalisations (mostly 100 Hz – 4 kHz). Anatomical evidence of ears cut out of dead and stranded humpback whales confirms such low-frequency hearing specialisation. Humpback whales have been observed to respond to low-to-mid frequency sound from airguns, as well as sonars and pingers. In the absence of hearing thresholds for humpback whales, humpback hearing was assumed to be ambient noise limited. A critical ratio of 20 dB was added to model pinger tone detection in broadband ambient noise. For all of the dolphin species, published audiogram and critical ratio data from *Tursiops truncatus* were used. For dugong, audiogram measurements of manatees were used, and a critical ratio of 20 dB was added.

Using the mean source levels of the fundamental and harmonics of the six pingers measured in Objective 1, applying the transmission loss model from Objective 2, and subtracting the hearing thresholds for the three animal groups, led to a table of pinger detection ranges. Based on this approach the F3s were estimated to be audible to humpback whales and dugong over 210 m in range, and to dolphins over 110 m in range. The F10s were estimated to be audible to humpback and dugong over 130 m in range, and to dolphins over 40 m in range. The output from some of the pingers at specific angles would be audible over much longer ranges. The nominal levels specified by the manufacturer would be audible over a few km in range.

Objective 4: Ambient Noise Monitoring

One of JASCO's autonomous underwater acoustic recorders was deployed four times during the year for up to one month at two locations off the Gold Coast beaches. These instruments recorded underwater ambient sound continuously at a sampling frequency of 32 kHz. Ambient noise below 30 Hz was mostly caused by wind and wave action in shallow water and by fluid flow. Between 100 Hz and 2 kHz a number of sources were identified, including boats, fish, humpback whales, and a sand pump. Above 2 kHz at the January, March and May location, snapping shrimp dominated, being louder at night than during the day. Snapping shrimp sound was reduced in the September data, likely due to the different geographic location of the September recorder. Fish sounds were heard throughout, however, distinct choruses were not detected. Humpback whales on their southern migration were heard throughout the September deployment. No humpback whales were detected in January and March. A few humpback calls were heard in May/June as they returned on their northern migration. Dolphins were detected in all data sets.

Boat passes were heard throughout the recordings. The September recorder site was about 2.4 km south of a sand pump operating every night and emitting loud sound between 100 Hz and 800 Hz. The sand pump was the strongest and most consistent contributor to ambient noise above 30 Hz during the month of September. For the later three deployments, the recorder was moved 10 km south, away from the sand pump, reducing the received level.

The September recorder site was about 1.5 km from the nearest shark net. At this range, the pingers contributed very little to ambient noise budgets. Neither the F3 nor the F10 fundamental were discernible in the ambient noise spectra; only the first harmonic of the F3 was visible. The January, March and May recorder site was about 500 m from the nearest shark net. The F10 fundamental was clearly visible in all three data sets. No F3 pingers were heard in January and March. The F10 pingers are installed throughout the year, whereas the F3s are only deployed during the humpback migration season and would not have been in operation during the January and March monitoring.

Recommendations:

There are currently 3-4 pingers per net of 200 m length. The number of pingers per net has changed over time. Modelling showed this pinger spacing to be more than adequate for humpback whales and dugong even at their top swim speeds. Given the low levels recorded from the F10 fundamental specifically targeted at dolphins, the F10 spacing was sufficient for dolphins at normal travelling speeds, and only inadequate in the case of dolphins swimming at top speed perpendicular to (i.e., directly towards) a net.

Given the small sample size of pingers measured (three per type), it might be useful to test a larger number of units to achieve a better statistical representation of output levels. It would also be useful to measure at what time into a deployment the battery power becomes inadequate to sustain sufficient output levels, in order to advise on recovery times.

For potential future studies on behavioural responses of marine mammals to pingers, the received sound level should be measured in the field at the time, rather than relying on the manufacturers' specifications in combination with a simple (e.g. geometrical) sound propagation model.

1. Introduction

1.1. Usage of Pingers

Pingers, or acoustic alarms, were developed to reduce bycatch of marine mammals in fishing gear (Reeves *et al.*, 1996; Werner *et al.*, 2006). Pingers are used in gill net fisheries across the US and the European Union members (Gotz & Hastie, 2009; Kastelein *et al.*, 2007). The main goal of pingers on gill nets is to 'highlight' the nets, notifying marine mammals of their presence and location and hence reducing entanglements (Kastelein *et al.*, 2007).

The term 'pinger' is used in a generic sense by manufacturers, although the product names and implied functions vary (Table 1). There is significant latitude in the manufacturers' product titles given to the devices (such as pinger, deterrent, dissuader) and in the corresponding functional goals attributed to the devices (such as to warn, deter, alert or dissuade). Reeves *et al*. (1996) considered that cetaceans could be either deterred from the area around a net or deterred from being entangled in a net. There is no standardised nomenclature for behavioural responses. Reeves *et al.* (1996) suggested that it is not appropriate for the behavioural response related term *deterrent* to be automatically associated with acoustic alarms or pingers, and that *deterring* was different from *dissuading*, their recommended term.

Kastelein *et al*. (2006) noted that a striped dolphin did not change respiration rate but a porpoise did when exposed to acoustic alarm signals, yet there was no doubt that both animals detected the pinger sounds. While it is expected that responses vary on an individual, population and species level, and possibly also over time, measuring the responses, detecting all of the potential responses and relating responses exclusively to pingers (i.e. excluding other factors) is difficult. Observers may not be fully aware of the exact nature of the responses of an animal underwater at some distance to the observer (Southall *et al.*, 2007).

Table 1: Acoustic pinger manufacturers, device reference and function

Maker	Device model or type	Device reference	Device function
Airmar (www.airmar.com)	Gillnet pinger	Pinger	to warn
Aquatec (www.aquatechproducts.com)	Aquamak200	Deterrent	to deter
Fumunda Marine (www.fumunda.com)	FMDP -2000	Pinger	to alert
STM Products (www.stm-products.com)	DDD variants	Dissuader	to dissuade

It is worth noting that the manufacturers of 10 kHz constant frequency pingers, Airmar and Fumunda, attributed "to warn" and "to alert" characteristics to their devices respectively. These functions are what Goodson and Mayo (1995), Lien (1990) and Werner *et al*. (2006) agree the devices can achieve.

Pingers exist for various tonal ranges and sweep outputs. Most commercial pingers range from 3 - 130 kHz. High-frequency outputs of >70 kHz are aimed at animals with good high-frequency hearing such as harbour porpoises (Kastelein *et al.*, 2007; Kastelein *et al.*, 2008), while lower-frequency outputs are aimed at animals with low-frequency hearing sensitivity, e.g. the Memorial University whale alarms (Lien *et al.*, 1990), the Natural Heritage Trust dugong and whale alarms (McPherson *et al.*, 2004; McPherson *et al.*, 2001), and the Fumunda F3 alarms. Using a pinger designed for one species often does not evoke the same behavioural effect on others (Berrow *et al.*, 2008; Brotons *et al.*, 2008). Establishing the likely sensitive hearing ranges will assist in the device selection and will increase the probability of success.

Acoustic alarms were initially used by Lien *et al.* (1990) to reduce bycatch of humpback whales in Newfoundland's cod traps, and have been used by the QSCP since 1992 (McPherson *et al.*, 2001). The history of the acoustic alarm strategy employed in coastal Queensland gill net fisheries, and by the QSCP, is outlined in McPherson *et al.* (2001). The alarms deployed to minimise humpback whale entanglement are also designed to be above the hearing range of sharks, which, for most sharks investigated, approaches 2 kHz (McPherson *et al.* 2001).

Pingers have predominantly been used within the northern hemisphere as is evident from the abundance of literature on northern species (i.e., common dolphins, harbour porpoises, and various species of pinnipeds). However, deployment of acoustic pingers has rapidly increased within Australian fisheries. Pingers for bycatch mitigation and depredation mitigation are under consideration for active utilisation by the commercial fishing industry in most states of Australia (Denis Ballam, OceanWatch 2009, pers. comm. via Geoff McPherson). The Australian Government funded Natural Heritage Trust has provided in excess of 1000 acoustic devices to Gulf of Carpentaria fishermen with additional input from OceanWatch Australia. The bulk of alarms were specifically designed for commercial use (McPherson *et al.* 2004, Geoff McPherson (pinger designer) pers. comm.). Several acoustic devices are readily available throughout Australia. Applications include purse seine, trawl, gillnet and various baited line fisheries. There is a large gap of understanding in the application and effectiveness of acoustic devices in relation to Australian fauna. Commercial fishery experience, especially with obligatory requirement to remain with deployed nets, is the most comprehensive knowledge of marine mammal interaction.

1.2. Documented Behavioural Responses to Pingers

A good example of an effective change in behaviour was documented by Leeney *et al.* (2007): Continuous pingers (Aquatech UK), frequency modulated between 20 and 160 kHz, source level 165 dB re 1µPa @ 1m, reduced negative interactions of bottlenose dolphins (*Tursiops truncatus*) with nets in the Shannon Estuary in Ireland through behavioural changes without unduly deterring the dolphins from their habitat.

A controlled experiment was conducted with Dukane NetMark 1000 pingers on gillnets in California and Oregon, USA (Barlow & Cameron, 2003). Each net set was randomly assigned as an experimental set with pingers or a control set without pingers. The pingers emitted tones of 300 ms duration every 4 s with a fundamental frequency of 10-12 kHz and harmonics up to 100 kHz. The manufacturer reported a source level of 132 dB re 1 µPa @ 1 m, however independent calibrations showed a variation in source levels between 120 and 146 dB, with a mean of 138 dB re 1 µPa @ 1 m. The bycatch rate for common dolphins decreased significantly with pingers.

Entrapment mortality of depredating dolphin species in fish trawls has been reported within the European Commission's 'NEthrops and CEtacean Species Selection Information and TechnologY' (NECESSITY) Project (STECF, 2002). Dolphins usually enter the openings of fish trawls feeding on entrained fish. Precise reasons for the dolphin mortality are not fully understood although disorientation is probably a major factor. Pingers emitting at 10 kHz were placed on the nets to warn the dolphins where the net was, although dolphins can naturally be expected aware of the immediate presence of a trawl net > 200 m long (Connelly *et al*., 1997), towed by a >20 m trawler, in particular as both trawler and trawl would have acoustic signatures.

As recently as 2008, low-intensity gillnet bycatch and depredation pingers were still being attached to trawl nets (Reijnders, 2006; Stephenson & Wells, 2008) in pilot studies in an attempt to reduce bycatch and depredation-associated mortality. The acoustic noise field around operating fish trawls is expected to mask aspects of the signals from the pingers (McPherson *et al*., 2008). Even some higher-intensity pingers developed for the NECESSITY project could be masked by some trawl vessels (Reijnders, 2006). Not surprisingly most authors reported no change in dolphin mortality in trawl nets fitted with low-intensity acoustic pingers and often concluded that the pingers, and by default pingers generally, offered no promise for bycatch/depredation mitigation in trawl applications (Stephenson & Wells, 2008).

However, another study which looked at trawl and set net fisheries in the UK (Northridge & Kingston, 2009) concluded that pingers were an effective mitigation tool for reducing marine mammal bycatch, including common dolphins, when placed at regular intervals along a net. This study used appropriate pingers for the task, DDDs by STM Products, as opposed to low-intensity acoustic pingers.

The pingers developed within the European Commission (DDD by STM Products; CETASAVER by IXTrawl) offer demonstrated capability for depredation mitigation with bottlenose dolphins, and offer the most potential so far with common dolphins (Morizur, 2009). The Protector (Seamaster Products) could also be placed in the same category (McPherson *et al*., 2008).

Recent versions of the STM Products Dolphin Dissuasive pinger generate broadband sounds and FM tones with source levels in the range of 175 dB re 1 µPa @ 1m (rms) within the most sensitive hearing range of Queensland dolphin species. The DDD pinger has not yet been deployed in northern Australian waters but thousands are deployed throughout the Pacific region.

McPherson *et al*. (2008) described a preliminary version of a Seamaster pinger based on primarily frequency modulated (FM) tones between 7-115 kHz to mitigate depredation effects of Indo-Pacific bottlenose and Indo-Pacific humpback dolphins around squid fisheries. Dolphins were reported by the manufacturer and by end-user fishermen distributed throughout Asian waters to keep a distance from the Seamaster pinger (pers. comm. Geoff McPherson).

The observed responses of Atlantic bottlenose dolphins (Leeney *et al*., 2007), Indo-Pacific bottlenose and humpback dolphins to FM tones with source levels similar to those of the dolphins' own whistles resulted in the design and manufacture of a FM tone generator (i.e., pinger) for use by Queensland commercial gillnet fishermen. The pinger was designed by Engineering & Physical Sciences, James Cook University, for the Natural Heritage Trust funded project on Bycatch Mitigation Using Acoustic Pingers, administered by the Northern Gulf Natural Resource Management Group for the Gulf of Carpentaria Commercial Fishermen Association and OceanWatch Australia. Experience reports from the presidents of the Gulf of Carpentaria Commercial Fishermen Association and the Hinchinbrook Seafood Industry Association indicated that these dolphin species remained at some distance (100-150

m) from the pinger. The estimated source level of this pinger within the presumed best hearing sensitivity of Queensland dolphin species was approximately 155 dB re 1µPa @ 1 m (rms).

Amir (2009) used two observer programs to estimate and assess the effectiveness of Fumunda F10 pingers in reducing Indo-Pacific bottlenose and humpback dolphin bycatch in Menai Bay, Zanzibar. Pingers were found to reduce the bycatch in both drift and bottom set gillnets.

Some species from Australian waters such as inshore bottlenose dolphin (*Tursiops aduncus*) and Indo-Pacific humpback dolphin (*Sousa chinensis*) exhibit distinctly aggressive responses to 10 kHz fundamental frequency devices in isolation and when placed on QSCP nets (McPherson *et al.*, 2004).

Hodgson (2004) and Hodgson *et al*. (2007) tested short-term behavioural responses of dugongs in Moreton Bay, Queensland, to BASA pingers broadcasting at 4 kHz and 10 kHz at 133 dB re 1 µPa @ 1 m. Two pingers were deployed simultaneously 50-55 m apart, similar to pinger spacing on a net, however, there was no actual net in the experiment. No significant responses were observed during daylight operations in clear water: dugongs passed between pingers whether they were active or inactive, fed throughout the experiments, did not change their orientation to avoid or investigate the pingers and did not change their likelihood of vocalising. However, the pingers tested were not intended to actively divert animals. Also, during the daylight in clear water, dugong might have seen that there was no physical barrier like a net between the pingers. The pingers were lowered into and raised above the water for the experimental and control conditions, however, the pingers in air immediately above the water would have transmitted into the water (at least within a 26^{O} cone), and for dugong swimming in between and around pingers, the experimental (pinger on) and control (pinger off) conditions might not have been very different.

On the other hand, McPherson *et al*. (2004) reported dugong approaching and then moving around nets fitted with pingers emitting 3 kHz at 135 – 138 dB re 1 µPa @ 1 m during the hours of darkness and in turbid northern Queensland waters. Ichikawa *et al*. (2009) demonstrated for wild dugong in Thailand that playbacks of sounds of actual or synthetic dugong calls attracted dugong to within 10 and 19 m respectively from within a 250 m radius. Playback of 3.5 kHz tones of 141 dB re 1 µPa @ 1 m source level resulted in a nearest approach, or furthest retreat, of dugongs to 100 m.

In summary, behavioural studies are extremely difficult to conduct in the wild, partly because of the difficulty to determine other factors that affect behaviour. The reported effectiveness of pingers varies, even when the same species and similar pingers are investigated, although care must be taken to ensure that the scenario is also the same, e.g. bycatch reduction versus depredation mitigation. There can be several reasons for this variance, including differences in study paradigms and data analysis, variability in emitted sound characteristics (e.g. as pingers age and battery power drops, emitted source levels decrease), and simply variability in animal response from population to population—even when belonging to the same species, but living in different geographical and acoustical habitats.

1.3. Potential Habituation

The term ‘habituation’ is used in a variety of contexts in the study of marine mammals, often without reference to literature and potentially in conflict with the use of the term in psychological or biomedical literature (Wright & Highfill, 2007). This matter of nomenclature was examined in a special edition of the International Journal of Comparative Psychology entitled 'Considerations of the Effects of Noise on Marine Mammals and other Animals', and after discussions at a workshop, it was decided to use the term 'acclimation' instead.

Acclimation: After repeated or chronic exposure to a single stressor, an animal no longer perceives the stressor to be threatening and reduces its physiological stress response. The decrease in stress response is specific to that stressor and does not generalise to other stressors as long as the animal is capable of distinguishing between them.

Information on acclimation to pingers is limited, due to the limited number of completed works on general interactions between species and pingers, to a lack of measurement and reporting standards, and to potential bias introduced by a reliance on parties such as fishing fleet observers or activist groups. It is often assumed that 'habituation' would lead to increased bycatch. However, this has never been demonstrated in longer-term studies (Carretta *et al.*, 2008; Palka *et al.*, 2008). The opposite, a lasting reduction in bycatch, has been demonstrated, and can be explained by associative learning. Palka *et al.* (2008) found no increase in mortality of harbour porpoise in 25,000 fishing net sets over seven years and thus no evidence of 'habituation'. Carretta *et al.* (2008) reported no increase in mortality over 12 years of Oregon offshore gillnet fishery. Also, Indo-Pacific bottlenose dolphins did not 'habituate' to 10 kHz Fumunda pingers over two separate one-year periods in Zanzibar (Amir, 2009).

One complication to the potential habituation effect could include the 'dinner bell' effect of acoustic devices (Bordino *et al.* 2002), which was associated with seals coming in after the pingers had successfully reduced the dolphin bycatch. The increased attention of pinnipeds was simply a reinforced attraction to the sound of the nets with pingers with most energy within their audible range. This could possibly be avoided by combining devices designed for both dolphins and seals.

1.4. Project Background

Acoustic pingers are becoming a major part of marine mammal mitigation worldwide, and Queensland is no exception, with both commercial fisheries and the QSCP (part of Queensland Boating and Fisheries Patrol, within DEEDI) deploying them. At present, the QSCP is the primary user of pingers near shore along the east coast, and has been since 1992 (McPherson *et al.*, 2001). This, combined with QSCP's request for a new style of alarm in response to the increase in whale entanglements during the 2009 season, led to the support for this project.

Table 2: Acoustic specifications of pingers utilised in the Queensland Shark Control Program as of 2009

Pinger Manufacturer	**Model Frequency and Type**	**Harmonics**	**Source Level**	**Omni-directionality**
Dukane	Pre Netmark 1000 Tonal CF 9-11 kHz	Significant	Average 132 dB re 1µPa (rms) at 1m at fundamental (*,**,***). (46 Hz analysis bandwidth) Significant energy in harmonics	Good (***)
NHT 2.9kHz	Non-commercial, NHT 2.9kHz	Significant	SPL approximately 136 dB re 1 µPa at 1 m ***	Good (#)

BASA	Dolphin Tonal CF 10 kHz	Weak	Average 121-132 dB re 1µPa (rms) at 1m at fundamental frequency (***). (46 Hz analysis bandwidth)	Poor (***)
BASA	3.5kHz whale alarm (9v or 6v battery)	Significant	9v version - Average Broadband SPL 135.3 dB re 1µPa (rms)***,***** 6v version (more commonly used), approximately 7dB lower than 9v ***,##	Moderate
Airmar	Tonal CF 10 kHz	Suppressed	Average 132 dB re 1µPa (rms) (**), (46 Hz analysis bandwidth)	Poor, up to 6 dB loss (****)
SaveWave	Endurance Sweep 5-95 kHz	Broadband	Average 140 dB re 1µPa (*), 134 dB re 1µPa (rms) at 1m (**) and 112-116 dB re 1µPa (rms) at 1m at frequencies 7-95 kHz (**,***) (46 Hz analysis bandwidth)	Poor, up to 25 dB loss (***)
Fumunda	F10 Tonal CF 10 kHz	Significant (***)	Average 132 dB re 1µPa (rms) at 1m at fundamental (*), 141 dB re 1µPa (peak-peak) at 1m (**) (46 Hz analysis bandwidth) Significant energy in harmonics, different results from different authors.	Similar to Airmar (***)

* Manufacturer's specifications.
**(Kastelein *et al.*, 2007)
***QSCP testing using reference signal from DSTO (McPherson *et al.*, 2004; McPherson *et al.*, 2008)
****(Shapiro *et al.*, 2009)
***** (Baldwin, 2002)
# (McPherson *et al.*, 1999)
BASA alarms were constructed using a Sonitron SP27 piezo (Geoff McPherson, pers. comm.), which emits 94 dB (A) @ 9V DC @ 1 m (Sonitron SP27 Datasheet http://www.sonitron.be/site/bestanden/download.php?filename=SP27Datasheet.pdf)

A range of pinger types has been previously deployed on QSCP nets (Table 2), with up to two pingers placed at the same location on a net, one to alert humpback whales, the other to alert dolphins. The humpback whale pinger deployments are seasonal based on the migration of the whales, whereas the dolphin pingers are a permanent fixture. A map of QSCP shark nets along the Gold Coast is shown in Figure 1.

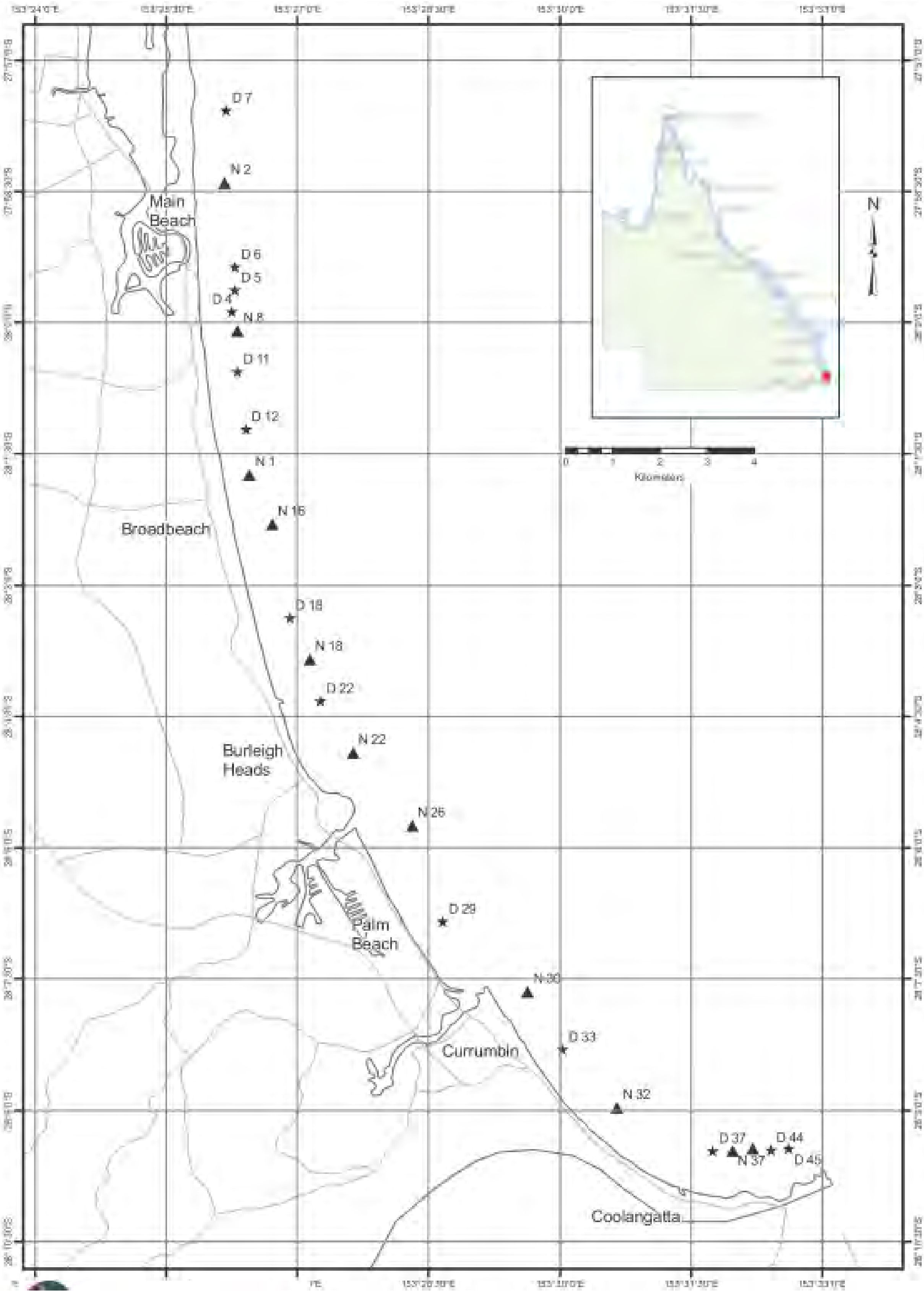


Figure 1: Locations of QSCP shark nets (N) and drums (D) along the Gold Coast in 2005.

Different types of pingers perform differently. Stemming from QSCP's review after the entanglements of 2009, QSCP replaced all pingers on the nets with Fumunda Marine products, either F3s (3 kHz for humpback whales) or F10s (10 kHz for dolphins) in July-August 2010.

This recent replacement has rendered all previous knowledge regarding the acoustic energy output of pingers used by the QSCP obsolete, as all previous studies (Baldwin 2002, McPherson *et al*. 1999, 2001, 2004) examined alarms which have been phased out of service.

The project objectives were to:

1. Characterise the sound output of all pinger types currently used by the QSCP through underwater recordings of three F3s and three F10s.

2. Model the acoustic energy footprint of each pinger type for a sample environment using appropriate sound propagation tools.

3. Predict ranges of pinger detection by marine mammals based on marine mammal species' audiograms and critical bands (where information is known).

4. Determine the ambient noise levels for a geographic area of interest through acoustic monitoring with autonomous recorders. Compute the statistical noise distribution and identify contributors to the noise budget of the area (e.g. wind & wave noise, boats, marine mammals, fish). Determine the contribution of deployed pingers to the total noise budget.

5. Summarise results in a management-oriented report on noise characterisation of pingers used by QSCP, sound mapping of pinger output, marine mammal detection modelling, optimal pinger deployments, characterisation of ambient noise in areas where pingers are used, and contribution of pinger energy to total noise budgets.

2. Methods

2.1. Objective 1: Pinger Recording

The Fumunda F3 and F10 pingers were measured using calibrated equipment to determine acoustic signatures. A sketch of the pingers is shown in Figure 2.

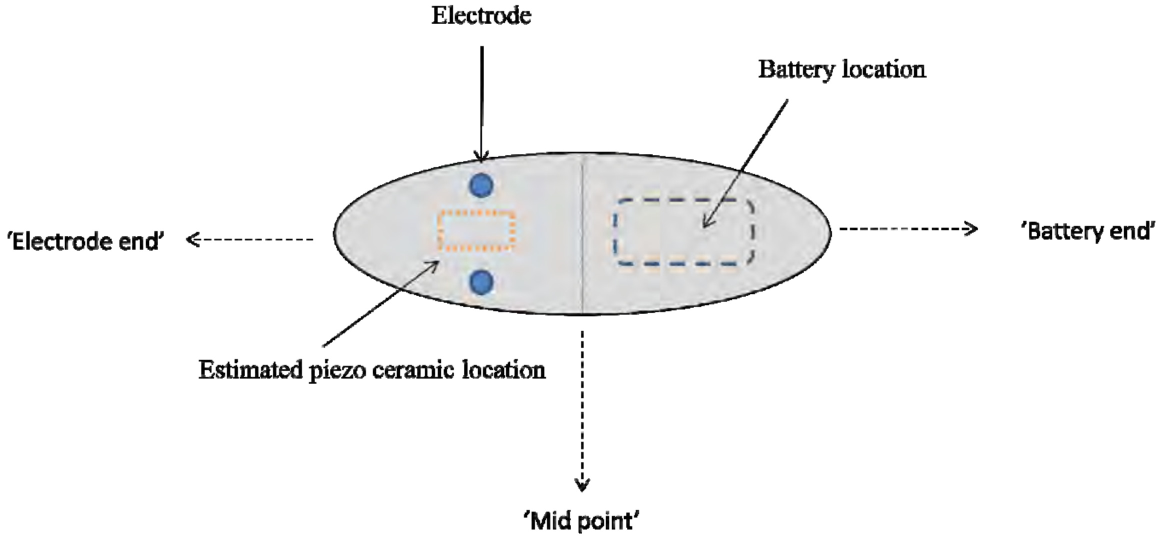


Figure 2: Basic design of the pingers tested. The exact location and shape of the piezo cannot be determined without physical separation of components within the pinger encasement. The battery and connections make up half of the pinger shell. The midpoint of the pinger related to the joint location where the pinger can be opened for battery changes.

Eight F3s and two F10s were received from QSCP, supplemented with two F10s from a JASCO collaborator (Table 3). All pingers had their battery levels measured, as well as their acoustic output, but time was only available to analyse three F3s and three F10s, shaded grey in Table 3. All but one of the pingers analysed had fresh batteries. It was decided to analyse the pinger which had already operated for exactly 60 days (F3-1), in order to examine a potential change in performance over time.

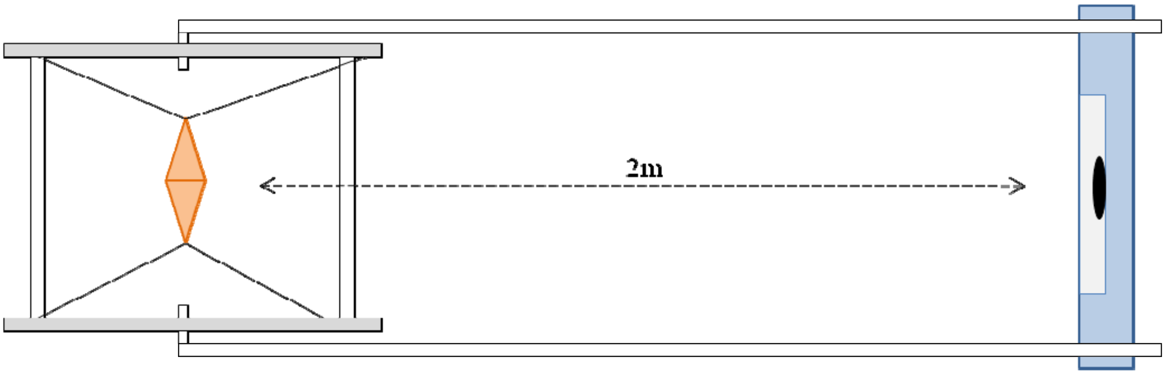
Table 3: Pingers supplied for testing

Pinger	Serial	Description	Voltage (v)	Testing Notes
F3-1	NA	Exactly 60 days of use, via QSCP Contractor, prior to testing	3.584	
F3-2	NA	New	3.64	
F3-3	NA	New	3.63	
F3-4	NA	Approximately 90 days of use prior to testing	3.62	
F3-5	NA	Approximately 90 days of use prior to testing	3.61	Did not activate when tested
F3-6	NA	New	3.64	
F3-7	NA	New	3.64	
F3-8	NA	New	3.643	Did not activate when tested
F10-1	FMP07A0208	Fresh battery	3.654	
F10-2	Fumunda 01B0689	Fresh battery	3.66	
F10-3	Fumunda 08A0168	Fresh battery	3.668	
F10-4	Fumunda 08A1906	Fresh battery	3.66	

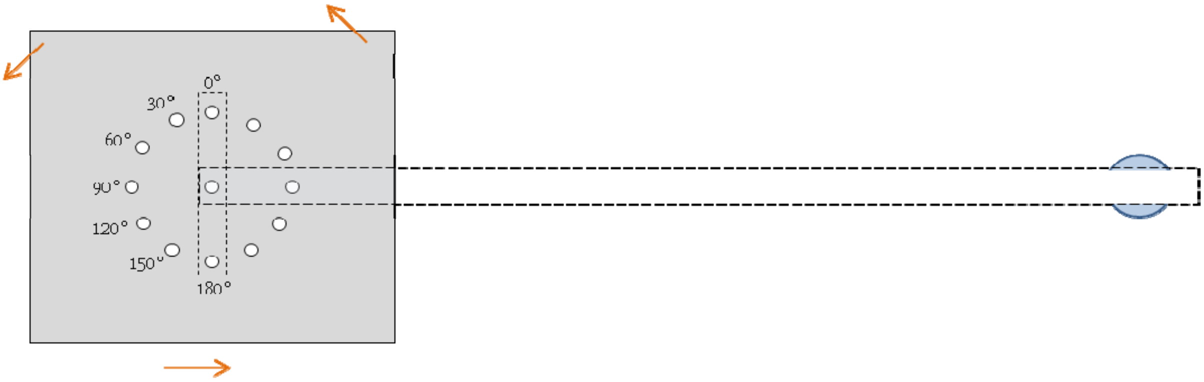
Pingers were mounted in a purposely-built wooden frame allowing full rotation of the source to measure directivity, and ensuring a fixed distance of 2 m to the recording hydrophone (Figure 3). The entire system was suspended off the side of a boat so that the apparatus was suspended within the water column. Each pinger was measured in the horizontal and vertical planes. In the horizontal plane, the pingers were recorded in two rotations: 1) from ‘midpoint’ to ‘midpoint’ focusing on the end containing the piezo, and 2) from the ‘battery end’ to the ‘electrode end’. Each rotation was measured at set angles (0, 30, 60, 90, 120, 150, 180^{O}). Each pinger was recorded for approximately 1.5 minutes at each angle.

Pinger Recording Apparatus

Side view, pinger in vertical position



Top view, with apparatus reference rotation angles



Side view, pinger in horizontal position

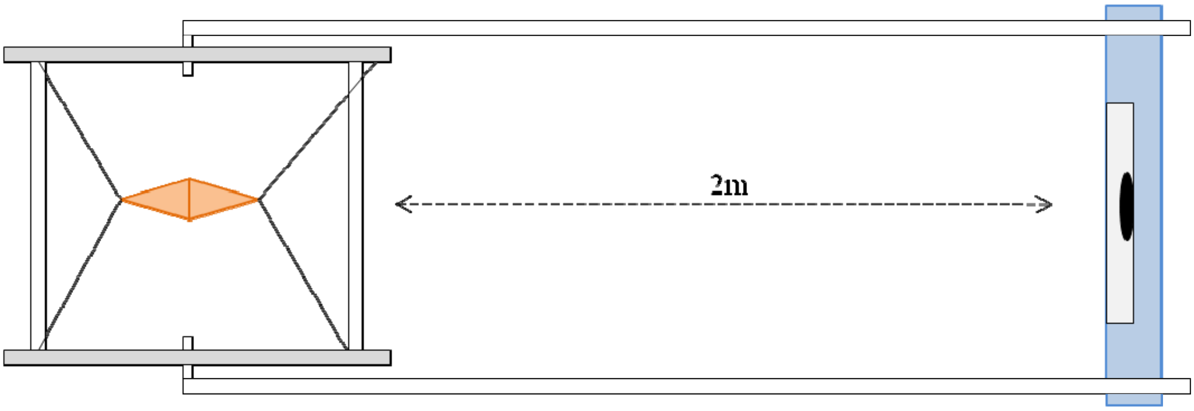


Figure 3: Representation of the pinger recording apparatus. The pinger is shown in orange, a hydrophone is shown in black, mounted at the opposite end of the frame, shown in blue. The mount of the pinger rotates about the central axis and locks into points of set angles (see top view).

The recording system consisted of a Reson TC4043 hydrophone with built-in pre-amplifier, a sensitivity of -201 dB re 1V/µPa (± 2 dB) and a bandwidth of 2 Hz – 160 kHz, and a High Tech Inc. HTI 96 hydrophone with a built-in pre-amplifier, a sensitivity of -164 dB re 1V/µPa (± 2 dB) and a bandwidth of 2 Hz – 30 kHz. Both channels were recorded on a Sound Devices SD722 digital audio recorder. Sound was sampled at 192 kHz and 24 bits. The frequency response curves of the hydrophones are calibrated to NIST (National Institute of Standards and Technology) standards. Before measuring the pingers in the field, the entire recording system was calibrated at one frequency using a G.R.A.S. pistonphone.

Custom-written spectral analysis software was used to compute the following for each angle around the source:

- received spectra highlighting emitted energy distribution with frequency
- received levels in terms of pressure
- directivity pattern of source
- frequency of received tones
- length of received pings

Received levels were back-propagated to calculate source levels using a spherical geometric spreading term: $20 \log_{10}(2\text{m}) = 6$ dB.

2.2. Objective 2: Modelling the Pinger Sound Field

JASCO’s Marine Operations Noise Model (MONM) was used to model the pinger sound field. MONM computes acoustic propagation for arbitrary three-dimensional (3-D), range-varying acoustic environments. At low frequencies (< 6 kHz), this is achieved via a wide parabolic equation (PE) solution to the acoustic wave equation. At mid-to-high frequencies (> 6 kHz), a Gaussian-beam ray trace approach is used instead. MONM takes into account the water and seabed properties of the area and can handle variations in the propagation environment with direction, depth and distance from the source.

The parabolic equation code in MONM is based on the U.S. Naval Research Laboratory’s Range-dependent Acoustic Model (RAM), which has been extensively benchmarked for accuracy and is widely employed in the underwater acoustics community (Collins, 1993). The RAM algorithm in MONM has been augmented to model acoustic propagation from directional sources, such as airgun arrays (MacGillivray, 2006) and to simulate bottom loss from elastic seabed environments (Zhang & Tindle, 1995). The ray trace code in MONM is the widely-used BELLHOP Gaussian beam propagation model (Porter & Liu, 1995). The Gaussian-beam algorithm is superior in accuracy to other ray trace codes in that it is capable of avoiding numerical artefacts associated with non-linear eigenray solvers and it generates transmission loss (TL) solutions that are consistent with full-wave benchmark models over a wide frequency range.

MONM computes acoustic fields in 3-D by modelling transmission loss along evenly distributed radial traverses covering a 360 ° swath from the source (so-called N×2-D modelling). A full area footprint of the sound level from the source is generated within the software by modelling a dense fan of radials and re-sampling the results on a geo-referenced Cartesian grid. The model makes use of several types of environmental data including bathymetry, sound speed profiles, and geo-acoustic profiles.

In shallow water environments, such as the Gold Coast, underwater sound propagation is strongly influenced by the geo-acoustic parameters of the seabed, which include the density, seismic P-wave and S-wave speeds, and the seismic wave-attenuation of seabed materials. Geo-acoustic parameters for the seabed sediments and underlying bedrock were derived (Buckingham, 2005; Erbe, 2009; Hamilton, 1980) and are summarised in Table 4. We modelled a 30 m layer of fine sand over sandstone bedrock based on measurements in Moreton Bay and along the Gold Coast (Erbe, 2009; Jones & Davies, 1979; Marshall, 1980).

Table 4: Geo-acoustic profile parameters used for modelling the seabed at the Gold Coast

Material	**z (m)**	**c_p (m/s)**	**ρ (g/cm^3)**	**α_p (dB/λ)**	**c_s (m/s)**	**α_s (dB/λ)**
Fine sand	0	1650	1.8	0.165	418	5.5
	10	1700	1.6	0.17		
	20	1750	1.62	0.175		
	30	1800	1.65	0.18		
Sandstone bedrock	35	2900	2.4	0.348		
	40	3000	2.4	0.36		
	50	3500	2.5	0.42		
	200	3800	2.58	0.456		
	2000	4000	2.6	10		

Conductivity-temperature-depth (CTD) casts done at the Gold Coast in September 2010 (at the September location) showed well-mixed water with a mean sound speed of 1523 m/s, slightly increasing with depth by 0.2 m/s over the top 10 m.

A simplified Gold Coast environment was created for the model. Bathymetry was read off a Gold Coast chart along a 5 km west-east transect passing through the shark net off Mermaid Beach at 28.0385^{O}S and 153.4452^{O}E. The coastline was “straightened” to run from north to south. The west-east slope was kept constant over the rectangular modelling region extending 10 km north-south.

Pingers are deployed at the bottom of the nets, at a constant depth of 6 m below the sea surface independent of tide, and this source depth was therefore used in the modelling. Three different tides were modelled: a mean tide, where the water depth was 10 m, a high tide yielding 13 m water depth and a low tide yielding 7 m water depth. These extremes were chosen to assess the variability in propagation ranges due to tidal differences.

2.3. Objective 3: Modelling Pinger Detectability

To estimate ranges and regions over which pinger sound is detectable by marine mammals, information on audiograms and critical ratios for the species occurring in pinger deployment areas was gathered through a broad literature search.

An audiogram is a graphic display of hearing sensitivity (detection levels) at different frequencies. A critical ratio is the difference in dB between the sound pressure level of a pure tone just audible in the presence of a continuous noise of constant spectral density and the sound pressure spectrum level for that noise. Numerically, if *It* denotes the intensity of the tone and *PSDn* the power spectral density (intensity per Hertz) of wideband noise at the levels where the tone is just audible through the noise, then the critical ratio (CR) becomes (see e.g. Erbe (2008)):

$$CR = 10\ log_{10} \frac{It}{PSDn}$$

Critical ratios indicate how much higher the intensity of the pinger tone has to be than the intensity of the ambient noise for the pinger tone to be audible. Information on audiograms and critical ratios is only available for some species that occur in captivity, and is completely unknown for baleen whales. In the absence of direct data on hearing sensitivity, we searched for indirect information stemming from observed behavioural responses to sound and from vocalisation ranges of the species in question.

Marine mammals along the Queensland coast which might interact with shark nets are

- *Humpback whales (Megaptera novaeangliae)*
- *Indo-Pacific bottlenose dolphins (Tursiops aduncus)*
- *Bottlenose dolphins (Tursiops truncatus)*
- *Indo-Pacific humpback dolphins (Sousa chinensis)*
- *Common dolphins (Delphinus delphis)*
- *Snubfin dolphins (Orcaella heinsohni)*
- *Dugongs (Dugong dugon).*

In order to estimate detection ranges of pingers, the transmission loss modelled under Objective 2 was applied to the source levels measured from the three F3s and the three F10s under Objective 1 yielding received levels. These were compared to ambient noise levels recorded under Objective 4 (see below) and to hearing thresholds estimated for the marine mammals above. Given that the pingers operate at one frequency (plus harmonics), the pure-tone detection threshold needs to be subtracted from the received level to determine audibility. This detection threshold is the higher of two levels: 1) the audiogram level measured in the absence of noise, and 2) the ambient noise power spectrum density level plus the critical ratio.

2.4. Objective 4: Ambient Noise Measurement

2.4.1. Recorder Detail

An Autonomous Multi-Channel Acoustic Recorder (AMAR, Figure 4), designed and built by JASCO, was used to measure underwater sound. The AMAR features eight channels of 24-bit analog-to-digital conversion at a simultaneous sample rate up to 128 kHz and supports one channel of 16-bit digital sampling at rates up to 1 MHz. The unit was set to sample at 32 kHz for this project. A Geospectrum M8 hydrophone with a bandwidth of 200 kHz was used with the AMAR. The AMAR has a constant noise floor at -131 dB re Full Scale/√Hz, which equates to 42 dB re 1 µPa/√Hz for an M8 hydrophone. In addition to having fully calibrated spectral response curves, the recorder was calibrated at one frequency immediately prior to deployment and immediately after recovery using a G.R.A.S. pistonphone in the field.

Figure 4: JASCO's Autonomous Multi-channel Acoustic Recorder (AMAR).

2.4.2. Deployment and Recovery

The recorder was deployed four times during the year at two different sites. Table 5 gives the dates and locations of all of the deployments. The recorder was programmed to record for three weeks at a time. The second deployment was cut short due to the severe storms which southeast Queensland experienced in January 2011. A map of the locations is shown in Figure 5. CTD casts were done using an Instrumentation Northwest AquiStar CT2X.

Table 5: Deployment dates and coordinates

Deployment	**Date**	**Coordinates**
1	9th September 2010	S 27.95971, E 153.43552
2	4th January 2011	S 28.03542, E 153.44434
3	11th March 2011	S 28.03452, E 153.44404
4	14 May 2011	S 28.03452, E 153.44404

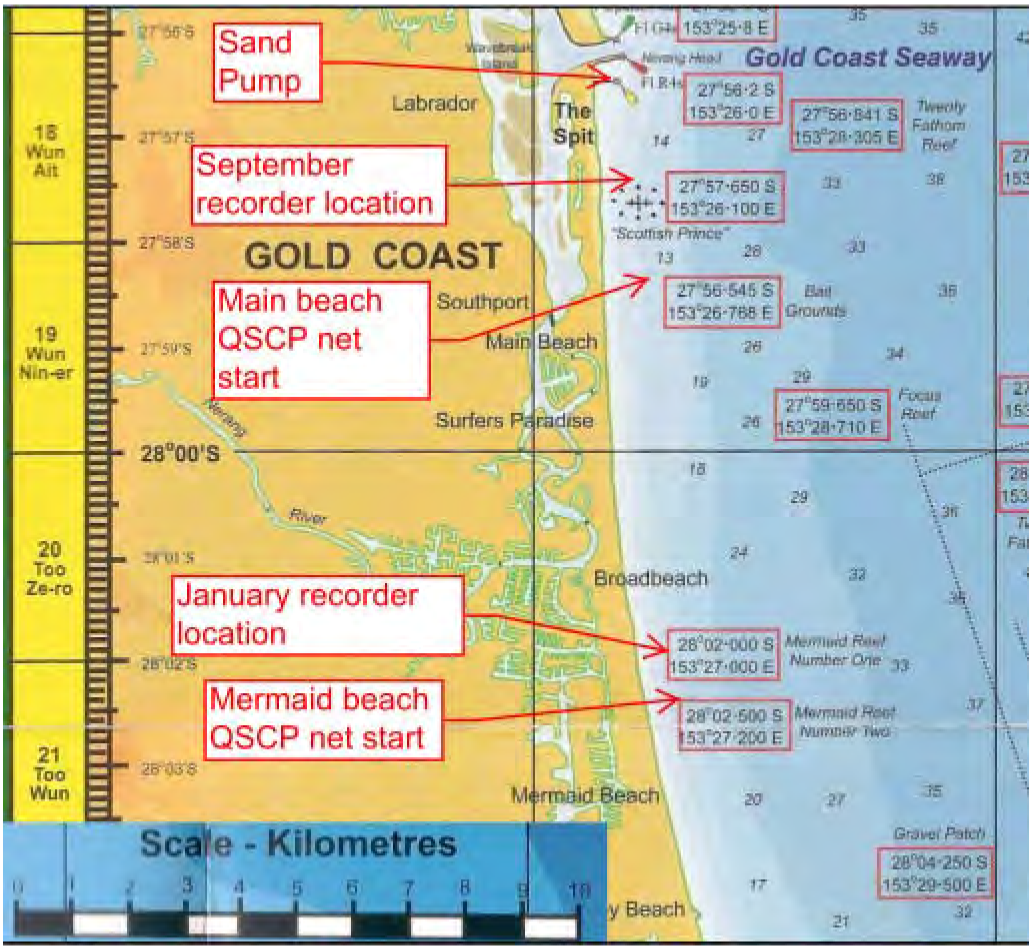


Figure 5: Map showing deployment sites; MC52/210 Camtas International Pty. Ltd., scale 1:135000, GWS 1984. In March and May, the recorder was deployed at the January site.

2.4.3. Data Analysis

2.4.3.1. Ambient Noise Percentiles

The statistical distribution of ambient noise over time was computed by applying a Fast Fourier Transform (FFT) to the recorded time series over 1s long windows with 50% overlap and Hamming window function, thus calculating power density spectra in 1 Hz bands. The statistical distribution of levels within each 1Hz band was computed and the 5th, 25th, 50th, 75th and 95th percentiles were plotted for each 1Hz band. The nth percentile gives the level that was exceeded n % of the time. The 50th percentile is equal to the median.

2.4.3.2. Sound Spectrograms

Daily sound spectrograms were computed by FFT on 1s segments of time series data. The resulting power density spectra were averaged over 1 min and plotted as a vertical line for each minute, and stacked in time to yield a 24 h spectrogram.

Monthly sound spectrograms were computed by FFT on 1s segments of time series data. The resulting power density spectra were averaged over 16 min time blocks and plotted as a vertical line for each block, and stacked in time to yield a monthly spectrogram.

2.4.3.3. Decade Band Levels

Band levels were computed by integrating power density spectra over frequency. The broadband level is the integral over frequency from 1 Hz to 16 kHz. Decade band levels correspond to the integral over narrow bands, one decade wide, i.e., from 10–100 Hz, 100 Hz – 1 kHz and 1–10 kHz. With a sampling frequency of 32 kHz, the maximum frequency that could be resolved was 16 kHz. Band levels were calculated over 1 min segments, and their variation with time was plotted.

2.4.3.4. Signal Detection

All recordings were analysed with JASCO's proprietary SpectroPlotter software package. SpectroPlotter displays waveforms of acoustic recordings, computes spectra, spectrograms and band levels in real-time, so the user can view the sound in the time and frequency domains while listening to the data. SpectroPlotter also allows the user to scroll through waveforms and spectrograms to examine data by eye much faster than in real-time. Features of interest are reviewed and selected for further analysis.

JASCO has also developed software for automatic signal detection and classification (Delarue *et al.*, 2009; Erbe, 2000; Erbe & King, 2008), which is incorporated into SpectroPlotter and works well for ship noise, seismic survey sounds, band-limited animal calls and tonal signals. The ship detections reported in this report were found automatically and confirmed manually. Fish were detected throughout, by random listening and scrolling through the spectrograms. Humpback whales were present in such large numbers in September that their calls showed up easily on the condensed monthly spectrogram.

3. Results

3.1. Objective 1: Pinger Recording

A systematic analysis of the pinger signal strength at different angles is important for characterising the directivity of the emitted sound. The following figures display the position rotations. Two 180^O rotations were measured in the horizontal plane in order to determine potential symmetries about the two pinger axes in the horizontal plane. There is a 90^O overlap between the two rotations. These angles were not measured twice.

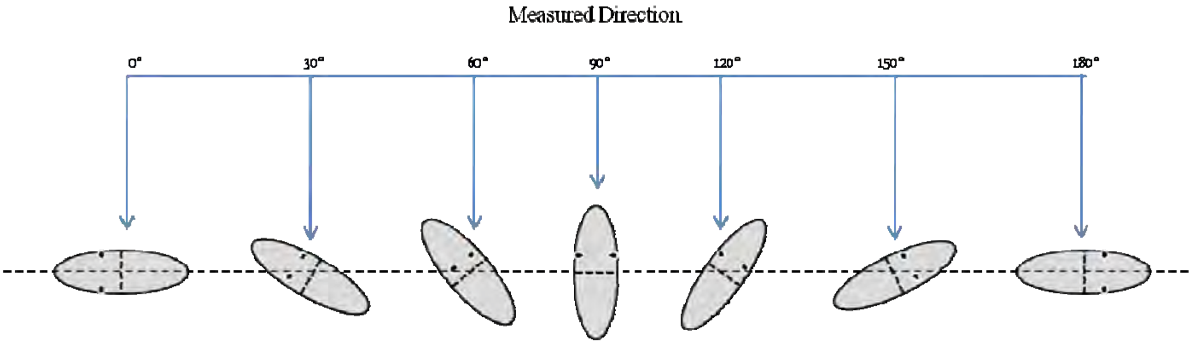


Figure 6: The pinger in horizontal position, view is from above the pinger, which rotated 30° for each sample, starting from 0°. This is the midpoint-to-midpoint rotation.

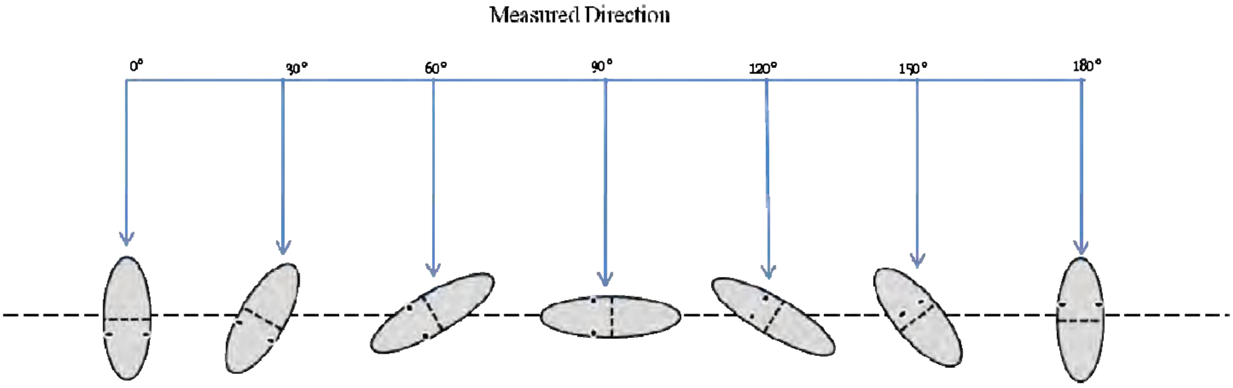


Figure 7: The pinger in horizontal position, battery-to-electrode-end rotation.

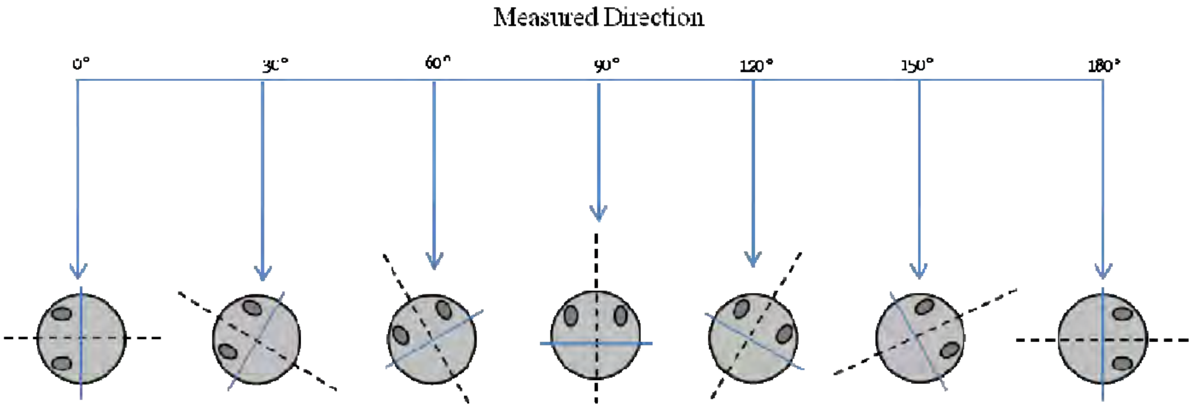


Figure 8: Pinger in the vertical position. The view point is from above the pinger. The darker spots are the electrodes.

3.1.1. Fumunda F3 Pinger

The fundamental frequencies of the three F3 pingers measured were: 2.7 kHz for the F3-1, 2.8 kHz for the F3-2 and 2.6 kHz for the F3-3. Multiple harmonics existed for each pinger, shown up to 20 kHz in Figure 9. There was a ping-to-ping variation in the frequency of the fundamental of up to 20 Hz, standard deviation 3 Hz. The tone lengths were 465 ± 13 ms for F3-1, 401 ± 4 ms for F3-2 and 403 ± 4 ms for F3-3. The average period was 6.9 s for the F3-1 and 6.0 s for the F3-2 and F3-3, with standard deviations < 0.1 s.

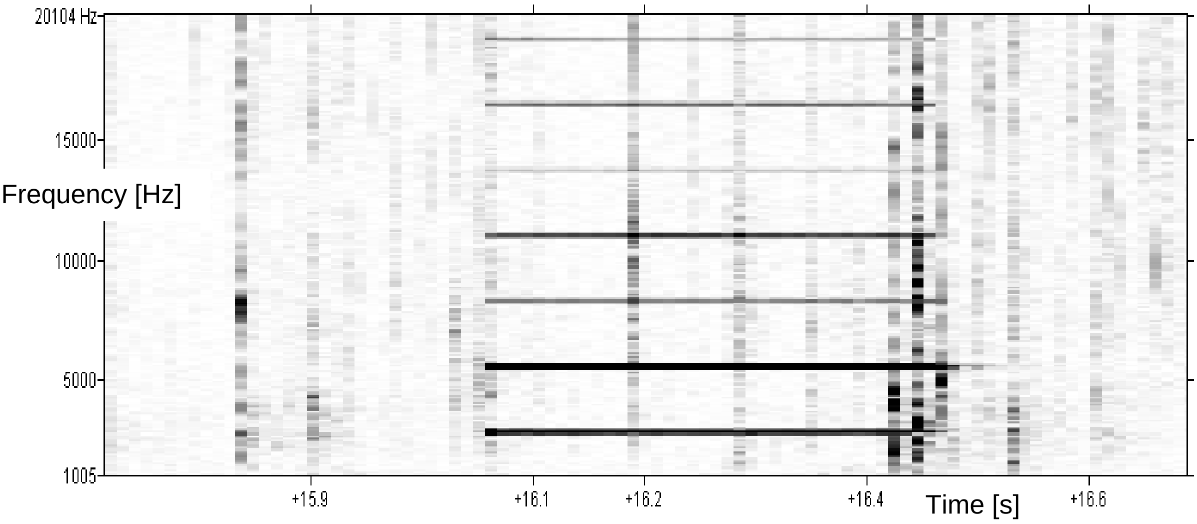


Figure 9: Spectrogram of a ping recorded from F3-1 in the horizontal orientation.

In each position, five pings were recorded and a mean spectrum computed. Spectra for the F3-2 pinger at various orientations in the horizontal plane are plotted in Figure 10 between 2 and 9 kHz, showing the fundamental and the first two harmonics. The 3dB bandwidth was 1-2 Hz for all tones (Figure 11).

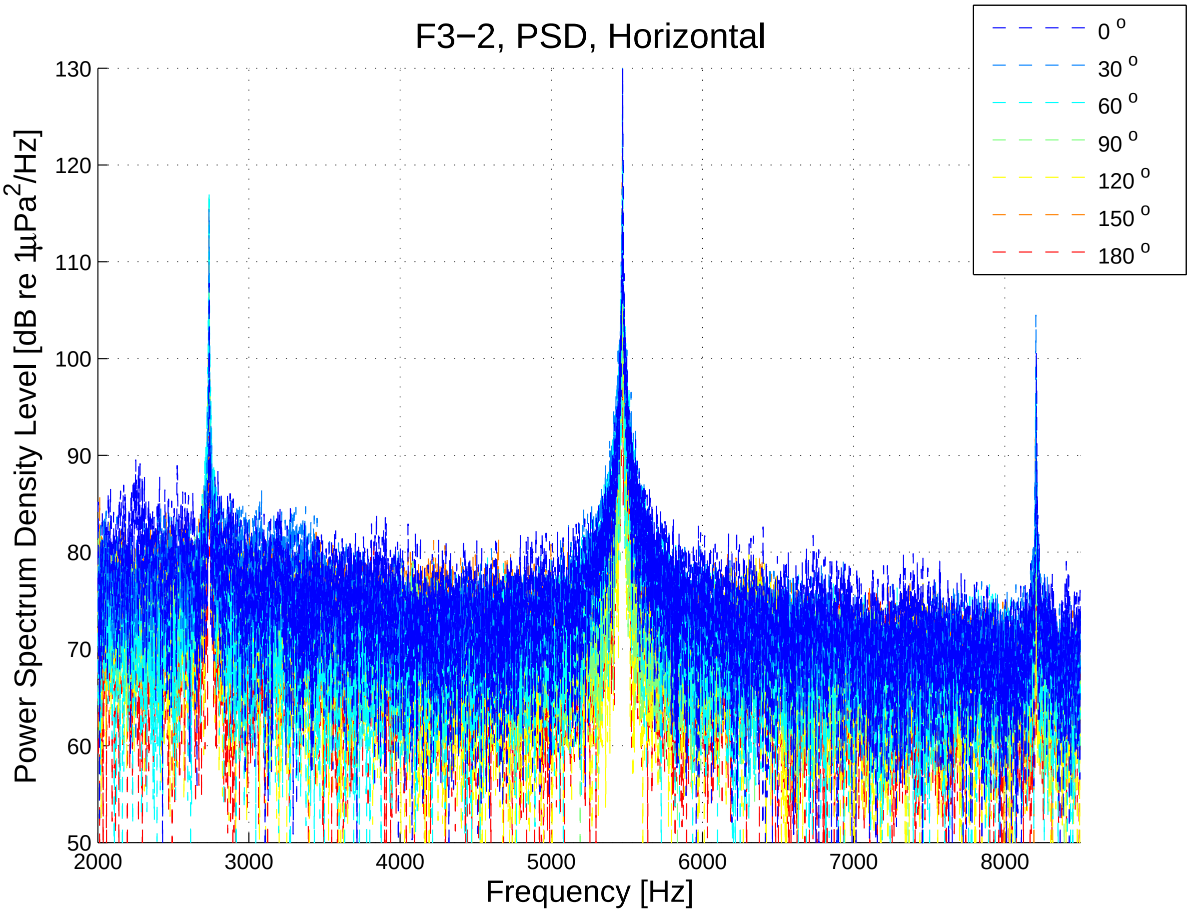


Figure 10: Spectrum of the F3-2 pinger recorded at various angles in the horizontal plane.

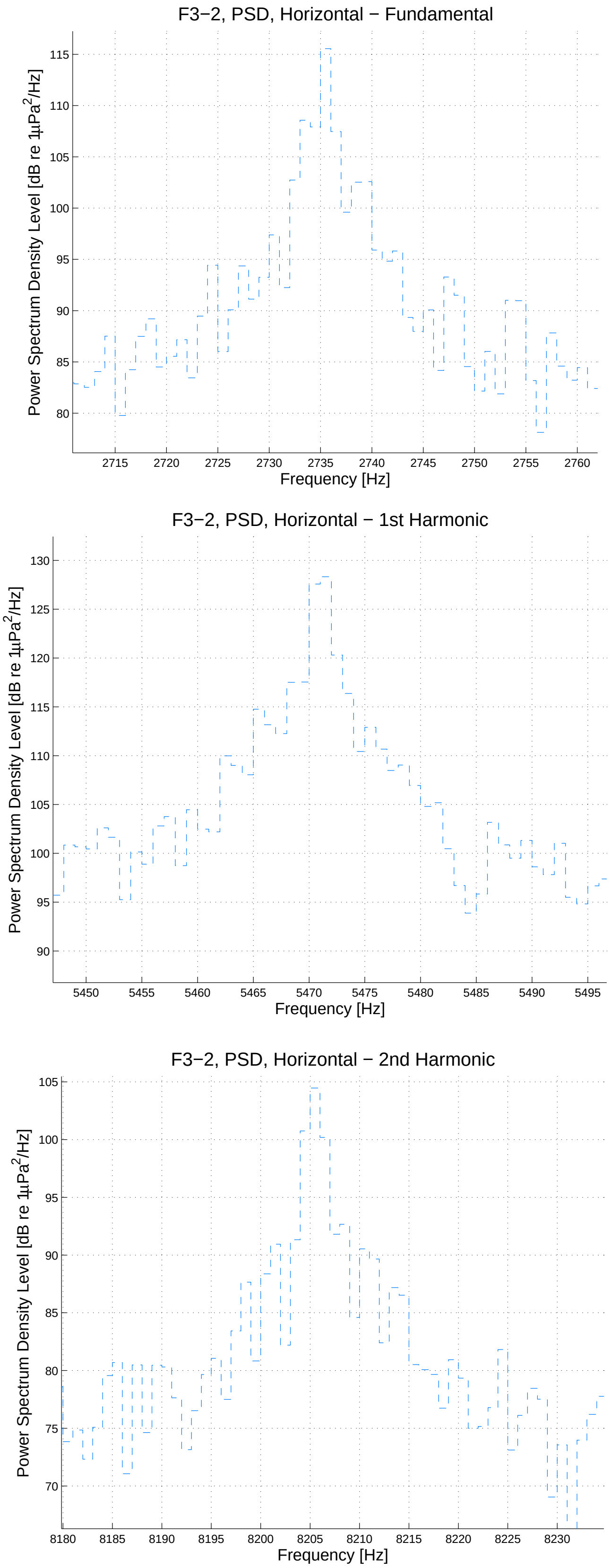


Figure 11: Bandwidths of F3 tones.

The ping-to-ping variation in sound level was measured for each of the three pingers over ten successive pings in one position, i.e. at one angle. The level varied from ping to ping by up to 5 dB, standard deviation < 2 dB.

The level also varied as a function of angle. The horizontal directivity in the midpoint-to-midpoint rotation is shown in Figure 12, and in the battery-end-to-electrode rotation in Figure 13. There is an overlap of 90^O between the two plots; 0-90^O in the midpoint-to-midpoint rotation is equal to 90-180^O in the battery-end-to-electrode rotation. This quadrant was not measured twice, but only plotted twice. The vertical directivity is shown in Figure 14. The levels plotted are means over five successive pings.

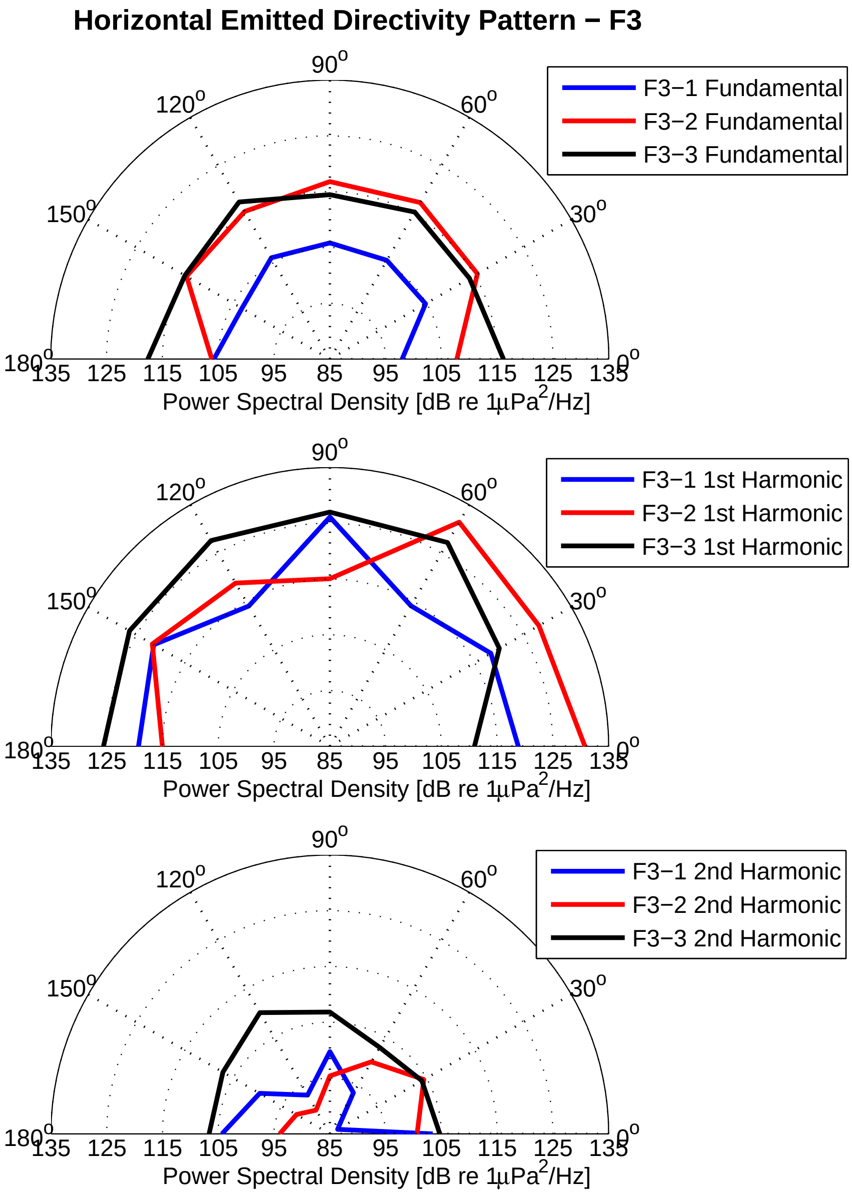


Figure 12: Polar plots comparing the signal strength of individual pingers in the horizontal position, midpoint-to-midpoint rotation, for fundamental and two harmonic tones at each angle.

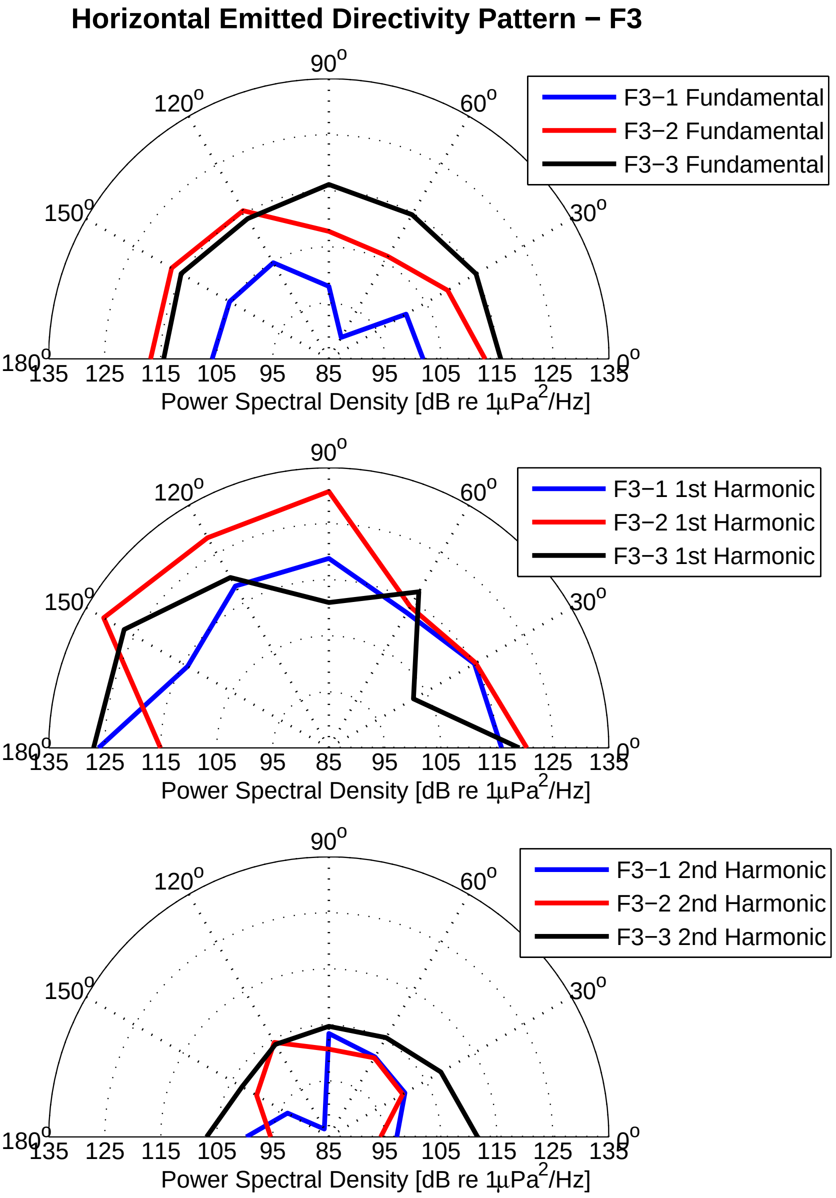


Figure 13: Polar plots comparing the signal strength of individual pingers in the horizontal position, battery-end-to-electrode rotation, for fundamental and two harmonic tones at each angle.

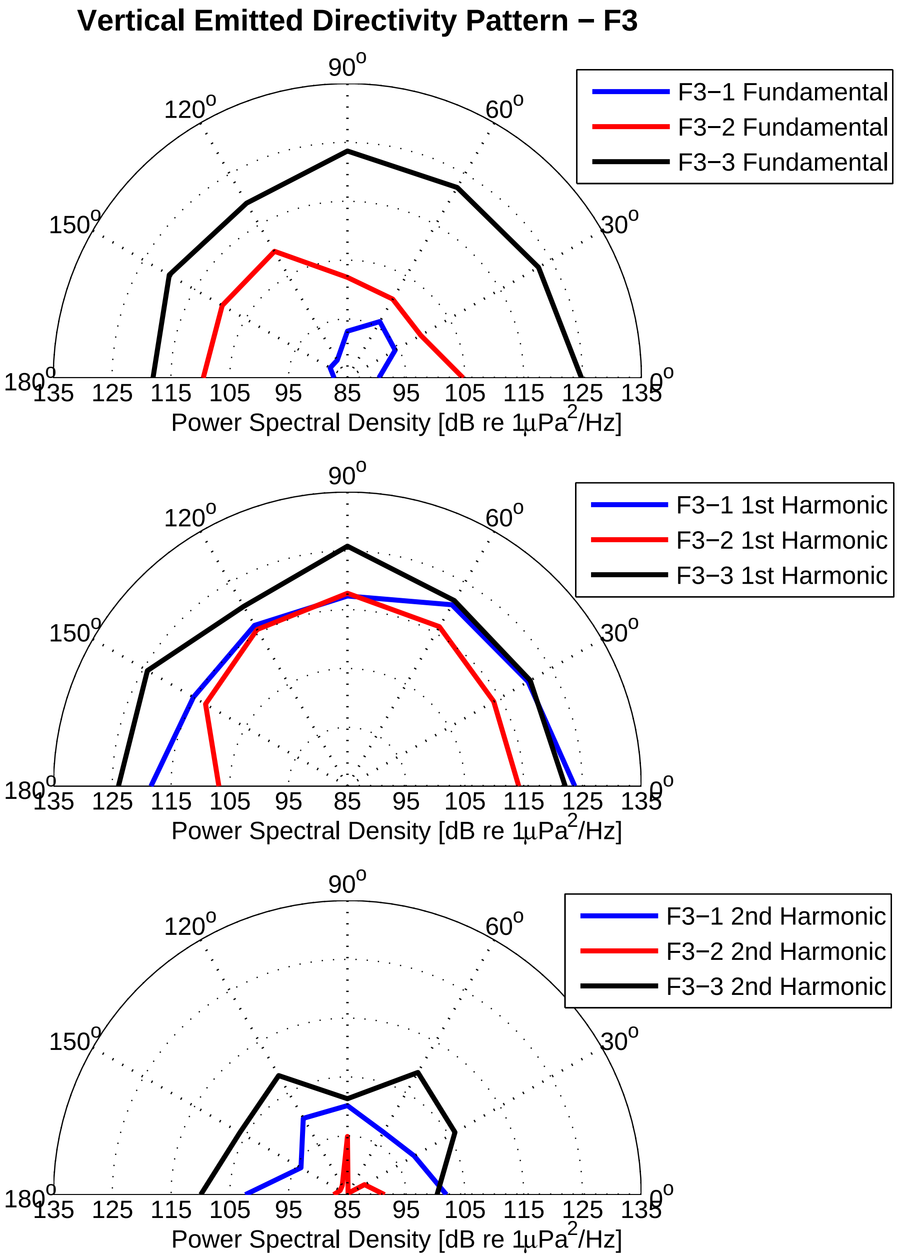


Figure 14: Polar plots comparing the signal strength of individual pingers in the vertical position, for fundamental and two harmonic tones at each angle.

The broadband root-mean-square sound pressure level SPLrms was computed over five pings in each direction, and is plotted in Figure 15 and Figure 16 for the two horizontal and the vertical rotations. The vertical plots are identical in both figures. Energy below 2 kHz was filtered out.

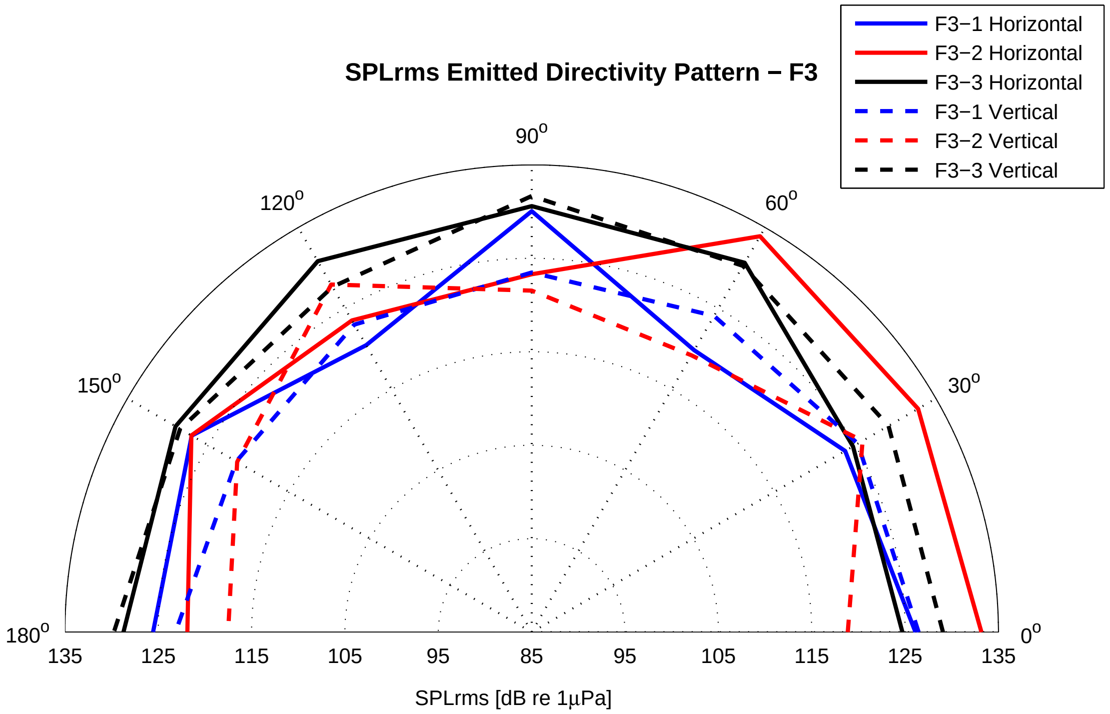


Figure 15: The SPLrms compared between the positions of the three F3 pingers in the horizontal (midpoint-to-midpoint) and vertical positions.

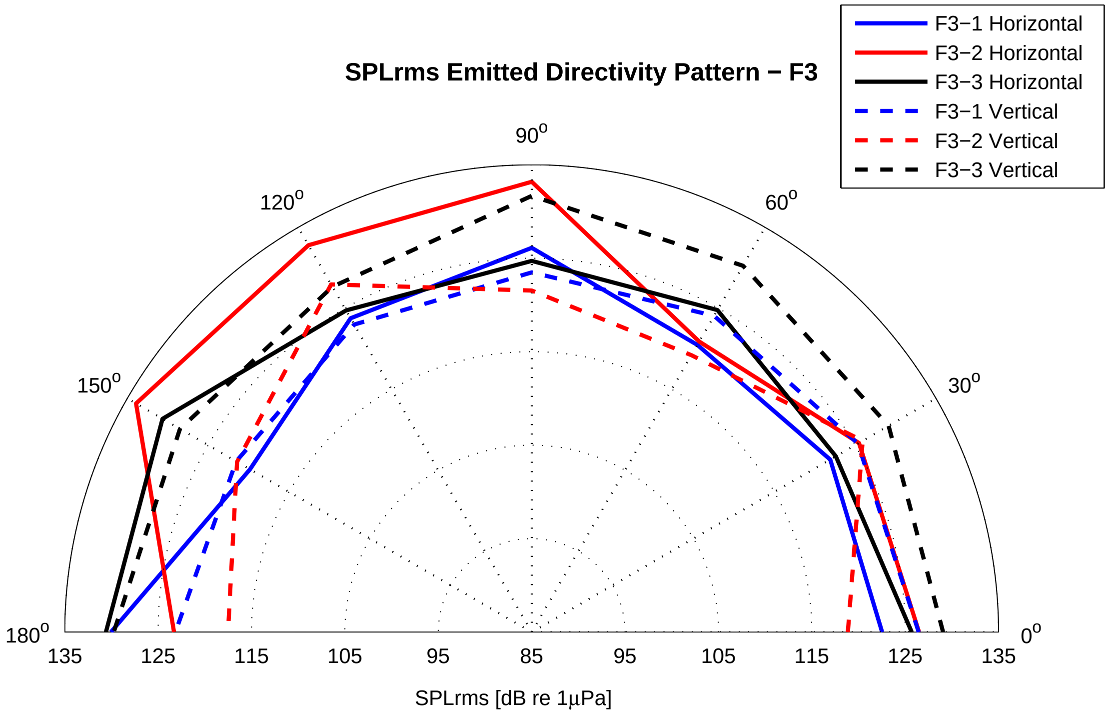


Figure 16: The SPLrms compared between the positions of the three F3 pingers in the horizontal (battery-to-electrode end) and vertical positions.

There was less variation in output level with angle over the vertical rotation than over the horizontal rotations. The horizontal midpoint-to-midpoint rotation appeared slightly more symmetrical than the endpoint-to-endpoint rotation, as expected due to the location of the piezo near one end. F3-3 had less angular dependence than F3-1 and F3-2. No symmetrical and no consistent directivity pattern was obvious when comparing all three pingers. This is partly due to the likely lack of consistent positioning and orientation of the piezo within the pinger housing. This is also partly due to the ping-to-ping variation in sound level. Levels were averaged over five pings at each angle; however, the inter-ping variation was a few dB for the 10-ping sequence investigated in one position. This variation could be investigated at other angles to determine how much of the apparent angular dependence was actually due to a ping-to-ping variability in output level.

Pingers on shark nets are not rigidly positioned; the angle from the pinger to the animal varies as the net moves, as the pinger moves, as the mounting changes from pinger to pinger, and with the animal swimming past the net. For the subsequent analysis, we therefore computed the mean output levels over all horizontal and vertical orientations (Table 6).

Table 6: Recorded minimum, mean and standard deviation for each F3 pinger. All levels are referenced to 1 m.

	Minimum (dB re 1 µPa²/Hz)	**Mean (dB re 1 µPa²/Hz)**	**Standard Deviation of Mean (dB re 1 µPa²/Hz)**
Fundamental			
F3-1	87.24	97.58	7.11
F3-2	99.43	109.28	5.67
F3-3	113.93	118.02	3.48
Harmonic 1			
F3-1	112.85	118.14	3.59
F3-2	106.85	118.18	6.62
F3-3	102.48	121.31	6.50
Harmonic 2			
F3-1	86.63	98.43	4.51
F3-2	83.24	93.43	6.33
F3-3	100.27	106.39	3.09
SPLrms (>2kHz)	**Minimum (dB re 1 µPa)**	**Mean (dB re 1 µPa)**	**Standard Deviation of Mean (dB re 1 µPa)**
F3-1	119.84	123.81	2.70
F3-2	117.51	124.76	5.04
F3-3	122.60	128.14	2.66

The specified level of the F3 pingers is 135 dB re 1 µPa @ 1 m (http://titley-scientific.com/fumunda-marine-pingers-f3). This level was confirmed for F3-3 at some angles and some tones, however, the mean output level of the pingers over five tones at all angles was less than specified by the manufacturer: 124, 125 and 128 dB re 1 µPa for the three pingers. A variation of up to several dB was measured from ping to ping, from angle to angle and from pinger to pinger.

One would expect a decrease in output level over time as battery power drains, and the 60-day old F3-1 had a weaker fundamental (11 and 20 dB less) than the other two F3s, however the difference in tonal output between the depleted pinger and the weaker of the two new ones was comparable to the variability between the two fresh units. Also, the broadband output level of the depleted pinger was only 1 and 4 dB below those of the fresher pingers due to strong harmonics. One of the 90-day old pingers (F3-5) did not activate when tested; the other 90-day old pinger (F3-4) was not tested. To determine how the output level drops over time, and to recommend a maximum deployment duration, a long-term study of one or more pingers should be done rather than comparing output levels of different pingers (differing in age), in order to eliminate pinger-to-pinger variability.

3.1.2. Fumunda F10 Pinger

The fundamental frequencies of the F10 pingers were: 9.4 kHz for the F10-1, 9.6 kHz for the F10-2 and 9.5 kHz for the F10-3. Multiple harmonics existed for each pinger, shown up to 40 kHz in Figure 17. There was a ping-to-ping variation in the frequency of the fundamental of up to 160 Hz, standard deviation 80 Hz for the F10-1. The other two pingers were more consistent in frequency; the fundamental of the F10-2 varied by up to 10 Hz, standard deviation 3 Hz; the fundamental of the F10-3 varied by up to 18 Hz, standard deviation 4 Hz. The tone lengths were 340 ± 20 ms for F10-1, 395 ± 4 ms for F10-2 and 399 ± 6 ms for F10-3. The period of the F10-1 was 4.4 s; the periods of F10-2 and F10-3 were 4.5 s; standard deviation < 0.1 s.

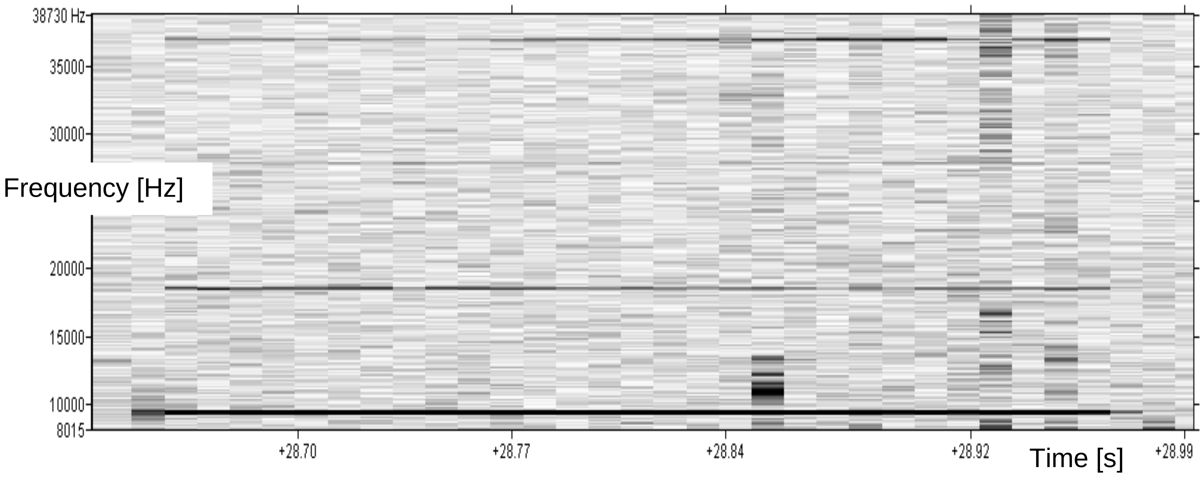


Figure 17: Spectrogram of a ping recorded from F10-1 in the horizontal orientation.

In each position, five pings were recorded, and a mean spectrum computed. Spectra for the F10-2 pinger in the horizontal plane are plotted in Figure 18 between 2 and 20 kHz, showing the fundamental and the first harmonic. The 3dB bandwidths were 1-2 Hz as for the F3s (Figure 19).

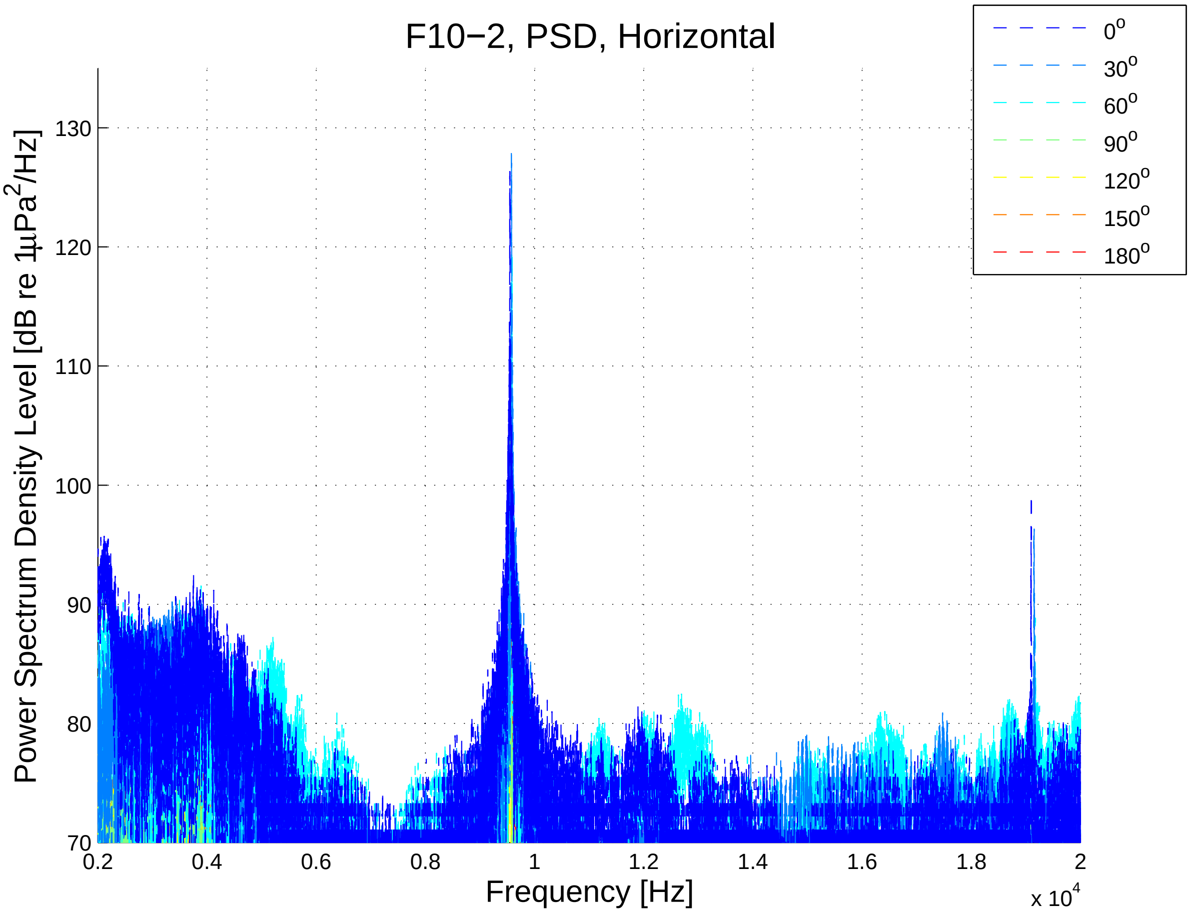


Figure 18: Spectrum of the F10-2 pinger recorded at various angles in the horizontal plane.

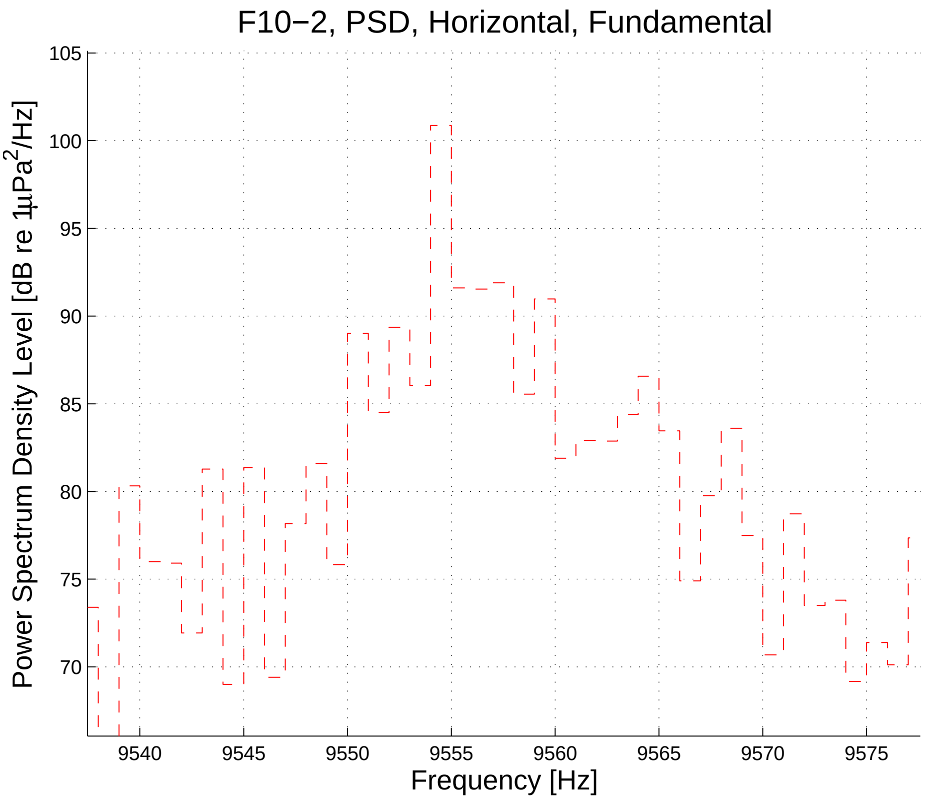


Figure 19: Bandwidth plot of the F10-2 fundamental.

The ping-to-ping variation in sound level was larger than for the F3s. The standard deviations of levels from 10 successive pings were 5 dB for F10-1 and 2 dB for F10-2 and F10-3. Levels also varied as a function of angle. The horizontal directivity in the midpoint-to-midpoint rotation is shown in Figure 20, and in the battery-end-to-electrode rotation in Figure 21, for the fundamental only. Levels of the harmonics were not investigated in detail, as the frequency of maximum energy (the intended transmit frequency) was 10 kHz for the F10 pingers, and we expected significantly less energy at higher harmonics. This was corroborated by the spectrum plots (Figure 18). There is an overlap of 90^O between the two directivity plots; $0\text{-}90^O$ in the midpoint-to-midpoint rotation is equal to $90\text{-}180^O$ in the battery-end-to-electrode rotation. This quadrant was not measured twice, but only plotted twice. The vertical directivity is shown in Figure 22.

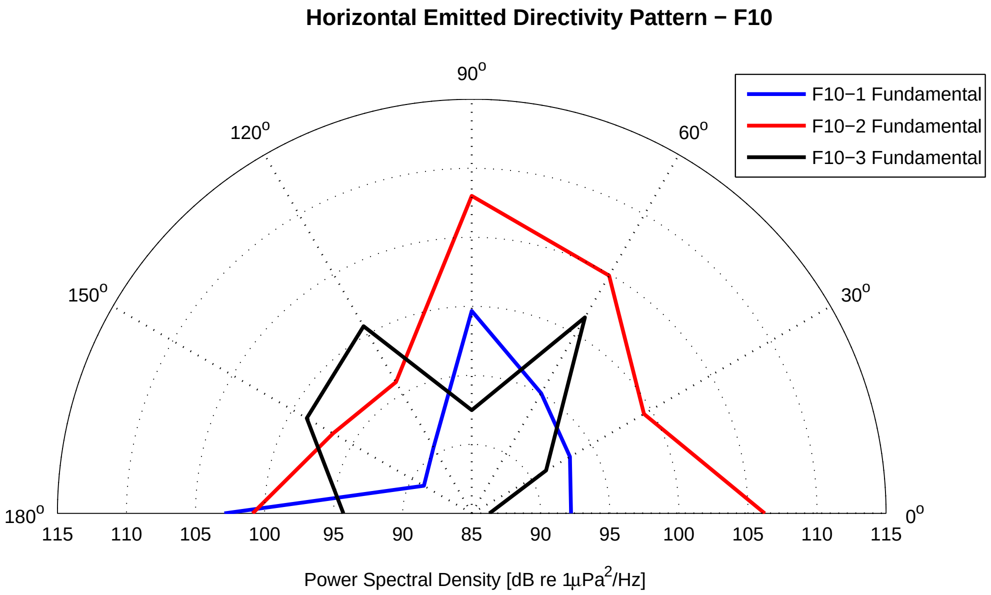


Figure 20: Polar plot comparing the signal strength of individual pingers in the horizontal (midpoint-to-midpoint) position at their fundamental tones at each angle.

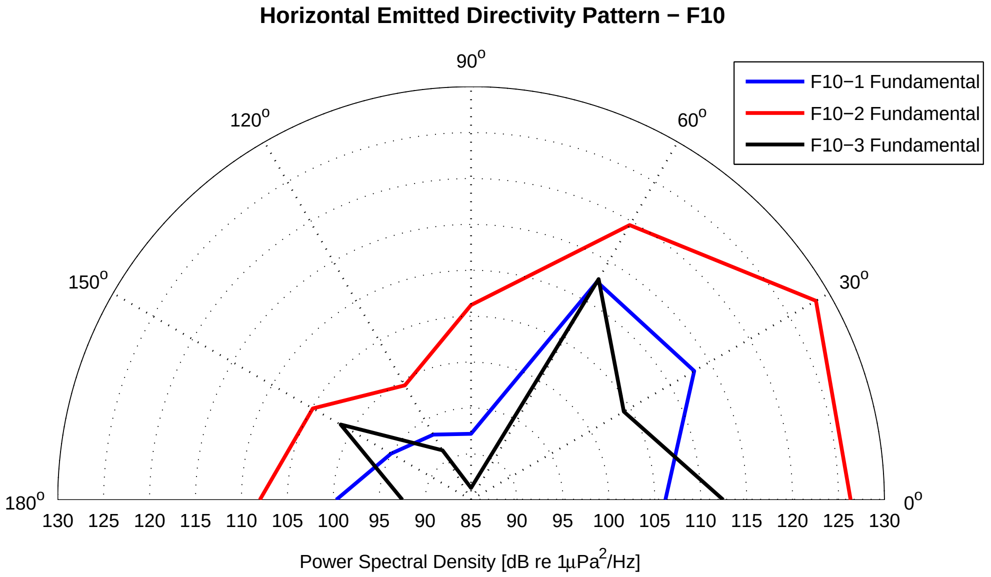


Figure 21: Polar plot comparing the signal strength of individual pingers in the horizontal (electrode-to-battery-end) position at their fundamental tones at each angle.

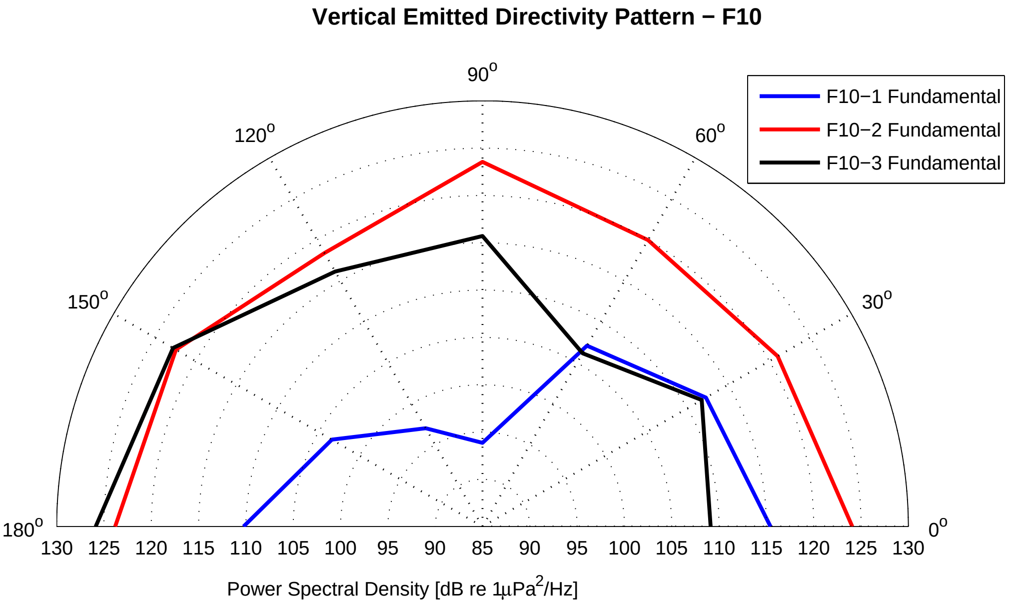


Figure 22: Polar plot comparing the signal strength of individual pingers in the vertical direction at their fundamental tones at each angle.

The F10s emitted higher and more consistent (as a function of angle) levels in the vertical plane than in the horizontal plane at the fundamental frequency. The broadband levels though, which include harmonics up to 96 kHz (sampling frequency 192 kHz) show much less angular variability and appear rather symmetrical about the 90^{O} midpoint (Figure 23). The vertical rotation is plotted in both figures for comparison to the two horizontal rotations (Figure 23 and Figure 24).

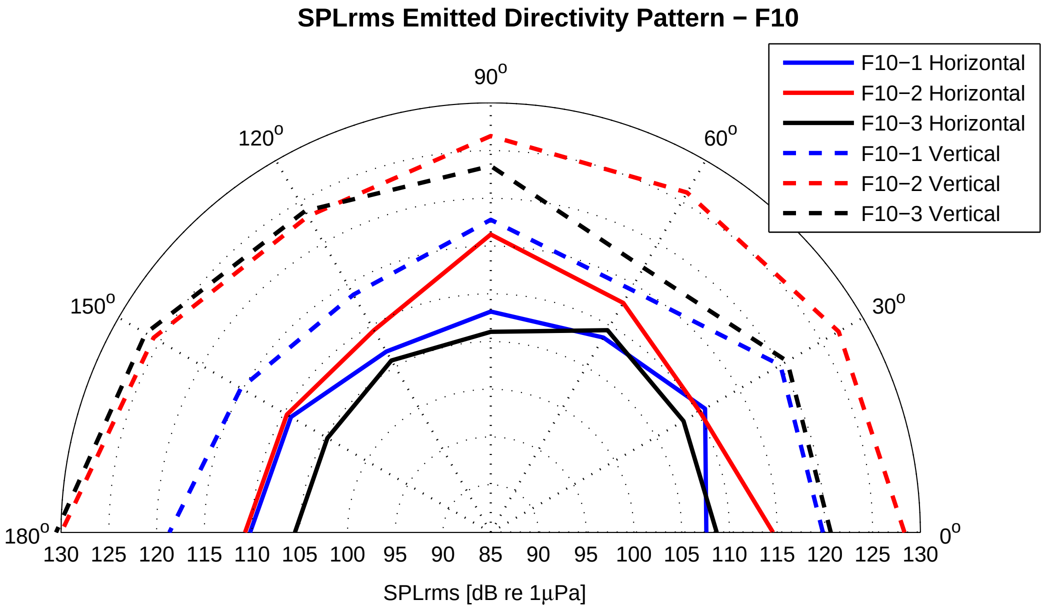


Figure 23: The SPLrms compared between the positions of the three F10 pingers in the horizontal (midpoint-to-midpoint) and vertical positions.

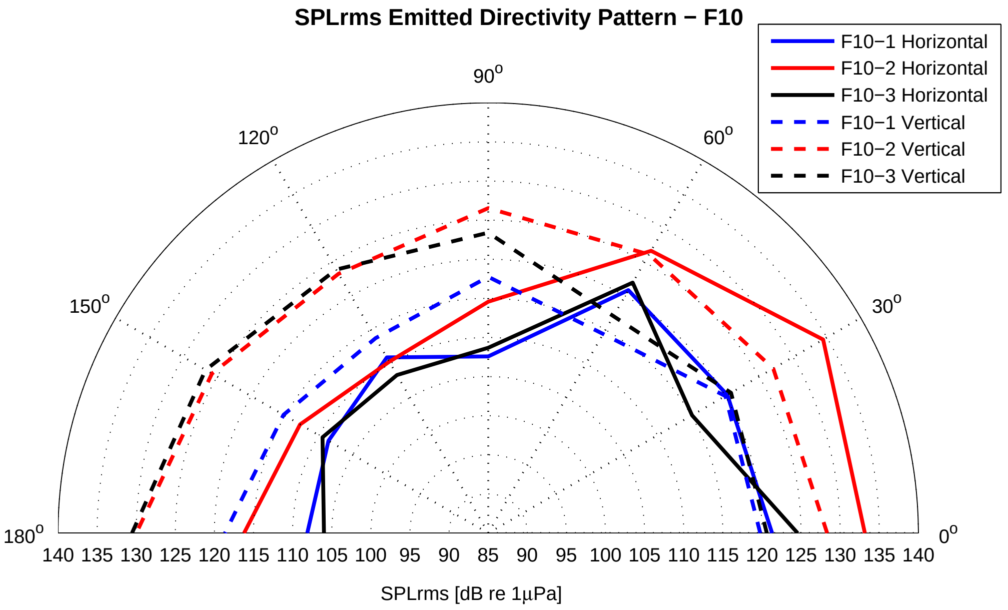


Figure 24: The SPLrms compared between the positions of the three F10 pingers in the horizontal (battery-to-electrode end) and vertical positions.

The increased variability in level as a function of angle in the horizontal plane compared to the vertical plane is also obvious in Table 7.

Table 7: Recorded minimum, mean and standard deviation for each F10 pinger. All levels are referenced to 1 m.

	Minimum (dB re 1 µPa^2/Hz)		**Mean (dB re 1 µPa^2/Hz)**		**Standard Deviation of Mean (dB re 1 µPa^2/Hz)**	
Fundamental	*horizontal*	*vertical*	*horizontal*	*vertical*	*horizontal*	*Vertical*
F10-1	89.00	93.85	99.42	105.61	8.88	7.98
F10-2	95.98	118.38	108.62	121.89	11.98	2.17
F10-3	86.28	106.15	99.57	115.35	8.69	7.11
SPLrms (>2kHz)	**Minimum (dB re 1 µPa)**		**Mean (dB re 1 µPa)**		**Standard Deviation of Mean (dB re 1 µPa)**	
F10-1	106.87	113.76	112.39	117.08	5.93	2.61
F10-2	109.47	123.26	117.80	126.73	9.84	2.11
F10-3	104.76	117.01	106.93	123.29	1.83	4.42

It is interesting to note that the broadband SPLrms levels were significantly higher (< 12 dB) than the fundamental tone levels. The 3dB bandwidth of the fundamentals was 1-2 Hz, yielding a tone level in dB re 1 μPa that was at most 3 dB higher in numerical value than the power spectrum density level in dB re 1 μPa^{2}/Hz. With lower energy at higher harmonics, the difference between the broadband level and the tone level was a result of significant output energy at low frequencies. The F10 pingers emit a band of energy at frequencies below the intended 10 kHz. In Figure 18, the emitted power spectrum density between 2 and 4 kHz was 88-96 dB re 1 μPa^{2}/Hz. Energy in this band added to the tone levels and increased the broadband SPLrms.

The output level specified by Fumunda for these pingers is 132 dB re 1 µPa @ 1 m (http://www.fumunda.com/how). The F10-2 reached this level at multiple orientations. However, on average, over all orientations, the broadband SPLrms was less than the nominal specification for all of the three tested pingers. Also, it is unclear whether Fumunda measured the output level in the time or in the frequency domain. In other words, it is unclear whether the nominal output level applies to the target frequency of 10 kHz or to the broadband output level, which would include the noise floor at frequencies below 10 kHz.

3.2. Objective 2: Modelling the Pinger Sound Field

This section deals with sound propagation modelling of pinger tones. The detection of pinger tones by marine mammals was part of Objective 3. Transmission loss was modelled for four frequencies: the fundamental and the first two harmonics of the F3 pingers (2.7, 5.4 and 8.1 kHz), and the nominal fundamental of the F10 pinger (10 kHz). The nominal fundamental was used rather than the fundamental measured from the three pingers (9.4 – 9.6 kHz) to set the frequency somewhat more apart from the second harmonic of the F3s. Sound propagation was modelled in 3-D, but to plot the results, the maximum transmission loss over all depths at each frequency was shown in Figure 25. The beige rectangle on the left is the coast; it runs north-south in this simplified model. In reality, at these coordinates, the coastline runs slightly NNW – SSE. Bathymetry was read off a chart in a W-E direction at the location of the pinger. The same slope was used over the 10 km NS length of the box. The bathymetry contours therfore run parallel to the coast in a N-S direction. The modelling area was 5 km W-E and 10 km N-S. Pingers are deployed within a few hundred metres from the coast. Migrating animals are expected to travel on the east side (deep-water side) of the nets.

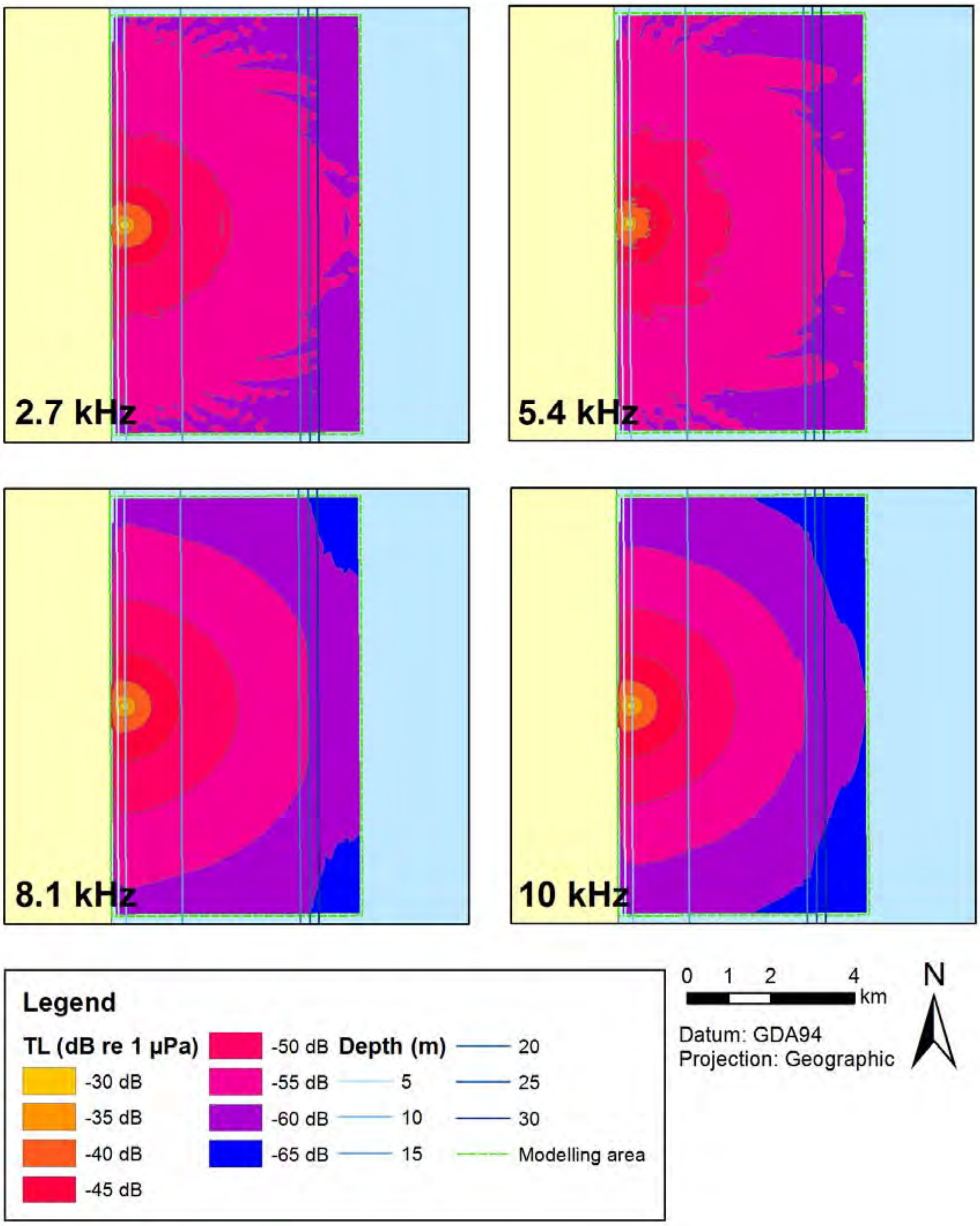


Figure 25: Transmission loss for a pinger at the Gold Coast at four different frequencies.

Over the first 4 km, transmission loss barely varied with frequency. The frequency-dependent losses that were accounted for are losses at the seafloor and absorption by ocean water. Absorption of acoustic energy by ocean water is about 1 dB/km for a frequency of 10 kHz, and less for lower frequencies. Differences in received level due to absorption therefore only become noticeable at a few km in range for the frequencies modelled. The ranges to certain transmission loss values are summarised in Table 8. The 95% radius is the radius of a circle encompassing 95% of the corresponding TL data. Transmission loss varied little with tide. The 95% radii for the mean sea level are plotted in Figure 26.

Table 8: Ranges to certain transmission loss values

Transmission Loss (dB re 1 µPa)	Maximum Radii (km)			95 Percentile Radii (km)		
Tide	low	mean	high	low	mean	high
2.7 kHz						
-20	0.05	<0.02	<0.02	0.05	<0.02	<0.02
-25	0.10	0.07	0.05	0.10	0.07	0.05
-30	0.11	0.10	0.11	0.11	0.10	0.11
-35	0.30	0.27	0.22	0.26	0.25	0.22
-40	0.63	0.57	0.60	0.59	0.54	0.46
-45	1.54	1.39	1.88	1.31	1.23	1.38
-50	3.78	3.66	4.09	2.86	2.93	3.13
-55	6.06	6.49	6.17	4.76	5.19	5.07
5.4 kHz						
-25	0.05	<0.02	<0.02	0.05	<0.02	<0.02
-30	0.14	0.10	0.07	0.14	0.10	0.07
-35	0.26	0.18	0.16	0.25	0.18	0.16
-40	0.94	0.63	0.50	0.78	0.56	0.40
-45	2.37	1.80	1.70	1.55	1.32	1.31
-50	5.74	4.38	4.09	3.57	3.03	2.86
-55	6.79	6.35	6.79	5.40	5.32	5.17
8.1 kHz						
-25	0.05	<0.02	<0.02	0.05	<0.02	<0.02
-30	0.11	0.10	0.08	0.11	0.10	0.08
-35	0.32	0.27	0.23	0.30	0.25	0.22
-40	0.71	0.62	0.54	0.66	0.57	0.50
-45	1.45	1.36	1.27	1.33	1.20	1.10
-50	2.67	2.55	2.45	2.55	2.38	2.26
-55	4.62	4.35	4.20	4.35	4.07	3.91
-60	>6.33	>6.27	>6.23	>5.58	>5.48	>5.43
10 kHz						
-25	0.05	<0.02	<0.02	0.05	<0.02	<0.02
-30	0.11	0.10	0.08	0.11	0.10	0.08
-35	0.32	0.26	0.23	0.30	0.22	0.22
-40	0.71	0.62	0.54	0.65	0.56	0.50
-45	1.40	1.31	1.18	1.25	1.14	1.04
-50	2.47	2.35	2.21	2.33	2.17	2.03
-55	3.98	3.85	3.70	3.79	3.59	3.45
-60	>5.90	>5.57	>5.43	>5.22	>5.09	>5.02

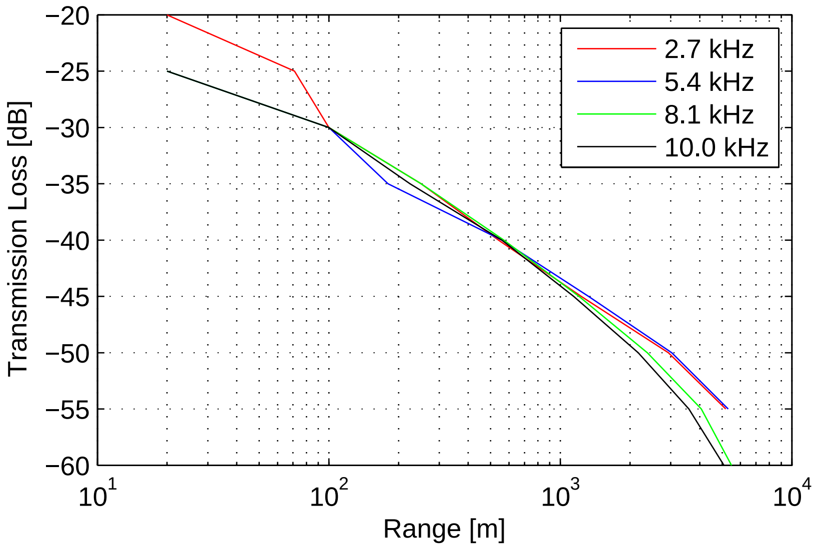


Figure 26: Transmission loss versus range for four pinger frequencies at mean tide level.

With a tone length of about 400 ms and a period of 4 – 7 s, the duty cycle of pinging was very low: DC = 1/10 – 1/18. There are currently 3-4 pingers per net of 200 m length, and they are not synchronised. The chance of hearing multiple pingers at the same time, i.e. the chance of exact alignment in time between pings, is consequently low. A cumulative model simulating multiple sources operating simultaneously so that their acoustic fields superpose was therefore not run.

3.3. Objective 3: Modelling Pinger Detectability

3.3.1. Hearing Abilities

A literature search for information on audiograms and critical bands of the following species was undertaken:

- *Humpback whales (Megaptera novaeangliae)*
- *Indo-Pacific bottlenose dolphins (Tursiops aduncus)*
- *Bottlenose dolphins (Tursiops truncatus)*
- *Indo-Pacific humpback dolphins (Sousa chinensis)*
- *Snubfin dolphins (Orcaella heinsohni)*
- *Common dolphins (Delphinus delphis)*
- *Dugongs (Dugong dugon)*

3.3.1.1. Humpback Whales

Baleen whales do not exist in captivity and have therefore never been accessible for behavioural audiogram measurements that require conditioning or training. There have been several attempts to develop a portable audiogram system that could measure audiograms electrophysiologically on live, stranded or entangled animals within a few minutes. Auditory evoked potential (AEP) audiograms have successfully been measured for odontocetes; no baleen audiogram, however, has been recorded successfully to date. One problem with AEP methods is the blubber thickness or distance between the source of the AEP signals in the auditory nervous system and the skin, where electrodes would be placed. AEP signals are attenuated by bones and tissues, and the travel distance from brain to skin is considerably larger in mysticetes than odontocetes. A gray whale calf spent a couple of months at SeaWorld San Diego. Audiogram measurements were attempted but were unsuccessful due to logistical and technical difficulties (Ridgway & Carder, 2001).

In the absence of direct behavioural or AEP data on baleen hearing, several inferences have been made:

a) All animals can hear their own vocalisations, and often the frequency bandwidth of vocalisations overlaps with the frequency range of best hearing sensitivity. Therefore, a study of baleen whale vocalisations can yield an indication of the frequency range of best hearing.

b) A few dissections and subsequent anatomical studies of baleen ears taken from dead, stranded animals have been done. Hearing sensitivity has been estimated from anatomical data using software models. Such studies yield a relative audiogram, indicating the frequency range of best hearing and relatively poorer hearing.

c) The literature on observed behavioural reactions of baleen whales in the wild to biological and industrial sounds is constantly increasing. Obviously, animals hear the sounds they react to. These studies give absolute suprathresholds of hearing. Animals might not react to a sound that is just audible, but only react to a sound that is a certain level louder. Reaction thresholds will depend on the current behavioural state of the animal; its previous experience or prior exposure, which can lead to either habituation or sensitisation; its age, gender and health; group composition (groups with calves sometimes appear more responsive); habitat and geographic location (e.g. close to shore versus offshore); and ambient noise.

Vocalisations

Male humpback whales produce song with most of the acoustic energy between 100 Hz and 4 kHz at source levels of 144-189 dB re 1 µPa @ 1 m (Cerchio *et al.*, 2001; Payne & Payne, 1985; Thompson *et al.*, 1979). Song components can extend to as low as 30 Hz (Payne & Payne, 1985), and can have higher harmonics beyond 24 kHz (Au *et al.*, 2006). Both male and female humpback whales further produce social sounds in the same frequency range with reported source levels of 175-192 dB re 1 µPa @ 1 m (Cerchio & Dahlheim, 2001; Dunlop *et al.*, 2007; Thompson *et al.*, 1986; Winn *et al.*, 1979).

Anatomical Evidence

Anatomical and paleontological evidence suggests that baleen whales are adapted to hear low frequencies (Fleischer, 1976, 1978, 1980; Norris & Leatherwood, 1981). Baleen whale inner ear anatomy has been studied with dissected ears of dead, stranded animals. Baleen whales were predicted most sensitive at low sonic to infrasonic (<20 Hz) frequencies (Ketten, 1991, 1992, 1994; Ketten, 1997). The basilar membrane of the cochlea (inner ear) is much broader, thinner and less rigidly supported than in odontocetes, which are high-frequency hearing specialists.

Data from anatomical studies of humpback whale basilar membranes in combination with psychoacoustic data and anatomical hearing indices of well-studied land-mammals (the cat and the human) were used to predict a humpback whale audiogram of relative hearing sensitivity (Houser *et al.*, 2001). Since there are no data on absolute hearing thresholds in humpback whales, only relative frequency-dependent sensitivities could be predicted. The resulting U-shaped audiogram showed maximum sensitivity between 2-6 kHz, and a region of best sensitivity (defined as relative sensitivity < 0.2) between 700 Hz and 10 kHz. Reduction in sensitivity was about 16 dB/octave above 10 kHz and 6 dB/octave below 700 Hz. (Though using the data and processing methods discussed in their paper, we computed about 20 dB/octave above 10 kHz.) The range of best sensitivity was slightly higher in frequency than predicted from emitted vocalisations. Houser *et al*. (2001) suggested that this could be an inherent contribution of the cat and human audiograms used to predict the humpback audiogram.

The hearing level at the frequencies of best sensitivity lies between 40 and 70 dB re 1 µPa in other marine mammals (odontocetes and pinnipeds). To visualise the audiogram predicted by (Houser *et al.*, 2001), it was positioned on the y-axis to have a minimum of 40 dB re 1 µPa as a lower estimate and a minimum of 70 dB re 1 µPa as an upper estimate in Figure 27 (Erbe, 2002).

Evolutionary programming was used to develop a bandpass filter model of the humpback ear, yielding a similar audiogram (Houser *et al.*, 2001). The modelled bandpass filters should not be used directly as indicators of critical bandwidths [Houser, pers. comm.].

Ambient Noise Consideration

Ambient noise in the ocean likely played an evolutionary role in shaping marine mammal audiograms (Clark & Ellison, 2004). Historical levels of ambient noise (without industrial sources like shipping) might have shaped the humpback audiogram at the frequencies of humpback vocalisations. Clark and Ellison (2004) used a 10th percentile spectrum of ambient noise and added the critical ratio measured from other mammals. Critical ratios relate the energy of a signal to the energy of a noise at detection threshold. Clark and Ellison (2004) argued that evolution should have positioned the audiogram such that the dynamic range of the auditory system be used most efficiently. Critical ratios in other mammals range between 16-24 dB re 1 Hz (Richardson *et al.*, 1995). The resulting upper and lower envelopes of the predicted humpback whale audiogram are shown in Figure 27.

Applying the predicted audiograms to humpback whales in Glacier Bay, Alaska, it appeared that humpback whale hearing was ambient noise limited rather than audiogram limited in Glacier Bay (Erbe, 2002), see Figure 27.

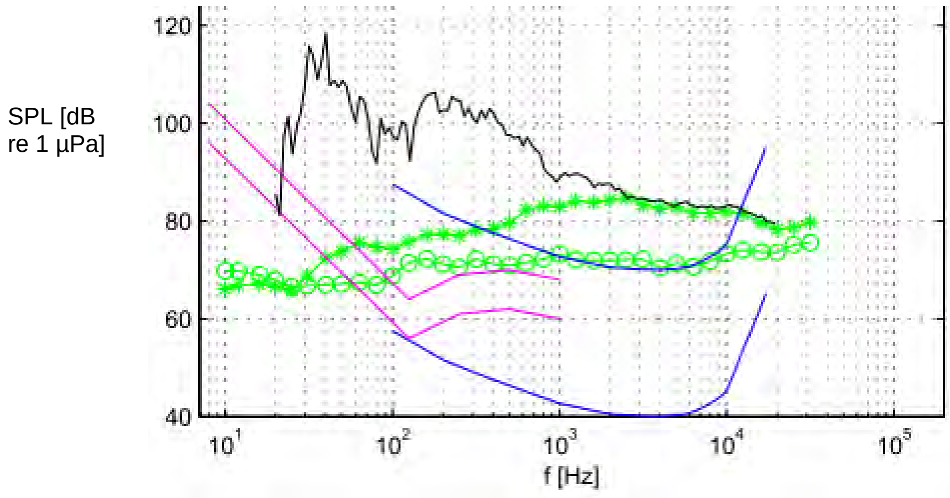


Figure 27: Upper and lower humpback audiogram limits predicted by Clark and Ellison (2003, pink) and Houser *et al*. (2001, blue); two samples of ambient noise in Glacier Bay, Alaska (1/3 octave band levels, green), and a humpback whale call (unspecified distance, black)(Erbe, 2002).

Behavioural Responses to Sound

Observed behavioural responses of humpback whales to underwater sounds are listed in Table 9. The lowest reported behavioural thresholds for humpback whales were 80-90 dB re 1 µPa received level from pingers centred at 4 kHz (Todd *et al*., 1992). Assuming that the response threshold likely lies somewhat above the audibility threshold, absolute sensitivity at 4 kHz is expected < 80 dB re 1 µPa, falling into the hearing ranges predicted above (Clark & Ellison, 2004; Houser *et al*., 2001).

Table 9: Behavioural responses of humpback whales to underwater sound

Sound	**f [Hz]**	**Received SPL [dB re 1 µPa]**	**Reaction**	**Reference**
Pingers	3500	-	Reduced entanglement	(Lien *et al*., 1992)
Pingers	Broadband, centred @ 4000 Hz	80-90	Reduced entanglement	(Todd *et al*., 1992)
Sonar	3300; 3100-3600	-	Avoidance; increase in swim speed	(Maybaum, 1990, 1993)
SURTASS LFA sonar	100-500	120-150	Cessation of song	(Biassoni *et al*., 2000; Tyack, 1998)
SURTASS LFA sonar	100-500	120-150	Increased song duration	(Miller *et al*., 2000)
Humpback call playback	400-550	102 (16 dB S/N); 100-115	Approach	(Frankel & Herman, 1993; Frankel *et al*., 1995; Tyack & Whitehead, 1983)
Synthetic FM sweep	10-1400	106	Approach	(Frankel *et al*., 1995)
ATOC 75 Hz	60-90	98-109; 120-130	Longer divers; change of swim direction	(Frankel & Clark, 1998, 2000)

Airgun	broadband	150-169	Startle response	(Malme *et al.*, 1985)
Airgun	broadband	140; 112	Avoidance; startle response	(McCauley *et al.*, 2000)

Conclusion

In the absence of a humpback audiogram, we assume that humpback hearing is ambient noise limited. Taking the ambient noise samples recorded off the Gold Coast, we add a critical ratio of 20 dB. For example, the median of ambient noise at 3 kHz was 60 dB re 1 µPa in January. With a critical ratio of 20 dB, this would yield a tone level at the threshold of detectability of 80 dB re 1 µPa. Others have further allowed for a 10 dB response threshold above detection, yielding a tone level of 90 dB at the threshold of response (McPherson *et al.*, 2004). This compares to the behavioural response thresholds of 80-90 dB re 1 µPa observed in the field (Todd *et al.*, 1992).

3.3.1.2. Indo-Pacific Bottlenose Dolphins

No information is available on the hearing capabilities of Indo-Pacific bottlenose dolphins (*Tursiops aduncus*). Indirect evidence for their hearing capabilities comes from recorded vocalisations and from observed behavioural responses to sound.

Hawkins (2010) recorded whistles from four populations of Indo-Pacific bottlenose dolphins in Australia (Moreton Bay, Byron Bay, Bunbury, and Monkey Mia). Over all four Australian populations, frequencies ranged between a mean of 5.0 kHz (s.d. = 109 Hz) for lowest frequency and 12.3 kHz (s.d. = 212 Hz) for highest frequency. Similar bandwidths and whistles up to 18 kHz were reported elsewhere (Hawkins & Gartside, 2009a; Hawkins & Gartside, 2009b; Hawkins & Gartside, 2010).

There is some information on Indo-Pacific bottlenose dolphin reactions to underwater sound. An example of the variability in behavioural responses to sound is provided by Chilvers and Corkeron (2001). They found that two communities of Indo-Pacific bottlenose dolphins in Moreton Bay, Queensland, responded differently to the presence of trawlers. One community was not affected by the noise produced by trawlers and continued to forage in their presence, while the other did not forage behind trawlers. Behavioural observations were not correlated with received levels.

Dolphin surface behaviour changed upon approach by powerboats; acoustic behaviour did not change (Lemon *et al.*, 2006). Received levels were not estimated. Lemon *et al.* (2008) also found differences in foraging behaviour in response to the presence of boats. In this study, 83% of animals stopped foraging in response to powerboat approaches at 100 m.

Other behavioural responses by Indo-Pacific bottlenose dolphins to vessels include increased rates of change in group membership and more compact groups, more erratic speeds and directions of travel (Bejder *et al.*, 2006), and decreased resting and socializing behaviour (Christiansen *et al.*, 2010). Neither study reported responses as a function of received level, unfortunately.

Conclusion

Based on the recorded vocalisations of Indo-Pacific bottlenose dolphins, we expect good hearing sensitivity between 5 and 12 kHz. Good sensitivity is expected to extend to higher frequencies used for echolocation, however no description of echolocation signals emitted by this species was found in the literature. While sound emission indicates good high-frequency hearing, this species clearly responds to more low-frequency anthropogenic sound from boats and ships. For the subsequent analysis of pinger detectability, we used the *Tursiops truncatus* audiogram for *Tursiops aduncus*.

3.3.1.3. Bottlenose Dolphins

The bottlenose dolphin (*Tursiops truncatus*) is perhaps the most-studied marine mammal in terms of hearing. Johnson (1967) produced the first detailed audiogram for bottlenose dolphins (Figure 28) and this is still the standard today. Johnson (1967) found that bottlenose dolphins have functional hearing from 100 Hz to 150 kHz, with best sensitivity between 15 and 110 kHz. Behavioural and AEP measurements of the hearing capabilities of bottlenose dolphins made since Johnson (1967) show similar results (Brill *et al*., 2001; Houser & Finneran, 2006; Houser *et al*., 2008; Popov *et al*., 2007).

While audiograms measured from bottlenose dolphins generally exhibit the same shape and similar thresholds, it is important to note that there is variability among individuals. For example, bottlenose dolphins exhibit high frequency hearing loss with age and males tend to lose their hearing at an earlier age than females (Brill *et al*., 2001; Houser & Finneran, 2006), see Figure 29. Figure 30 shows mean audiograms measured from 42 bottlenose dolphins ranging in age from 4-47 years. These audiograms show that older dolphins had higher hearing thresholds, especially above 50 kHz, as compared to younger dolphins. Another source of variability is geographic variation. For example, Pacific bottlenose dolphins had significantly lower hearing thresholds at 40 kHz and 60-155 kHz when compared to Atlantic bottlenose dolphins (Figure 31, Houser *et al*. 2008). Houser *et al*. (2008) hypothesised that these differences reflect genetic differences between the two populations. Bottlenose dolphins are the only species in which audiograms have been produced for large groups of individuals. It is important to keep possible inter-individual and inter-population variability in mind when examining hearing data for other species. Small sample sizes likely do not provide a complete picture of the hearing capabilities of an entire species.

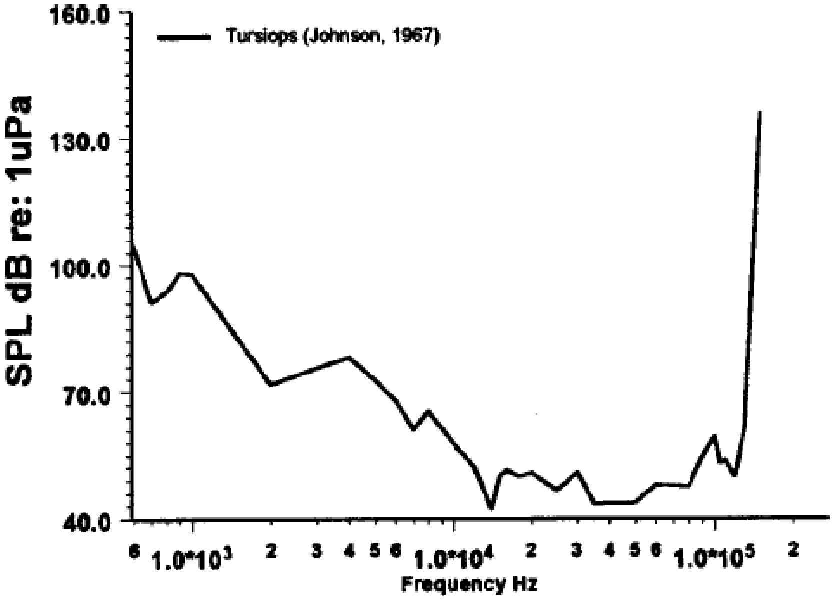


Figure 28: The standard audiogram for the bottlenose dolphin (from Brill *et al*. 2001, after Johnson 1967).

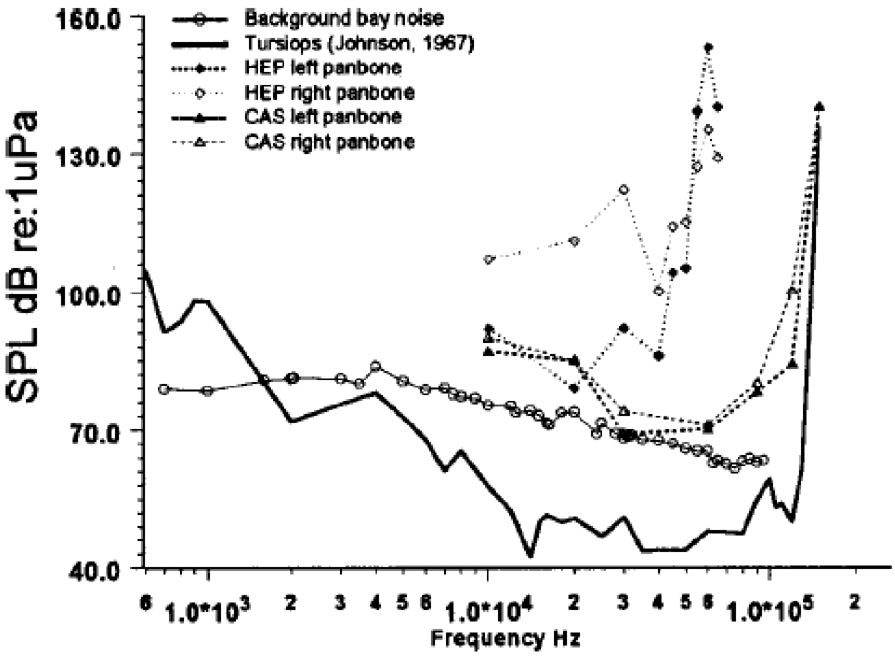


Figure 29: Hearing thresholds measured from a male (HEP) and a female (CAS) bottlenose dolphin. The male dolphin shows high frequency hearing loss. The behavioural audiogram measured by Johnson (1967) is shown as a solid line. Ambient noise measured from the test site (San Diego Bay) is also shown (from Brill *et al*. 2001).

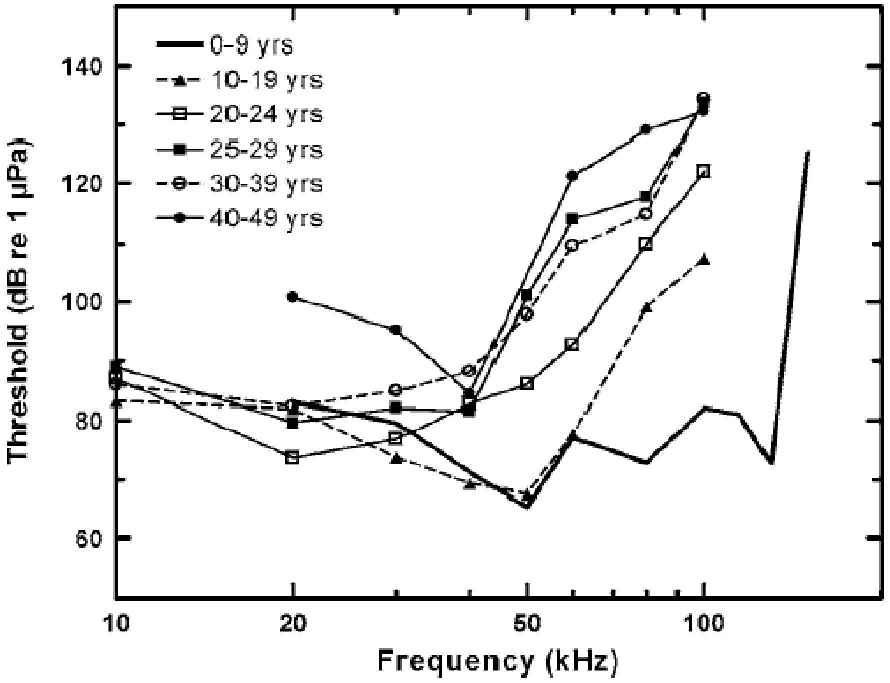


Figure 30: Mean AEP audiograms measured from 42 bottlenose dolphins, grouped by age (from Houser and Finneran 2006b).

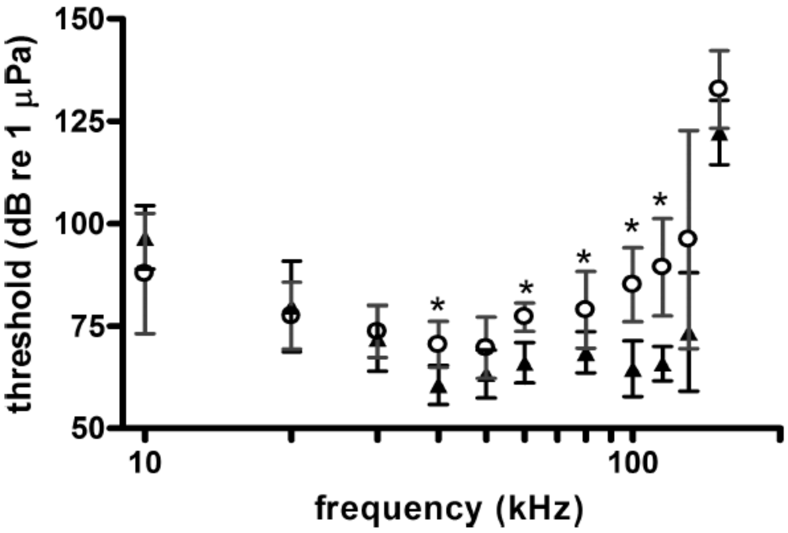


Figure 31: Comparison of audiograms measured from Pacific bottlenose dolphins (filled triangles) and Atlantic bottlenose dolphins (open circles). Asterisks denote significant differences between the two populations (from Houser *et al*. 2008).

Critical ratios of bottlenose dolphins at the Fumunda pinger frequencies were measured by Johnson (1968) and were on average 25 dB between 5 and 10 kHz.

Conclusion

For the *Tursiops* species, we took the audiogram levels measured by Johnson (1967) as these are the only data below 10 kHz, and the critical ratios measured by Johnson (1968).

3.3.1.4. Indo-Pacific Humpback Dolphins

There is no information on hearing capabilities of Indo-Pacific humpback dolphins (*Sousa chinensis*), however, their vocalisations have been recorded and likely coincide with the frequency band of good hearing sensitivity. Unfortunately, most of the recordings reported in the literature have been limited in bandwidth and therefore, above 22 kHz, very little is known of the vocalisations of this species.

Vocalisations

Echolocation clicks recorded from a school of Indo-Pacific humpback dolphins at Lantau Island, Hong Kong, contained energy from 30 kHz up to at least 200 kHz (Goold & Jefferson, 2004). The system used to make these recordings included a high-pass filter at 30 kHz, so it was not possible to determine whether these clicks contained energy below that threshold. However, Van Parijs and Corkeron (2001c) recorded clicks from Indo-Pacific humpback dolphins at Stradbroke Island, Queensland, and reported that the mean minimum frequency of these clicks was 12 kHz.

In addition to echolocation clicks, Van Parijs and Corkeron (2001c) also noted that these dolphins produced a variety of burst pulse sounds. Several different kinds of burst pulses were recorded, including ‘barks’, ‘quacks’ and ‘grunts’. Burst pulses had a minimum frequency of 0.6 kHz and a maximum frequency greater than 22 kHz. Due to the recording equipment used in this study, it was not possible to determine the maximum frequencies of clicks produced by Australian Indo-Pacific humpback dolphins (Van Parijs & Corkeron, 2001c).

Whistles recorded from Indo-Pacific humpback dolphins in Australia ranged from a mean minimum frequency of 1.2 kHz (Schultz & Corkeron, 1994) to a mean maximum frequency of at least 22 kHz (Van Parijs & Corkeron, 2001a; Van Parijs & Corkeron, 2001b; Van Parijs & Corkeron, 2001c). Due to the characteristics of the recording systems used to record these whistles, it has not been determined whether they contain energy above 22 kHz.

Behavioural Responses to Sound

The majority of research on behavioural responses of Indo-Pacific humpback dolphins to sound has focused on vessel noise. Van Parijs and Corkeron (2001a) found that whistling rates of Indo-Pacific humpback dolphins at Amity Point, Queensland, increased immediately after the passage of a vessel but click train and burst pulse production rates did not change. Van Parijs and Corkeron (2001a) hypothesised that vessel noise affects group cohesion and that the dolphins increase their whistling rates to re-establish contact with associates after the passage of a vessel. Indo-Pacific humpback dolphins have also been observed actively avoiding boats by increasing dive time and moving away from the direction of passage of boats (Karczmarski *et al.*, 1997; Ng & Leung, 2003).

Noises produced during under water percussive pile driving are the only other sounds for which behavioural reactions of Indo-Pacific humpback dolphins have been documented. Würsig *et al*. (2000) observed that Indo-Pacific humpback dolphins in Hong Kong travelled more than twice as fast during pile driving than they did when no pile driver was operating. None of these studies correlated behavioural responses with received levels.

Conclusion

From the available data on Indo-Pacific humpback dolphin vocalisations, it appears this species emits clicks and whistles similar in frequency range to those of bottlenose dolphins. In the absence of direct data on hearing thresholds, the *Tursiops truncatus* audiogram and critical ratios were used to model pinger detection by Indo-Pacific humpback dolphins.

3.3.1.5. Snubfin Dolphins

There are no audiograms for snubfin dolphins or their close relatives, the Irrawaddy dolphins (*Orcaella brevirostris*).

Only one description of the sounds produced by Australian snubfin dolphins is available in the literature. Van Parijs *et al*. (2000) made acoustic recordings of snubfin dolphins in Cleveland Bay and Halifax Bay, Queensland. The recording equipment they used (Sony Digital Audio Tape) had a frequency response of 20 Hz – 22 kHz, so they were not able to determine the maximum frequency of the clicks produced by snubfin dolphins, but all clicks ranged above 22 kHz. Snubfin dolphins produced echolocation click trains as well as burst pulses such as creaks, squeaks and buzzes.

The closely related Irrawaddy dolphin, recorded in Chilika Lagoon, India, produced broadband clicks ranging from 30 kHz to 130 kHz (Bahl *et al.*, 2007), and with a centre frequency of 100 kHz (Inoue *et al.*, 2007).

Van Parijs *et al*. (2000) described two types of whistles produced by snubfin dolphins. These whistles had a mean minimum frequency of 3.1 kHz (s.d.=1.4 kHz), a mean maximum frequency of 4.2 kHz (s.d.=1.4 kHz).

Irrawaddy dolphins in Indonesia emitted narrowband tonal pulsed calls between 484 Hz and 8.2 kHz, and whistles ranging from 1 to 12 kHz (Kreb, 2004).

No information is available on behavioural reactions to sound by snubfin dolphins, but several authors have reported on behavioural reactions of the closely related Irrawaddy dolphin. Irrawaddy dolphins in Indonesia exhibited significantly longer dive durations in the presence of boats versus when boats were absent (Kreb & Rahadi, 2004; Stacey & Hvenegaard, 2002). Kreb (1999) found that Irrawaddy dolphins always moved away from their research vessel. Again, received levels that led to behavioural reactions were not estimated.

In the absence of audiogram and critical ratio data for snubfin dolphins, we grouped these animals with *Tursiops truncatus*.

3.3.1.6. Common Dolphins

Audiogram

One auditory brainstem response audiogram (Figure 32) has been measured from one common dolphin from the Black Sea population (Popov & Klishin, 1996; Popov & Klishin, 1998). It was noted that this animal was unwell.

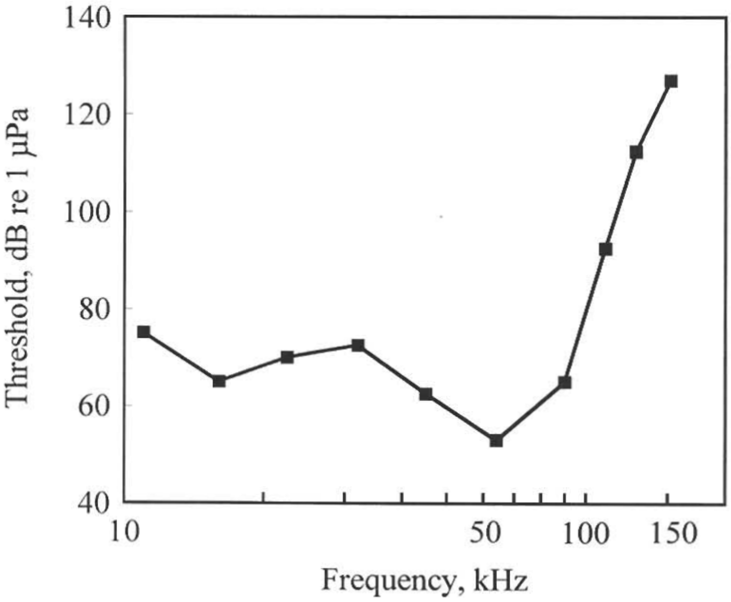


Figure 32: ABR audiogram of a common dolphin (Popov & Klishin, 1998).

Vocalisations

Whistle characteristics of common dolphins have been published from populations in the Mediterranean Sea (Gannier *et al.*, 2008; Gannier *et al.*, 2010), the Celtic and Irish Seas (Ansmann, 2005; Ansmann *et al.*, 2007; Griffiths, 2009; Scullion, 2004; Wakefield, 2001), the Eastern Tropical Pacific (Oswald *et al.*, 2007) and Hauraki Gulf, New Zealand (Petrella, 2009), with frequencies ranging from 3 to 28 kHz. Clicks with peak energy near 40 kHz, the upper limit of the recording system, were measured by Fish and Turl (1976). Click energy up to 70 kHz was reported elsewhere (Evans, 1973; Roch *et al.*, 2007). The minimum in hearing threshold at 55 kHz (Figure 32) is therefore likely an adaptation for echolocation.

Behavioural Responses to Sound

Goold (1996) monitored the presence of common dolphins visually and acoustically before, during and after seismic surveys and found a general avoidance by the dolphins. Barlow and Cameron (2003) determined reduced bycatch of common dolphins in gillnets when fitted with pingers emitting tones between 10 and 100 kHz at source levels of 120 – 146 dB re 1 µPa @ 1 m.

Conclusion

Even though there is an audiogram for common dolphins (Popov & Klishin, 1996; Popov & Klishin, 1998), only one individual has been measured once, and this animal was sick. Reported click characteristics appear lower in frequency than from bottlenose dolphins, however, for our model, we used the mean bottlenose dolphin audiogram as a representative for all odontocetes potentially occurring along the Queensland coast.

3.3.1.7. Dugongs

Audiograms of Manatees

No peer-reviewed and published information is available on the hearing capabilities of dugongs. Gerstein *et al.* (1999) measured underwater behavioural audiograms from two manatees (*Trichechus manatus*) in captivity. These manatees had good sensitivity at high frequencies and very limited low frequency hearing (Figure 33). Electrophysiological measurements of hearing in manatees indicate peak sensitivity at lower frequencies between 2 and 12 kHz (Bullock *et al.*, 1980; Klishin *et al.*, 1990; Popov & Supin, 1990).

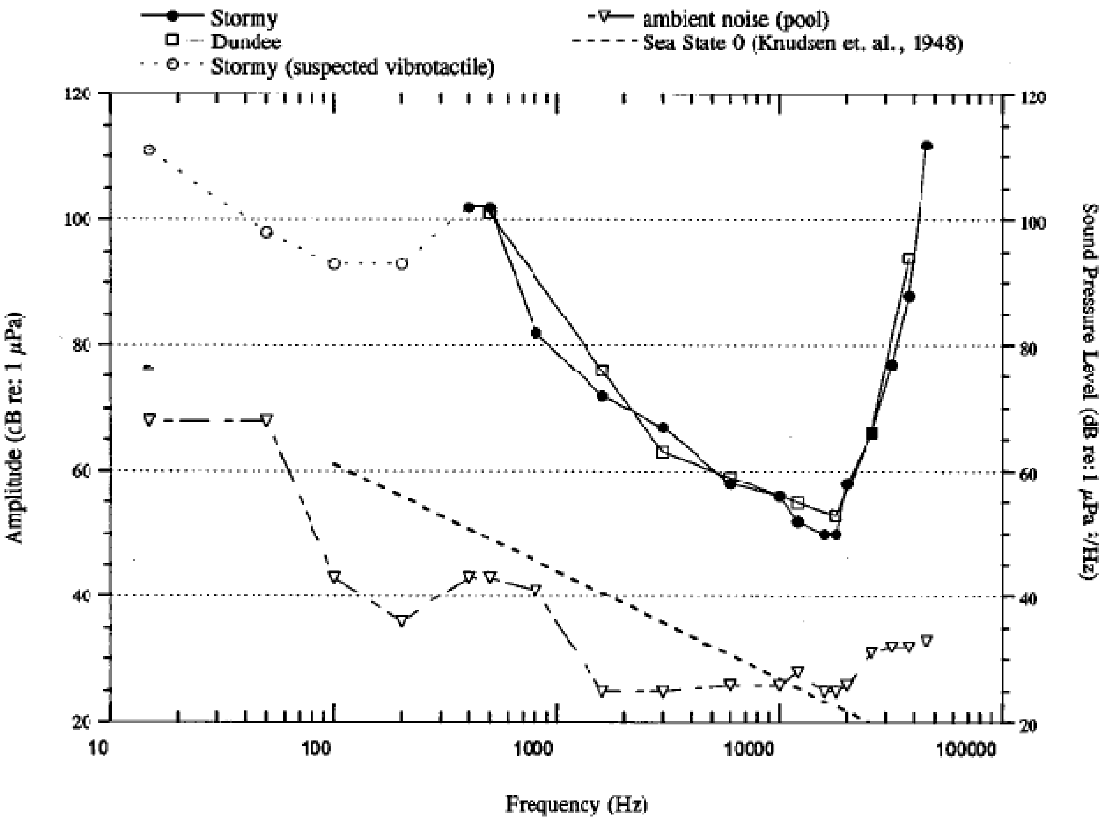


Figure 33: Behavioural audiograms for two manatees (Stormy and Dundee). Ambient noise in the pool where the audiograms were measured is also shown on the graph (from Gerstein *et al.* 1999).

Figure 34 shows third order polynomials fit to published curves of underwater audiograms for cetaceans and pinnipeds. These curves illustrate general trends in hearing sensitivity. Manatee hearing lies in between that of amphibious pinnipeds and fully aquatic, echolocating cetaceans. Based on the similarities among marine mammal audiogram curves, it is not unreasonable to assume that dugong hearing also falls somewhere between pinnipeds and cetaceans.

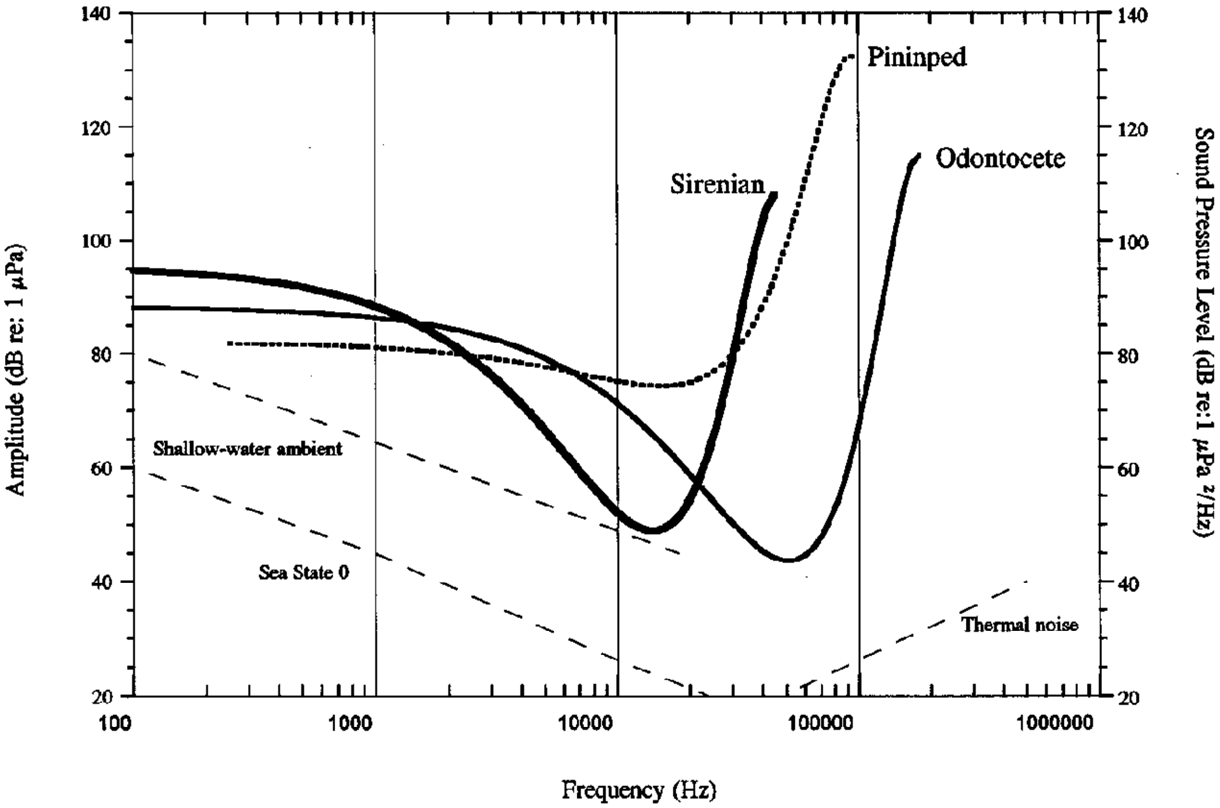


Figure 34: Third order polynomial curves fit to sirenian, pinniped and odontocete cetacean audiograms taken from the literature. Shallow water and noise curves are taken from Urick (1983) (from Gerstein *et al.* 1999).

Vocalisations

Dugong vocalisations have been categorised as chirp-squeaks, trills, pre-trills, barks, and pre-barks, covering the band from 0.5 to 18 kHz (Anderson & Barclay, 1995). Ichikawa *et al.* (2006) reported peak energy between 2 and 6 kHz. This range likely falls into the range of best hearing sensitivity, as it is expected that animals are sensitive at the frequencies of their own vocalisations.

Peak frequencies of manatee vocalisations range from 3 to 7 kHz (Nowacek *et al.*, 2003) and overlap with the range of best hearing sensitivity estimated by AEP methods (Bullock *et al.*, 1980; Klishin *et al.*, 1990; Popov & Supin, 1990). The behavioural audiogram of manatees indicated peak hearing sensitivity at 18 kHz (Gerstein *et al.*, 1999), however, which is above the reported peak call frequencies. A dugong audiogram is still outstanding.

Behavioural Responses to Sound

Hodgson (2004) and Hodgson *et al.* (2007) tested the behavioural responses of dugongs in Moreton Bay, Queensland, to single BASA pingers broadcasting at 3.5 kHz and 10 kHz with source levels of 133-134 dB re 1 µPa @ 1 m (Baldwin, 2002). No significant responses were observed: dugongs passed between pingers whether they were active or inactive, fed throughout the experiments, did not change their orientation to avoid or investigate the pingers and did not change their likelihood of vocalising.

This does not indicate that the animals did not hear the pingers. The pingers in this study were not switched on or off, but rather moved into and out of the water. Dugongs could have heard the pingers in air (at least within a 26^{O} cone), therefore the lowering of pingers into the water would not have been equal to a sudden onset of tones. Also, the pingers tested were not intended to induce a fright-and-flight response. These were pingers meant to be installed on nets to highlight the nets. Over time, animals are expected to associate pingers with nets (associative learning) and to modify their behaviour accordingly. During daylight in clear water, dugong might have seen that there was no net or other physical barrier present.

Ichikawa *et al*. (2009) demonstrated for wild dugong in Thailand unfamiliar to close human observation, that playbacks of actual and synthetic dugong calls attracted animals to within 10 and 19 m respectively from with a 250 m radius. Playback of 3.5 kHz tones at 141 dB re 1 µPa at 1 m in turbid water, however, resulted in a nearest approach of 100 m.

Most research related to behavioural responses of dugongs has focused on their response to boats. Richardson *et al*. (1995) reported that dugongs decreased their use of areas that had heavy vessel traffic and tended to move to deeper water. Anderson (1981) also observed evasive behaviour in response to vessel traffic. He reported that dugongs in Shark Bay, WA, responded to boats moving relatively slowly (5-8 knots) at a distance of 150 m by aggregating and moving quickly away. Anderson (1981) did not observe any evasive response to a rapidly approaching boat (27 knots). Hodgson and Marsh (2007) observed only mild behavioural responses to boat traffic. They reported that dugongs in Moreton Bay, Queensland, did not generally change their subsurface behaviour in response to boat passage, but they did discontinue feeding if a boat was less than 50 m away. They found that response rates were higher for slow moving boats than for fast moving boats and that animals in water depths of less than 2 m displayed more disturbed behaviour than those in water depths of 4 m. While these studies did not yield received levels that induced a behavioural change, they indicate that dugong can detect low-frequency boat noise to some extent.

Conclusion

In the absence of audiograms for dugong, we used the behavioural manatee audiogram (Gerstein *et al.*, 1999) for modelling of pinger detectability. In the absence of critical ratio measurements, we used the mean 20 dB CR measured from odontocetes at these frequencies (Richardson *et al.*, 1995).

3.3.2. Detection Thresholds

The detection of pure tones is limited either by the animal's audiogram or by ambient noise. Due to the lack of species-specific data on hearing abilities, marine mammals were grouped into three groups: humpback whales, dolphins and dugongs.

In the absence of data on humpback whale audiograms, pinger detectability was assumed to be ambient noise limited. Median ambient noise levels (in the presence of snapping shrimp) were used and a critical ratio of 20 dB was added to yield the humpback detection threshold for pingers (Table 10).

For dolphins, a critical ratio of 25 dB (Johnson, 1968) was added to the mean ambient levels at the pinger frequencies. The resulting levels were compared to the pure tone detection thresholds of *Tursiops truncatus* (Johnson, 1967). The higher level of the audiogram and the ambient noise plus critical ratio is the pinger detection limiting level.

For dugong, the manatee audiogram levels (Gerstein *et al.*, 1999) were compared to the ambient levels plus a 20 dB critical ratio, and the higher level was used to determine pinger detectability. For all three animal groups, pinger detectability was ambient noise limited rather than audiogram limited (Table 10). This was partly due to snapping shrimp raising ambient levels above 2 kHz, i.e. at the pinger frequencies.

Table 10: Audiogram and ambient-noise-plus-CR levels used to determine pinger detectability

		Humpback	Tursiops, Sousa, Orcaella, Delphinus		Dugong	
f [kHz]	Median Amb. [dB re 1 µPa]	Ambient + 20 dB CR	Audiogram	Ambient + 25 dB CR	Audiogram	Ambient + 20 dB CR
2.7	60	80	76	85	63	80
5.4	63	83	73	88	60	83
8.1	63	83	62	88	57	83
10	62	82	58	87	55	82

The mean tone levels measured for the three F3s over all orientations (Table 6) and for the three F10s over the vertical orientations (Table 7) were used to estimate the ranges of pinger detectability by the three animal groups (Table 11). The fundamental of the F3s was estimated through modelling to be audible to humpback and dugong over a 90 m range, and to dolphins over 45 m. The first harmonic of the F3s was estimated to be audible over the longest ranges: 210 m for humpback and dugong, 110 m for dolphins. The second harmonic of the F3s was only audible at less than 10 m. The F10 fundamental was estimated to be audible over a 130 m range by humpback and dugong, and over 40 m by dolphins. The F10 fundamental in the horizontal directions was on average 10 dB quieter than in the vertical directions and would only be audible to 10 m.

Table 11: Pinger detection ranges

		Humpback & Dugong			Tursiops, Sousa, Orcaella, Delphinus		
f [kHz]	SL [dB re 1 µPa]	Ambient + 20 dB CR	TL [dB]	Range [m]	Ambient + 25 dB CR	TL [dB]	Range [m]
2.7	108	80	28	90	85	23	45
5.4	119	83	36	210	88	31	110
8.1	99	83	16	10	88	11	10
10.0	114	82	32	130	87	27	40

These detection ranges are short. If the pingers broadcasted their nominated level (135 dB for the F3s and 132 dB for the F10s) at the fundamental frequencies rather than broadband over the fundamental and all harmonics, then the detection ranges would be considerably longer. The F3 fundamental would be audible to humpbacks and dugongs over 5.2 km, and to dolphins over 2.9 km. The F10 fundamental would be audible to humpbacks and dugongs over 2.2 km, and to dolphins over 1.1 km.

3.3.3. Pinger Spacing

There are various ways in which to conceptualise an optimal pinger spacing along a shark net. For humans, the primary sense used for navigation is vision; for marine mammals it's audition. An airplane landing in poor light will be guided along the runway by a series of lights. Pingers on shark nets are expected to highlight the nets to humpback whales migrating along the Queensland coast. Ideally, the animal would hear a number of pingers at any location. Dolphins can detect sound level differences of 0.5 – 3 dB depending on frequency and level (Richardson *et al.*, 1995). Assuming good intensity discrimination capabilities in humpback whales as well, pingers at greater distances will be heard at quieter levels, and pingers in series will thus highlight the location and direction of the net.

It is our understanding that there are currently 3-4 pingers per net of about 200 m length (http://www.wahinesurfing.com/news.asp?Id_news=47148; http://www.cabinet.qld.gov.au/mms/StatementDisplaySingle.aspx?id=70987). From Table 11, all of the F3s would be audible to humpback whales and dugong anywhere along the net, highlighting the entire net at any one location. With the F10 pingers and dolphins, the problem is the low fundamental tone level that was measured from the three pingers. Only 1-2 pingers would be audible at any location along the net. Higher harmonics could be audible over longer ranges, given that dolphin hearing sensitivity improves for frequencies greater than 10 kHz. We did not investigate the full spectrum of the F10 pingers. However, the broadband level of 132 dB re 1 µPa specified by the manufacturer and measured by us for one of the pingers (F10-2) at some angles would reach much farther and likely be detectable by dolphins over up to 1 km in range.

The previous two paragraphs dealt with animals swimming alongside a net. In the case of an animal swimming straight at a net, Figure 35 shows a worst case, where the animal is in between two pingers, hence farthest away from any one pinger. If the animal swims towards the net at a speed *v*, and if it is just outside the detection radius when the pingers ping, then one would want the next ping to occur before the animal hits the net. This scenario determines a maximum pinger spacing.

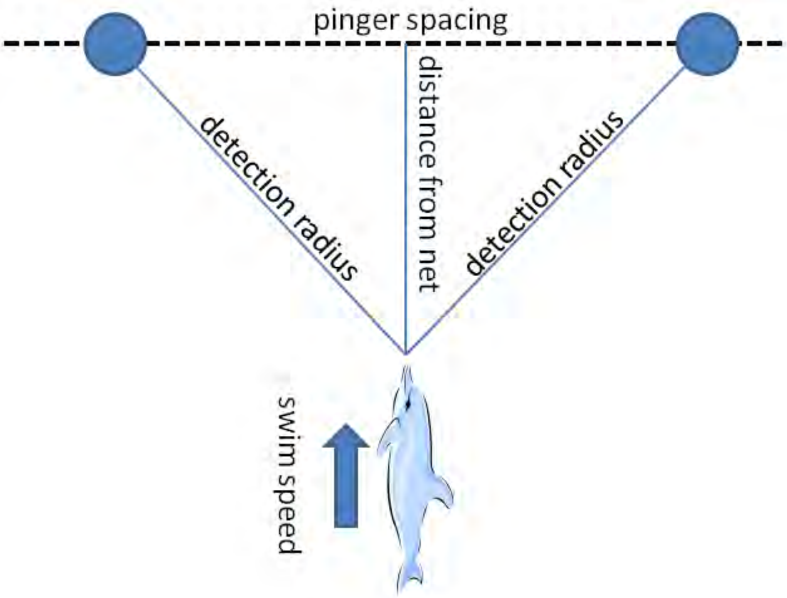


Figure 35: Sketch of a dolphin swimming towards a net with two pingers.

Clapham and Mead (1999) summarised swim speeds published for humpback whales. Relative to other baleen whales of the same Family, humpback whales are not fast swimmers. Reported or inferred swimming speeds of animals travelling or migrating ranged from 1.1 to 4.2 m/s. A maximum burst speed of 7.6 m/s was reported for a wounded whale being chased by a whaling vessel.

Reported swim speeds for bottlenose dolphins are 1.2 m/s to 6.9 m/s (Fish, 1993). The lower speeds are travelling speeds, the higher speeds are non-sustainable burst speeds: 6.0 m/s - 8.3 m/s (Hui, 1987; Lang & Norris, 1966) and 10.2 m/s (Nursall, 1962). Indo-Pacific humpback dolphins are slow swimmers, typically travelling at around 1.3 m/s (http://www.arkive.org/indo-pacific-humpback-dolphin/sousa-chinensis/#text=Biology). Common dolphins were observed to swim at horizontal speeds of 1.4 m/s – 1.8 m/s (Hui, 1987), with high speeds of up to 6.7 m/s (Rohr *et al.*, 2002). Dugong speeds range from 2.8 m/s to 6.9 m/s (http://www.ioseaturtles.org/Education/dugongbooklet.pdf).

The maximum pinger spacing *d* can be computed via:

$$d = 2\sqrt{r^2 - v^2T^2}$$

where d = maximum pinger spacing [m]

r = detection radius [m] = Range column in Table 11

v = swim speed [m/s]

T = quiet time in between two pings [s]

Some examples are given in Table 12.

With 3-4 pingers per 200 m net, the pinger spacing is about 67 – 100 m. For humpback whales hearing Fumunda F3 tones, this spacing is more than sufficient. For bottlenose dolphins listening to F10 fundamentals and swimming slower than 6.0 m/s, this spacing is also adequate. If bottlenose dolphins swim straight at a net at higher speeds, however, the current spacing might not be sufficient to cause timely avoidance. This calculation is based on the (vertical) levels measured from three F10 fundamentals. Significant energy at harmonics might increase pinger detection ranges.

Indo-Pacific humpback dolphins appear to be slow swimmers, and hence the current pinger spacing is adequate. Common dolphins swimming at slow travelling speeds will also have ample warning of the net; to forewarn dolphins swimming at their reported top speeds, however, pingers should be no more than 59 m apart.

For dugong the current pinger types and their arrangement seem to be more than sufficient, giving these animals more warning than any of the other marine mammal species. Detection ranges of the F3 harmonic and the F10 fundamental are in excess of 100 m. Pingers could easily be spaced more than 250 m apart.

Table 12: Maximum pinger spacing for animals swimming straight at a net

		detection radius [m]	speed [m/s]	pinger quiet time [s]	distance from net [m]	pinger spacing [m]
humpback whale	F3 fundamental	90	1.1	6	7	180
		90	2.7	6	16	177
		90	4.2	6	25	173
	F3 harmonic 1	210	1.1	6	7	420
		210	4.2	6	25	417
bottlenose dolphin	F10 fundamental	40	6.0	4	24	64
		40	8.3	4	33	45
		40	10.2	4	41	/
IP humpback dolphin	F10 fundamental	40	1.3	4	5	79
common dolphin	F10 fundamental	40	6.7	4	27	59
dugong	F3 harmonic 1	210	2.8	6	17	419
		210	6.9	6	41	412
	F10 fundamental	130	2.8	4	11	259
		130	6.9	4	28	254

3.4. Objective 4: Ambient Noise Monitoring

JASCO’s autonomous recorder captured 21 days of continuous acoustic recordings in September, March and May, and 15 days of useful recordings in January. The severe storms off south-east Queensland experienced in mid-January (Beaufort 7, at the time of the Brisbane floods) damaged the mooring and brought the recorder to the surface on 10 January; it was redeployed on 19 January 2011.

The measured ambient noise levels are presented as band level plots, spectrograms, and spectral level percentiles.

3.4.1. Ambient Noise Percentiles

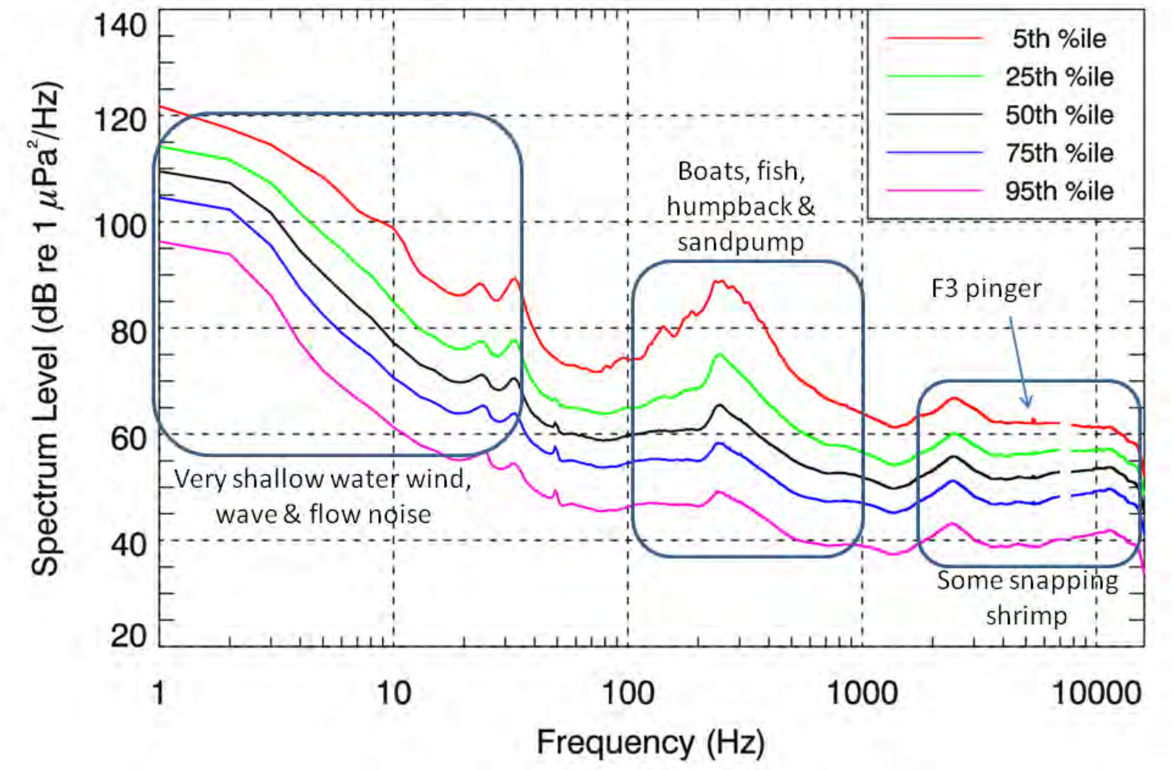


Figure 36: Ambient noise percentiles for the month of September.

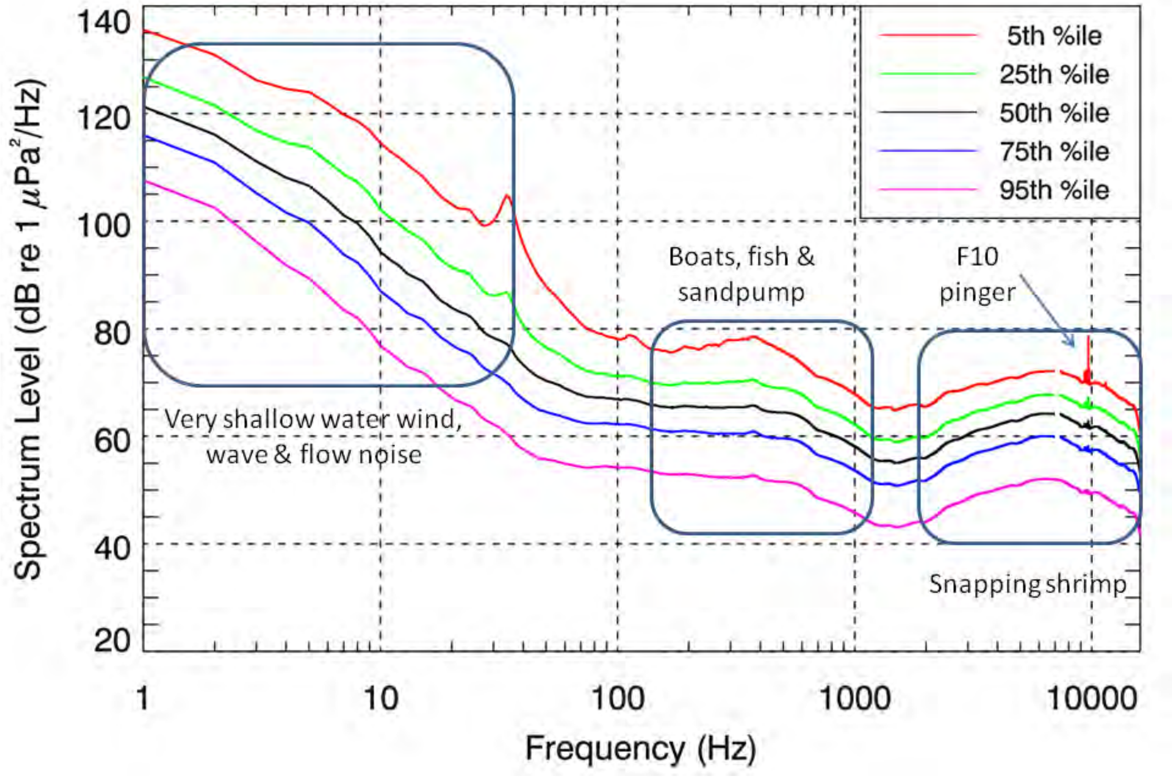


Figure 37: Ambient noise percentiles for the month of January, excluding the days when storms brought the recorder to the surface (10.-19.1.2011).

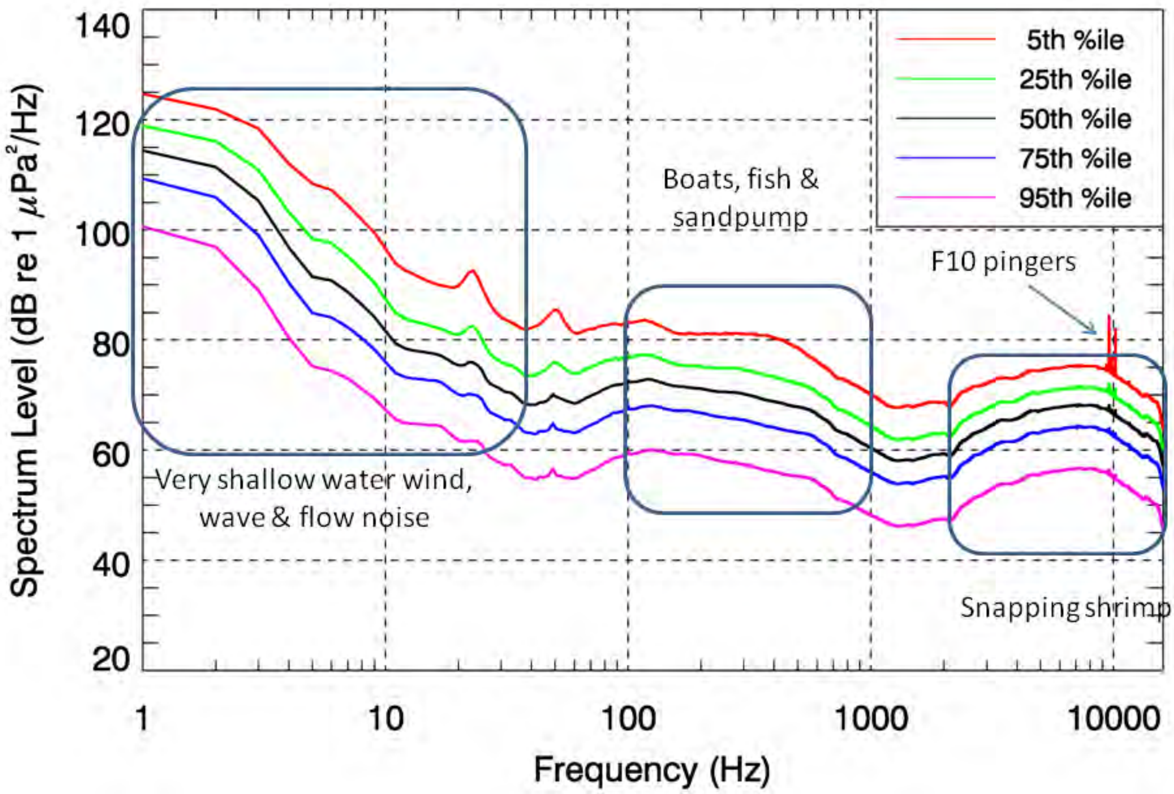


Figure 38: Ambient noise percentiles for the month of March.

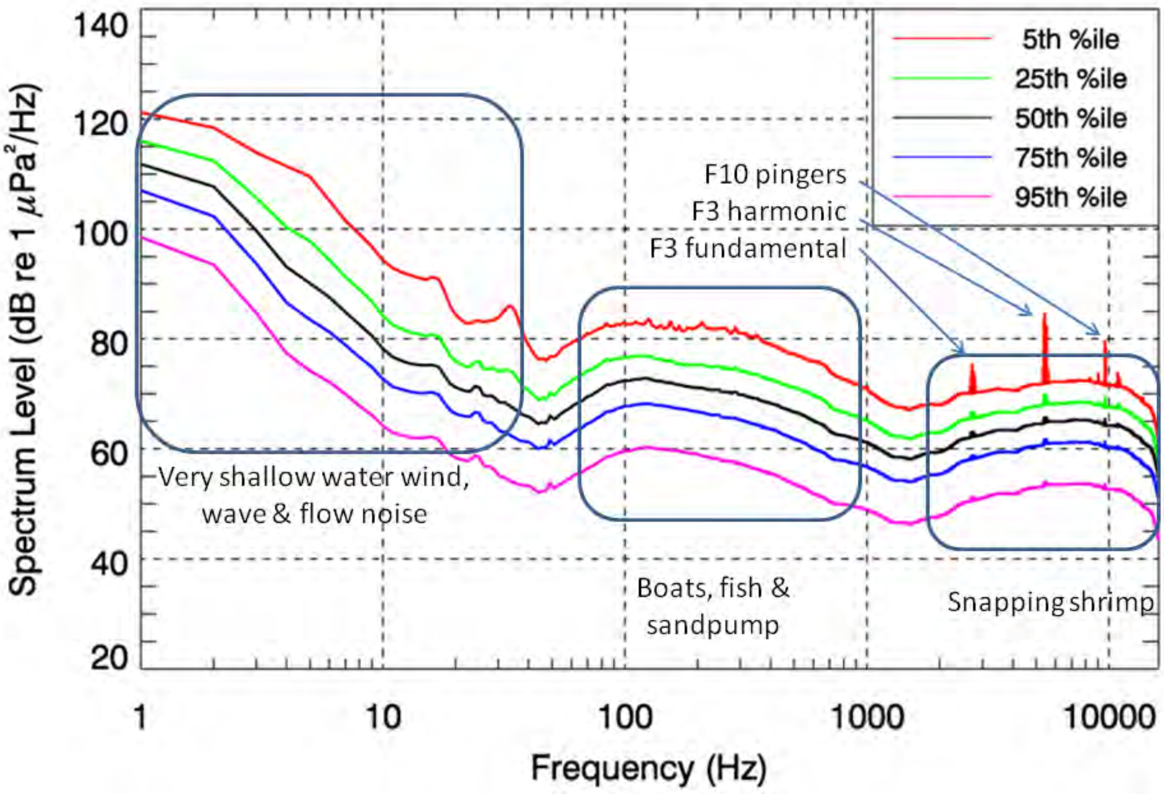


Figure 39: Ambient noise percentiles for the month of May.

In all of the data, energy at low frequencies (< 30 Hz) was due to wind and wave action over very shallow water, as well as flow noise around the recorder. Levels were more than 10 dB higher in January compared to the other three deployments, due to the strong storms, which southeast Queensland experienced in January.

In the September data, energy in the decade band from 100 Hz to 1 kHz was mainly due to a sand pump at the Gold Coast. The presence of this pump, which operated 2.4 km away from the monitoring site, was not known prior to the first deployment of the recorder. Humpback whales, fish and boats also contributed to energy in this band. However, the sand pump dominated. In January, March and May, the recorder was deployed a distance of 10 km from the sand pump to reduce the contribution of this equipment to the ambient noise recording. The sand pump was still detectable, however, at lower levels (< 6 dB). There were no humpback whales in January and March. A few humpback whale calls were heard at the end of May and early June.

Snapping shrimp typically dominate the ambient spectrum between 2 and 20 kHz. There was little snapping shrimp noise at the September site, and stronger snapping shrimp noise at the site of the later three deployments.

In September, the nearest F3 pinger was 1.48 km away. Its fundamental was not audible in the ambient noise recording, but the first harmonic was (see also Figure 48). At this range, the pingers barely contributed to the ambient noise budget; the harmonic was only visible in the 5th percentile at a level of about 63 dB re 1 µPa^2/Hz. With a duty cycle of a single pinger of 400 ms / 7 s = 5.7 % (measured from other F3s, see Section 3.1.1) one would not expect to see the pinger tones in the lower percentile curves. At the recorder location, tones at various levels from multiple pingers at various ranges were received, effectively increasing the duty cycle of pinger tone reception. With a transmission loss of about 45 dB (Table 8) from the nearest pinger to the recorder, the source level of the nearest pinger's first fundamental would have been about 112 dB re 1 µPa^2/Hz in this direction.

In January, March and May, the fundamental of the F10 pingers was clearly visible, as the nearest pinger was about 500 m away. With a transmission loss of about 40 dB at this range (Table 8), the source level of this pinger's fundamental would have been about 122 dB re 1 µPa^2/Hz in this direction in January and May, and about 127 dB re 1 µPa^2/Hz in March.

By the time the last recorder was deployed in May, the F3 humpback pingers had been reinstalled. F3 pingers are deployed seasonally at the time of humpback migration. The fundamental and the first harmonic of the F3 pingers were clearly audible. The nearest pinger was about 500 m away. The source levels would have been about 116 dB re 1 µPa^2/Hz for the F3 fundamental, and 125 dB re 1 µPa^2/Hz for the first harmonic in this direction.

3.4.2. Monthly Sound Spectrograms

Sound pressure levels (SPL) and spectrograms for the entire recording are presented in the Appendix (Figure 51), highlighting a range of the different noise sources encountered during the whole deployment period. SPL is plotted for broadband (10 Hz–16 kHz) and decade band levels, computed by integrating the power spectrum density levels in the spectrograms over frequency. The units are therefore different between the band level plots and the spectrogram plots.

3.4.3. Natural Sounds

Noise below about 30 Hz was correlated with tides. During tidal flow, this flow noise was loud. For about one hour around high tide and low tide, flow noise was low. The ambient levels in September, March and May were similar, with January having higher levels due to prolonged storms.

3.4.4. Biological Sounds

3.4.4.1. Fish

Fish were heard throughout the September recordings. Distinct tonal and pulsed calls were present at any time of the day, peaking in the afternoons and evenings. In January, March and May, fish chorus activity was reduced; faint choruses occurred for short durations in the evening and in the early morning hours.

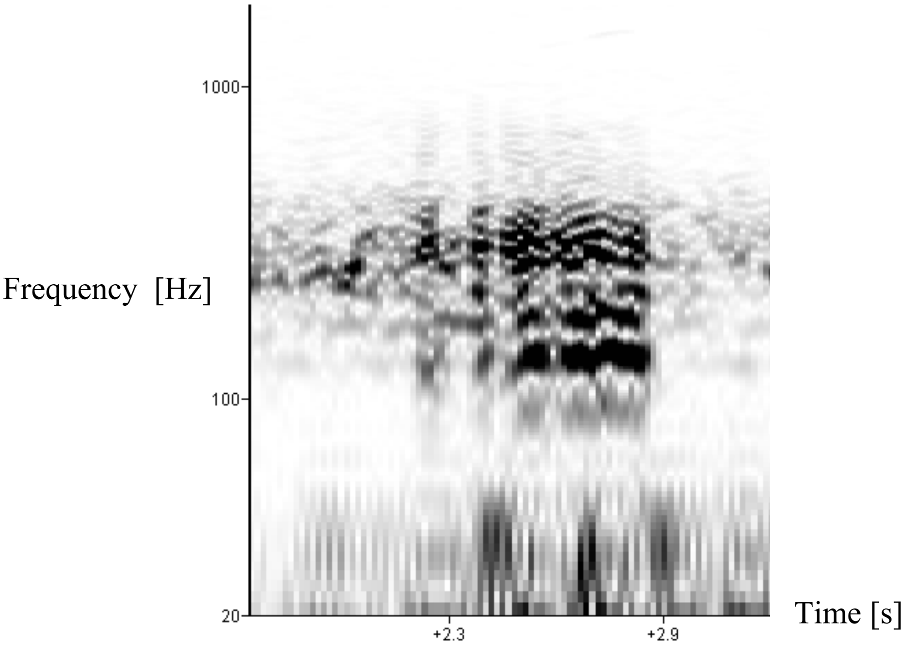


Figure 40: Spectrogram (NFFT = 2048) showing a fish call between 100 Hz and approximately 500 Hz.

3.4.4.2. Cetaceans

Humpback whales were heard throughout the first deployment (9 September – 1 October) more frequently at night than during the daylight hours. In the monthly spectrogram (Figure 51) the frequency range where the majority of calls occurred was highlighted with a box.

A sample spectrogram of humpback calls recorded in September is given in Figure 41. These are similar in frequency and duration to humpback calls reported by Dunlop *et al.* (2007). Note that the spectrograms in Figure 42 are plotted on a linear y-axis, while those in Figure 41 are plotted on a logarithmic y-axis.

Humpbacks were not recorded in January or March, but small numbers were observed in May. It was determined from the recordings that they travelled in small groups, with fewer vocalisations observed when compared to September. The travel pattern was confirmed by Craig Newton from QSCP, who observed humpback whales travelling in groups of up to three animals on the northward journey, in a widely distributed fashion. On the southbound trip they were observed in larger groups, closer to the beach (Craig Newton, pers. comm.).

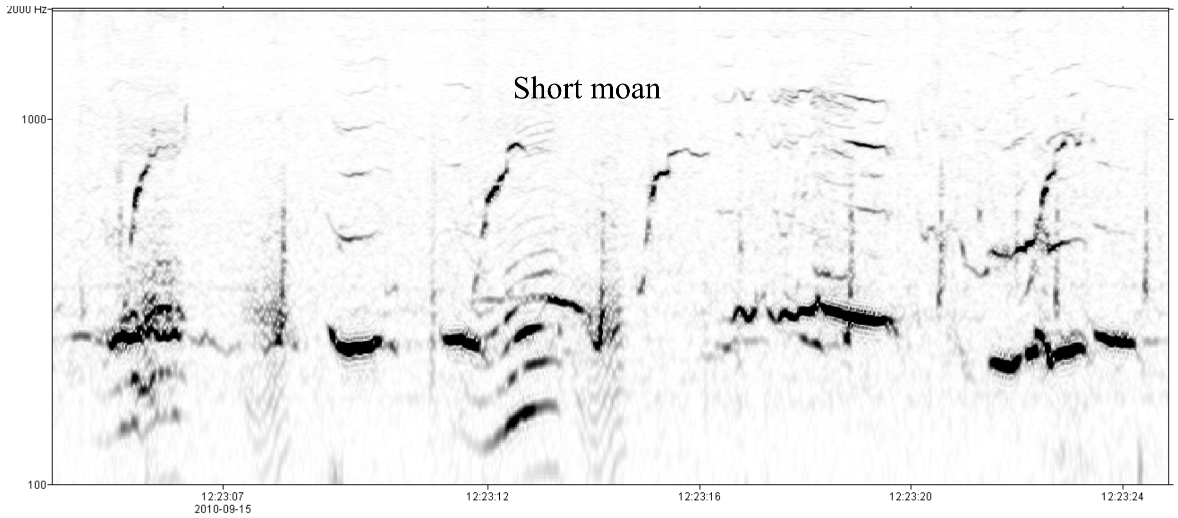
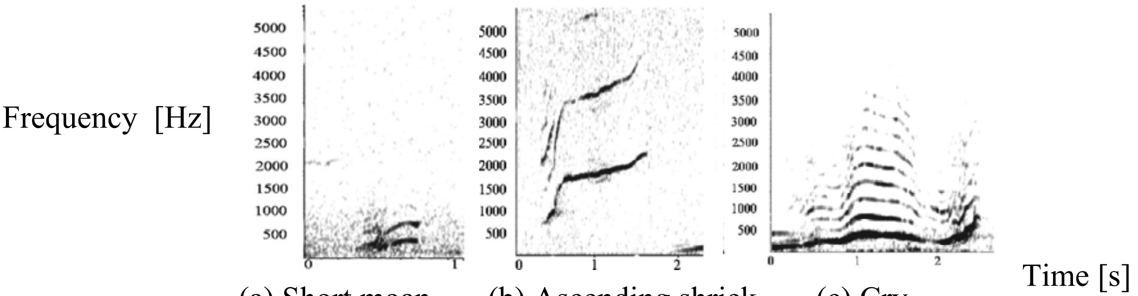


Figure 41: Humpback calls recorded in September. Number of Fourier components NFFT = 4096.



(a) Short moan (b) Ascending shriek (c) Cry

Figure 42: Humpback calls published by Dunlop *et al.* (2007).

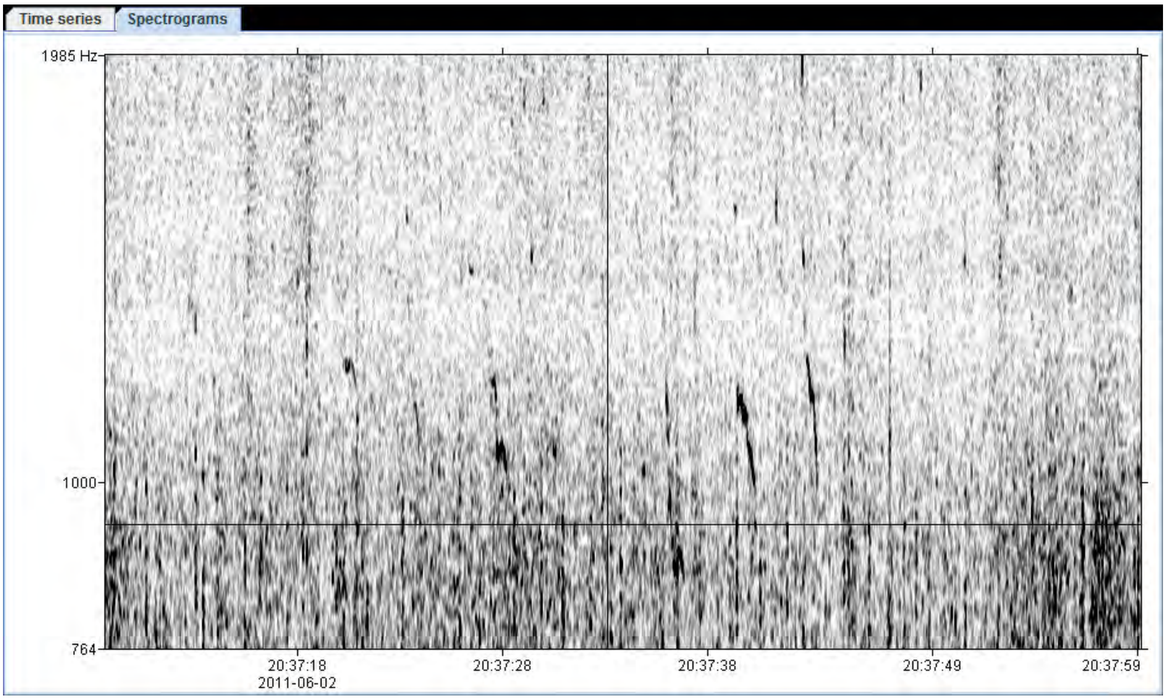


Figure 43: Humpback calls observed in June (2/6/2011), NFFT=16384.

Dolphins were heard on many days in all recordings, and their presence has been highlighted in the monthly spectrograms attached in the Appendix. Examples of dolphin vocal activity are provided in Figure 44 and Figure 45.

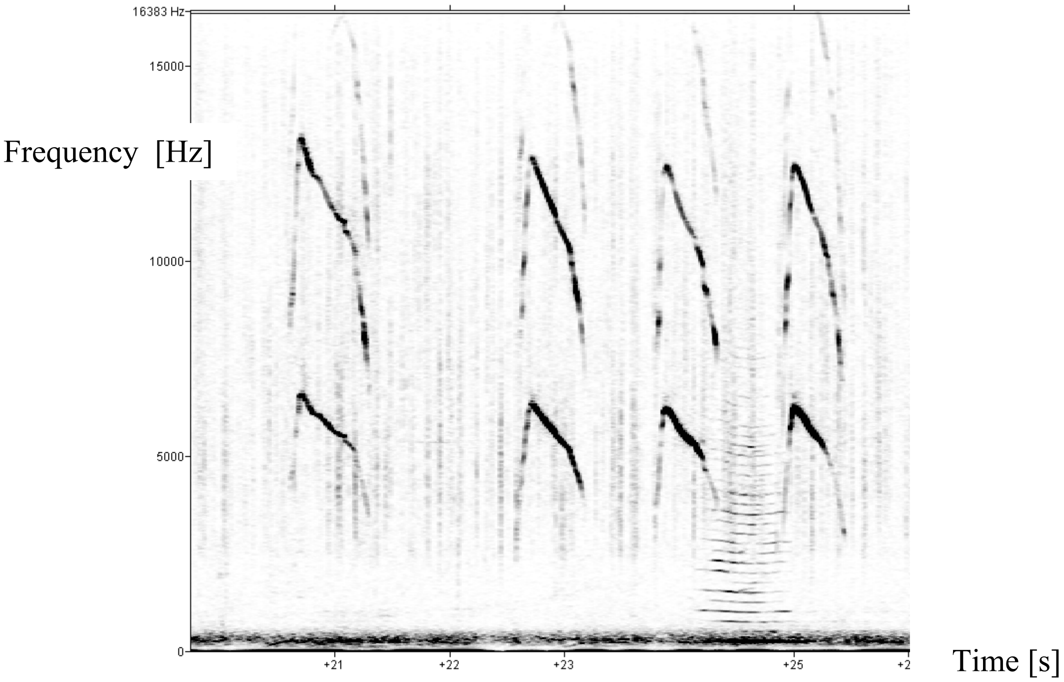


Figure 44: Dolphin whistles presented in a spectrogram with NFFT = 2048. This could be Indo-Pacific bottlenose dolphin whose whistles have a mean start frequency of 5.0 kHz and a mean length of 0.9 s (Hawkins, 2010; Hawkins & Gartside, 2010), which this particular example is very similar to.

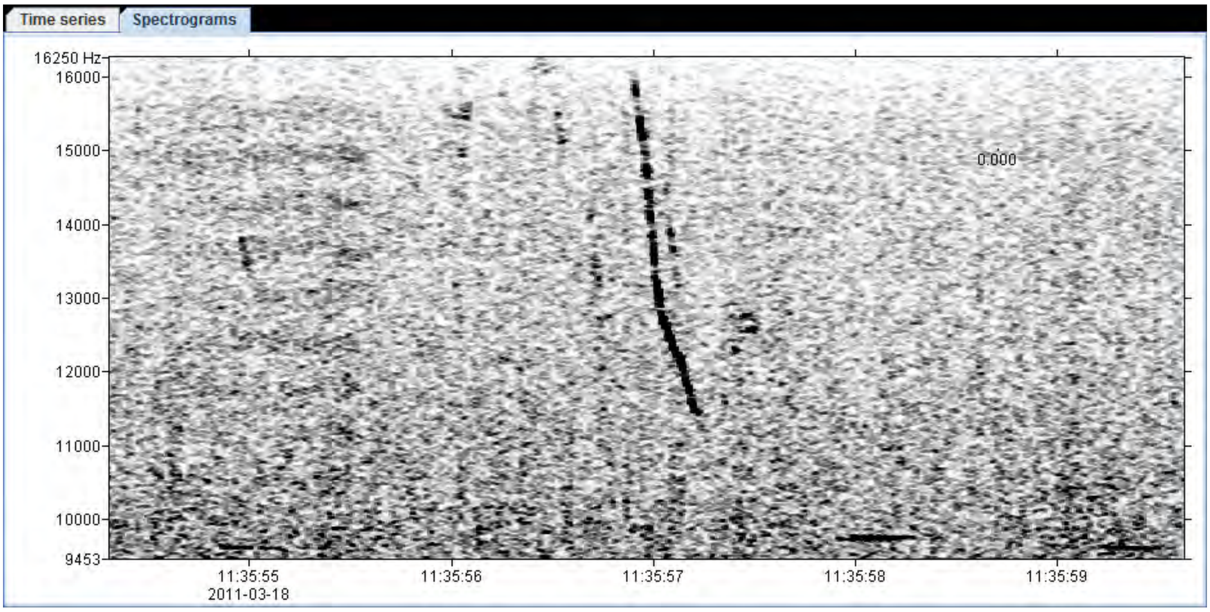


Figure 45: Dolphin down-sweep from the March deployment (18/3/2011), NFFT=16384. This is an example of a large number of similar whistles received within a 30-minute period. Echo-location clicks were also detected, but are not resolved in this image.

3.4.4.3. Snapping Shrimp

The characteristic sound from snapping shrimp dominated above 2 kHz in the January, March and May data. Snapping shrimp were less pronounced in the September data, which is likely due to the different geographic location of the September recorder. There was a diurnal pattern, with the snapping shrimp sound being a few dB louder at night time (6 pm – 6 am).

3.4.5. Anthropogenic Sounds

Sound associated with deployment of the frame was ignored in the analysis, and data were only analysed from the day after deployment.

A typical 24h spectrogram of sound recorded in September is shown in Figure 46.

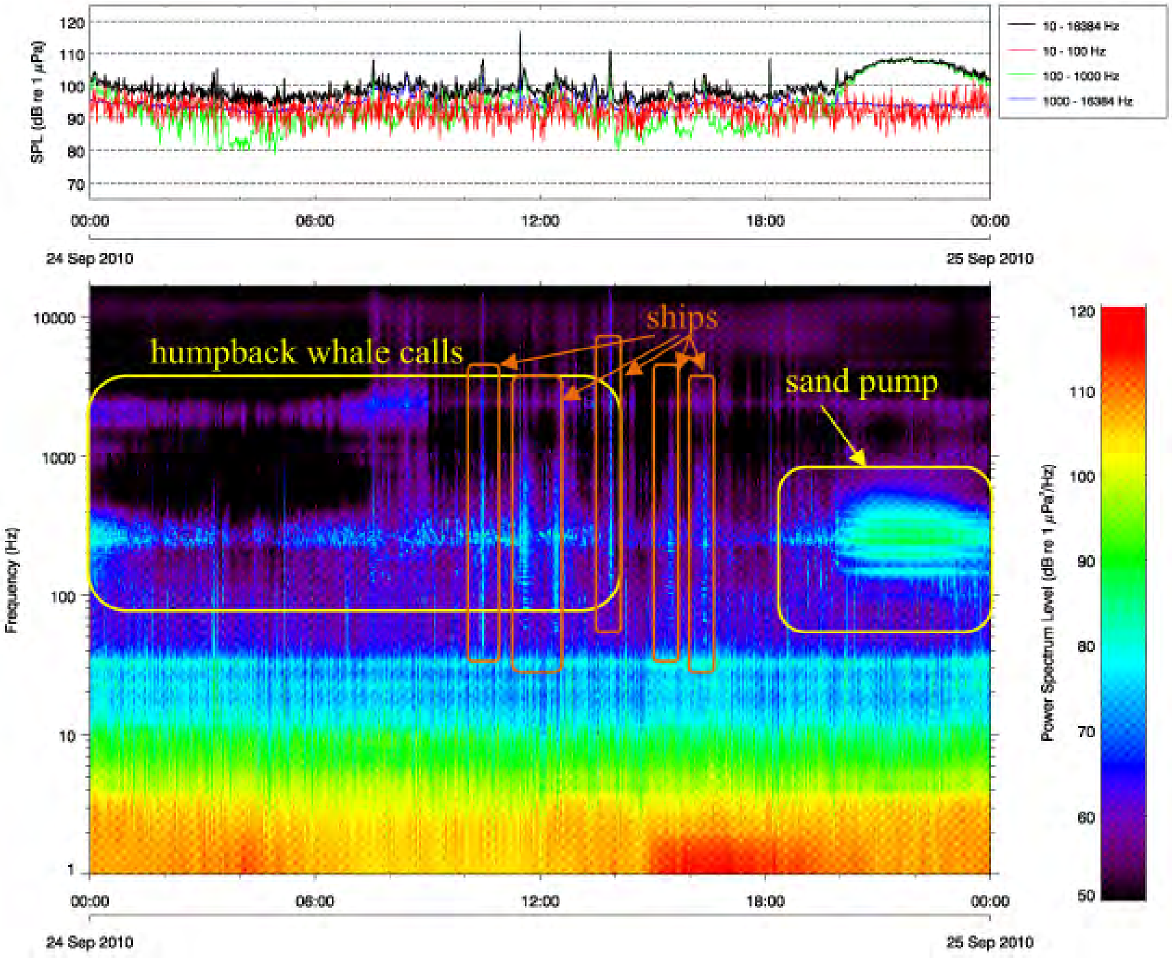


Figure 46: Daily spectrogram for 24 September 2010 displaying a typical pattern of ambient noise. Low frequency noise (< 30 Hz) was due to wind in shallow water and fluid flow. Humpback whales were detected in the band from 200 Hz to 2 kHz. The sand pump operated every night. There were a number of ships present during the day, this was common on each day.

A large number of passes by vessels small and large were recorded throughout the deployments, which was expected given the high traffic area the recorders were placed in.

The sand pump, highlighted in Figure 46 was a dominant feature of the soundscape in the first deployment, and occurred every night between 8 pm and midnight. Although efforts were made to reduce the influence of the sand pump during the subsequent deployments by relocating the position of the recorder approximately 10 km south, it was still present, though at levels a few dB lower than in the September deployment (compare Figure 46 and Figure 47).

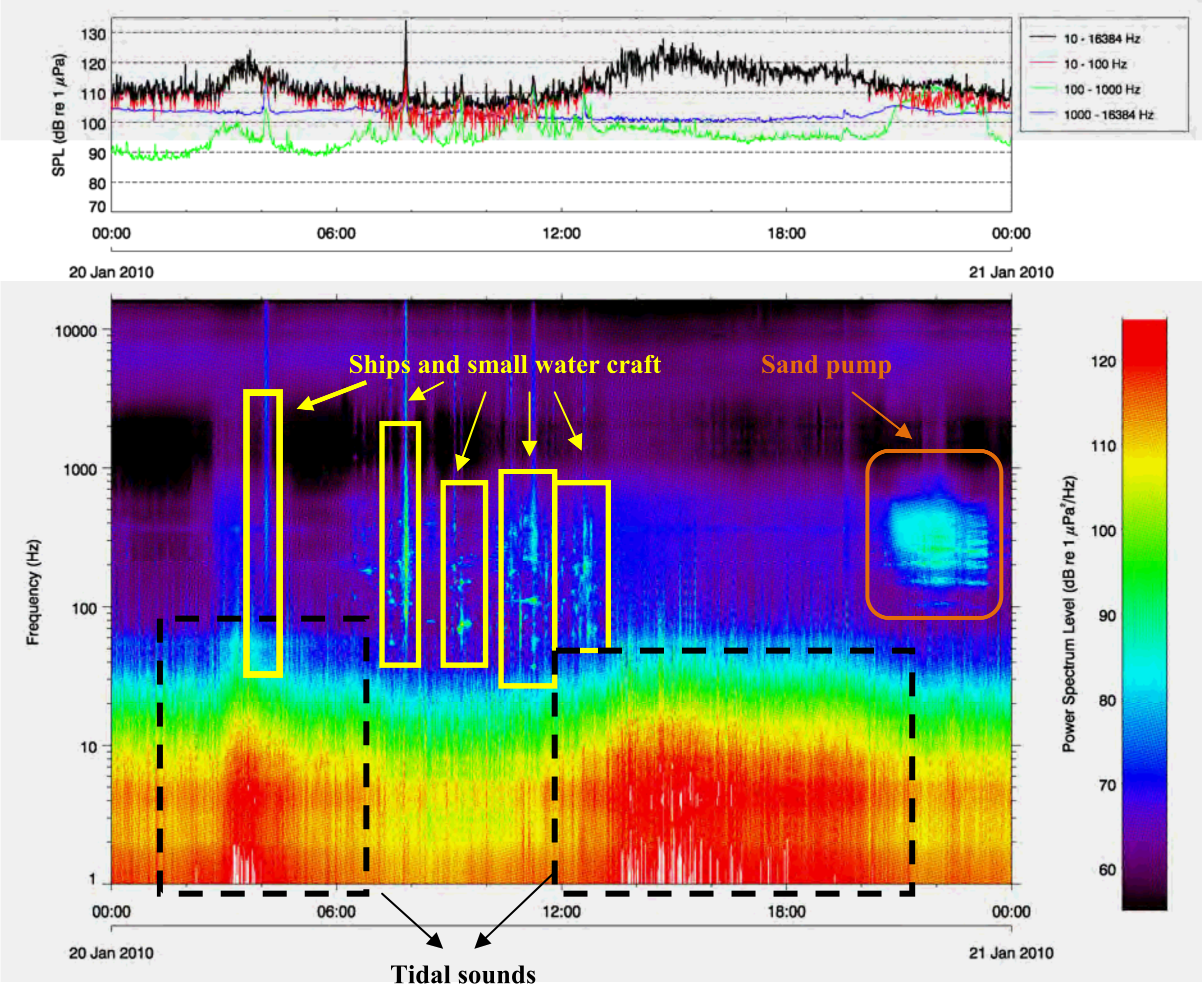


Figure 47: Daily spectrogram for 20 January 2011. Low frequency noise (< 30 Hz) was due to wind in shallow water and fluid flow. The sand pump operated every night. There were a number of ships present during the day.

Pingers were clearly heard during all deployments. F3 pingers were present in the September and May recordings; these pingers are only seasonally deployed at the time of humpback migration. F10 pingers were audible in all but the September deployment. The reason for their absence in September is unknown. The closest net was 1.48 km away from the recorder in September (compared to 500 m in January, March and May), and the 10 kHz tone might simply not have propagated far enough.

An example of recorded F3 tones is given in Figure 48. The fundamental was not detectable, but the first harmonic was. Multiple tones were detected from multiple pingers on the net. Note that the frequency varied by up to 150 Hz.

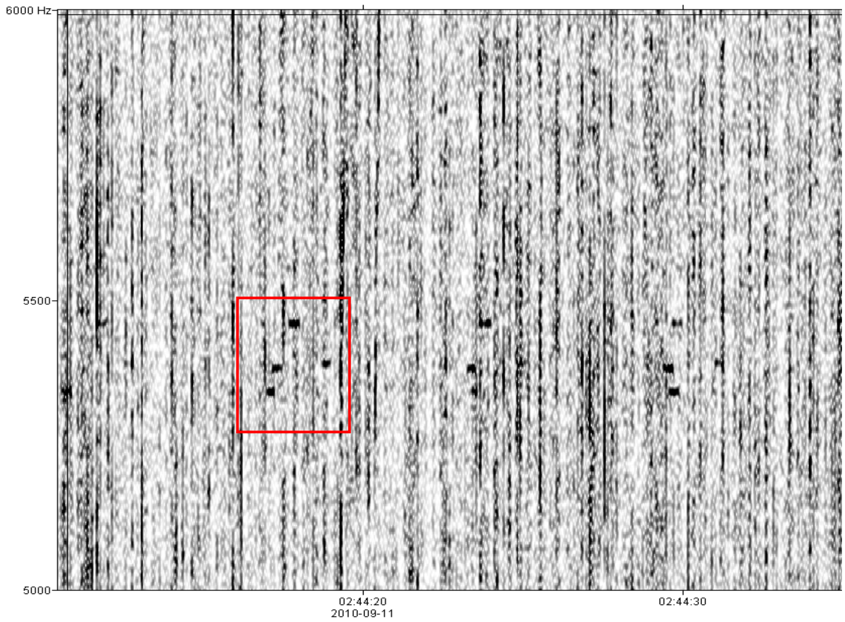


Figure 48: Spectrogram of F3 pinger harmonics (September), NFFT = 4096. In this recording four pingers were recorded (marked by the box). The first harmonic varied by up to 150 Hz between individual pingers. The fundamentals were not visible above ambient levels.

An example of F10 tones is given in Figure 49, along with more F3 tones. F10 fundamentals were received every 2 s. With a cycle time of 4 s, these tones must have come from two F10 pingers. Received tones varied in frequency, level and duration, as can be seen in Figure 49, likely due to intra- and inter-pinger variability in sound emission as well as a change in the emitted direction as the pinger and net moved with waves and currents. See Section 3.1 for measurements of variability and directivity patterns. At least four F3 pingers were recorded as well, based on a cycle time of 6 s. Again, note the changes in frequency and level. The F3 fundamentals were received at more variable levels than the harmonics.

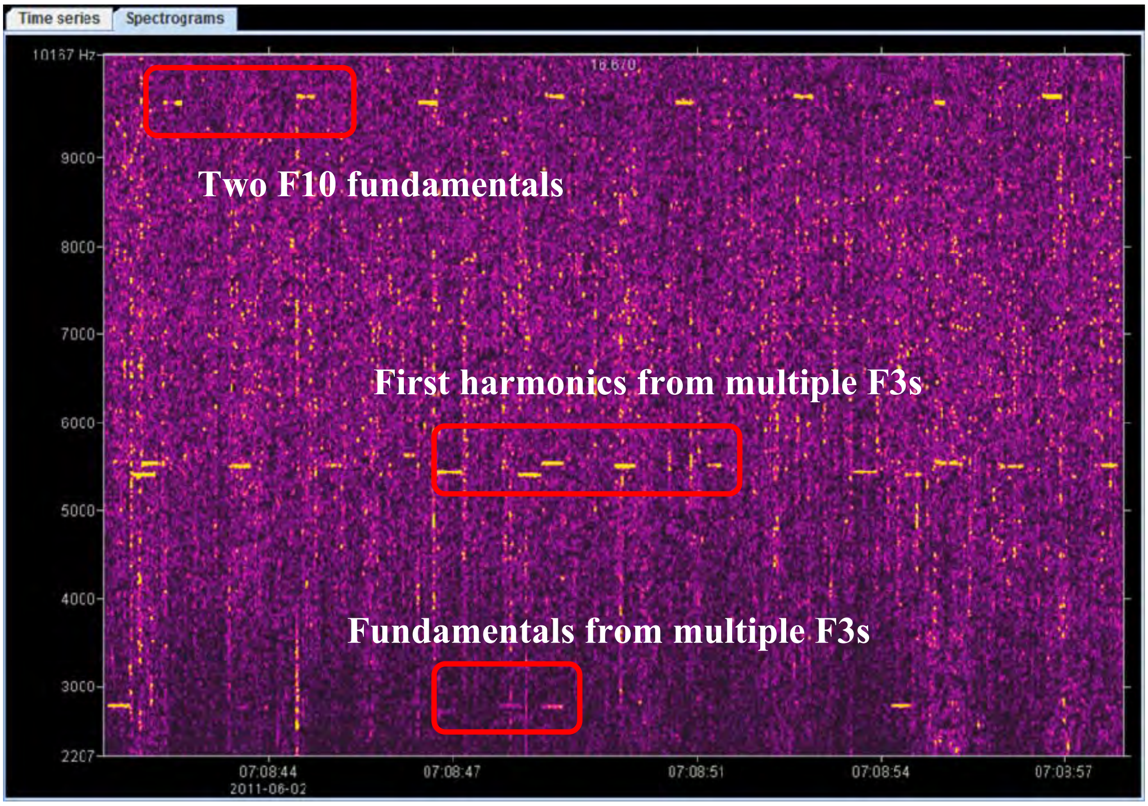


Figure 49: Spectrogram of F10 fundamental, F3 fundamental and first harmonic (2/6/2011), NFFT=16384.

The QSCP contractor operates in the vicinity of the nets every two days, checking the nets and drumlines, removing any captured sharks, and performing maintenance if required. In addition, a full net change takes place every few weeks, with the nets requiring cleaning to remove marine growth. This event is clearly seen on May 29, 2011, between 10 and 11 am. The 24 h spectrogram shows a large amount of small vessel traffic, a single larger vessel, and the sand pump (Figure 50).

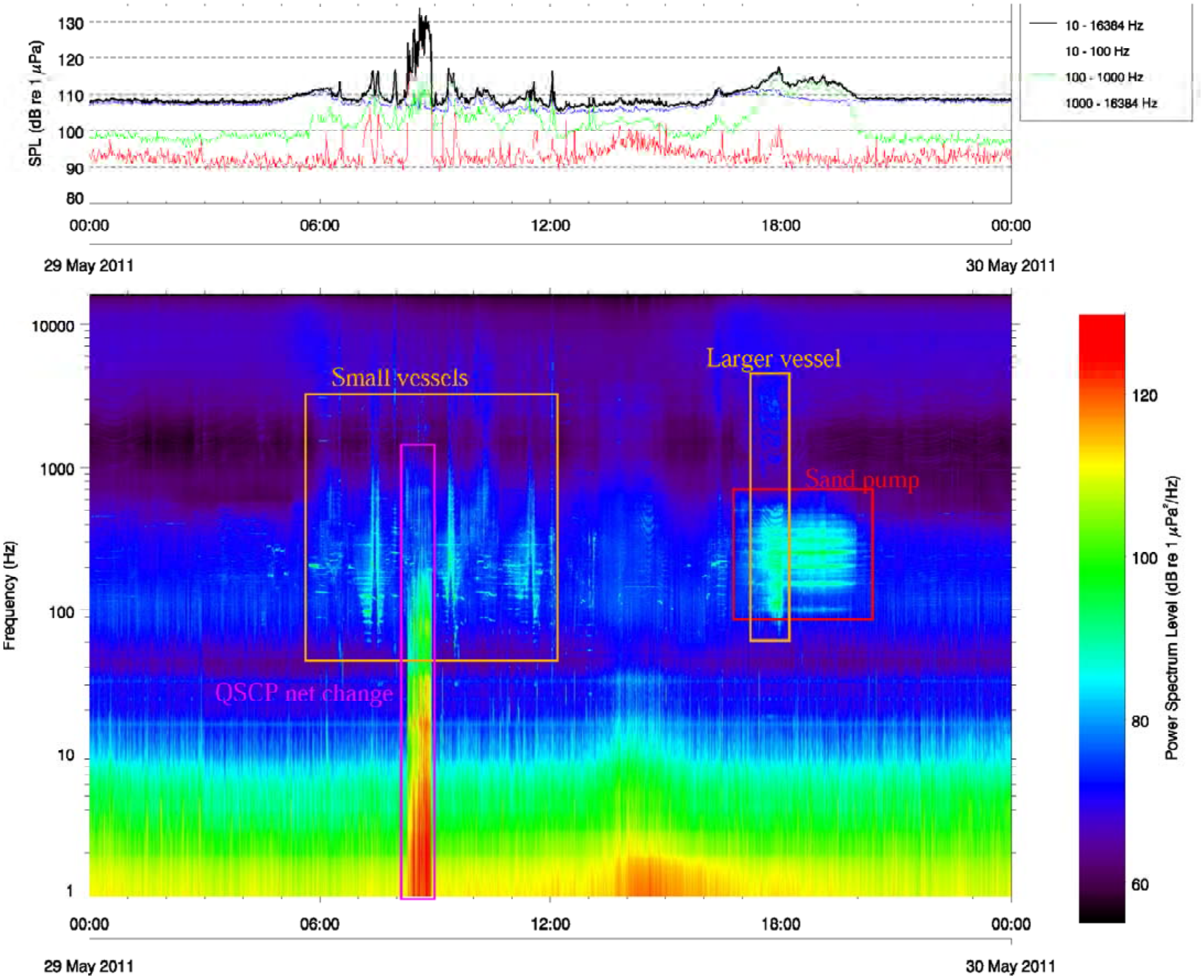


Figure 50: Daily spectrogram for 29/5/2011, demonstrating QSCP net change, sand pump, and vessel traffic.

4. Discussion

This study measured the acoustic output of Fumunda F3 and F10 pingers used on shark nets by the Queensland Shark Control Program. While the model numbers imply that these pingers emit tones at 3 and 10 kHz respectively, the emitted fundamental tones were a few hundred Hz less: 2.6 – 2.8 kHz for the three F3s measured and 9.4 – 9.6 kHz for the three F10s measured. These frequency deviations of 5 – 10% will have negligible impact on detectability by marine mammals.

All pingers emitted the fundamental tone and multiple harmonics. The frequencies of the emitted tones varied from ping to ping (by a few tens of Hz) and from pinger to pinger. The tone lengths (400 ms) and the periods (6 s for F3, 4 s for F10) varied from ping to ping and from pinger to pinger by more than 10%. Bycatch mitigation pingers are not sophisticated high-tech tools, nor do they have to be. For the purpose of highlighting nets to marine mammals, the variability is quite acceptable.

We estimated the angular directivity pattern of three F3s and three F10s by measuring the power spectrum density at 30^{O} intervals in the horizontal and vertical planes. The power spectrum density levels varied by up to 20 dB from angle to angle and from pinger to pinger. All pingers emitted a more symmetrical and less variable (i.e. more omni-directional) pattern in the vertical plane than in the horizontal plane, which was likely due to the fact that the vibrating piezo was located near one end of the pinger and not in the centre. The directivity patterns in the horizontal plane were not as symmetrical and were not consistent amongst pingers. This was likely due to the piezo not being seated at exactly the same spot and angle in all pingers. Also, the ping-to-ping variability somewhat masked the directivity pattern, which was measured by averaging over only five pings at each angle. With longer averaging times, the directivity pattern might have been less variable. Shapiro *et al*. (2009) found levels changed with angle by up to 5 and 26 dB for a 10 kHz Airmar and a broadband (20 – 160 kHz) Aquamark pinger.

Apart from power spectrum density levels, we also computed broadband root-mean-square sound pressure levels at all angles. The resulting directivity patterns were more symmetrical and consistent, as the broadband levels were integrated over all frequencies, and minima and maxima of the different frequencies happened at different angles. The directivity patterns were frequency dependent.

The broadband levels reached the manufacturer specified output levels for some pingers at some angles; on average over all angles, however, the output levels were up to 10 dB less than specified. McPherson *et al*. (2004) found that 33% of Airmar 10 kHz pingers failed to meet their manufacturers' specifications. We measured three pingers of each type, which is a small sample size. Better statistical results would be obtained from larger sample sizes. It is further unclear whether the manufacturer specified levels refer to the tone level at the target frequency (3 kHz for the F3 and 10 kHz for the F10), or to broadband output levels integrated over all harmonics. The first harmonic of the F3 was consistently louder than the target fundamental; and the F10 pingers emitted broadband energy below 4 kHz which would increase overall broadband levels compared to the targeted tone levels.

A decrease in output level over time could be expected as battery power drains; this was investigated by measuring an F3 which had been in operation for 60 days. While the energy at the fundamental was significantly less than with the newer F3s, the broadband power was similar. To estimate how long the pinger batteries last and when best to recover pingers, a long-term study should be done on a few pingers rather than comparing levels from pingers of different age.

Pingers on shark nets are not rigidly positioned; the angle from the pinger to the animal varies as the net moves, as the pinger moves, as the mounting changes from pinger to pinger, and with the animal swimming past the net. For the estimation of detection ranges, the mean output levels were therefore computed over all orientations. Transmission loss was modelled for a Gold Coast environment, for the frequencies of the F3 and F10 fundamentals, and the first and second harmonic of the F3s. Transmission loss varied little with tidal height. A well-mixed winter sound speed profile was used as input for the model. Propagation ranges will likely differ in other hydro- and geo-acoustic environments, for example over rocky seafloors, in particular limestone seafloors, or in seagrass regions. Miksis-Olds and Miller (2006) found increased transmission loss for frequencies > 2 kHz in shallow-water seagrass habitats of manatees. Sound propagation could be modelled for any environment with pingers, however, the differences will be more significant at longer ranges, and the levels measured from the pingers were not loud enough to reach much beyond a few hundred meters.

To estimate how far pingers might be audible to marine mammals, a literature search was conducted for audiogram and critical band information on humpback whales, a number of Queensland dolphin species, and dugongs. Given the lack of data, humpback hearing was assumed to be ambient noise limited; a *Tursiops truncatus* audiogram and critical ratio data were applied to all of the dolphin species despite their genealogic differences; manatee data were used for dugong. The results should give a general idea of pinger detectability, while keeping in mind that the local populations might hear and respond differently.

The fundamental, and the 1st and 2nd harmonic of the F3s as well as the fundamental of the F10s were modelled at the mean measured levels. Of the four tones, the 1st harmonic of the F3s was audible to all marine mammals over the longest ranges. This was because the intensity of the 1st harmonic of the F3 was greater than the intensity of the fundamental (targeted at whales), and the harmonic frequency was sufficiently high to be effective on the other species, which are more receptive to higher frequencies.

The detection ranges predicted for the mean measured output levels were short, less than 250 m for all tones and all animals. The output levels specified by the manufacturer would be audible over much longer ranges: 1-5 km, but these levels were reached by only two of the six pingers at a few angles. In the field, the detection ranges will be highly variable and depend on the individual pinger and on the angle towards the animal.

Based on the mean measured levels, the optimum pinger spacing was assessed. For animals travelling alongside the nets, it seems reasonable that a number of pingers in series would best be audible at any one location so as to highlight not only the presence of the net but also its direction and extension. Assuming good intensity discrimination capabilities in marine mammals, pingers farther away should be perceived as such due to their reduced received level. There are currently 3-4 pingers per net of about 200 m. Humpback and dugong would hear all of the pingers at any location along the net. Dolphins would only hear 1-2 pingers at any location. The harmonics of the F10 pingers were not investigated, but given that dolphin hearing becomes more sensitive with frequency above 10 kHz, it can be argued that higher harmonics might be audible to longer ranges if their levels were comparable to or in excess of the fundamental. From broadband measurements performed, however, higher harmonics would not appear to be significantly louder—if at all.

For animals swimming straight at a net, the maximum pinger spacing was expressed as a function of the animal's swim speed. A literature review for swim speeds showed long-duration travelling speeds of 1-3 m/s, and non-sustainable burst speeds of up to 10 m/s for some dolphin species. If an animal is outside of the detection radius at the time of a ping, the next ping must be heard before the animal reaches the net if successful aversion is to be achieved. This scenario determines a maximum pinger spacing if the pinging duty cycle is fixed. For humpback and dugong the current spacing is more than adequate; pingers could be spaced farther apart and these animals would still have ample warning. Similar results were obtained for dolphins travelling at slow speed. At the high speeds reported for some dolphin species, however, current pinger spacing would be too wide and an animal could reach a net without ever hearing a pinger pulse.

For the assessment of pinger detectability, modelled received levels needed to be compared to typical ambient levels. A single autonomous acoustic recorder was deployed four times at two different locations at the Gold Coast for up to one month each. Ambient levels varied with season and location. Humpback whales were recorded during their southern migration in September and during their northern migration in late May / early June. Dolphins were heard in all deployments, however never in large numbers. Fish were heard throughout the recordings. Snapping shrimp were present at the site of the January, March and May deployments, but less obvious at the September site. Boat passes were heard every day at all locations. A sand pump on the northern Gold Coast, of whose existence the monitoring team was unaware, dominated the ambient spectrum in September, as its location chanced to be near the recording station. The later recorder deployments were sited 10 km south from the sand pump; this slightly reduced the contribution of that equipment to ambient noise. Pingers were heard in all four deployments, less prominently in the first data set than in the later three, because the first recorder was 1.48 km from the nearest net, compared to 500 m for the other three recorders. Only the first harmonic of the F3 pingers was audible and visible in the ambient noise spectra in September. The fundamental was not obvious. It is unclear why no F10 tones were detected in September, as these pingers should have been in operation at that time. F10 pingers were very prominent in the January, March and May recordings. F3 pingers are intended for humpback whales and are deployed only during the humpback migration season, and were therefore absent from the January and March recordings.

Pinger tone propagation ranges will be shorter in higher levels of ambient noise. Ambient noise in the frequency range of QSCP pingers increases with sea state. Heavy rain can raise ambient levels to above 80 dB re 1 $\mu Pa^2/Hz$. Strong winds (mostly westerly) occur in the winter at the Gold Coast, causing a surface flurry of bubbles. A sheet of dispersing bubbles is pushed from the breaking wave tops out past the net line. These bubbles not only increase ambient levels, but also scatter and absorb pinger sound. Pingers used to be deployed near the top of the nets for easy deployment and recovery. They are now deployed near the bottom of the nets, away from surface action and well below potential bubble clouds. The current deployment depth is likely optimal.

Snapping shrimp sound is most energetic between 2 and 20 kHz, i.e. in the frequency range of QSCP pingers. Detection ranges were modelled using ambient noise recorded in January in the presence of snapping shrimp. In the absence of snapping shrimp, detection ranges would be longer.

4.1. Conclusion

The underwater sound characteristics of three Fumunda F3 and three Fumunda F10 pingers have been measured, and variability has been noted from ping to ping, from pinger to pinger, and with angle. Fumunda specifies 135 dB re 1 µPa for their F3s and 132 dB re 1 µPa for their F10s. While these levels were reached by some pingers at some angles, the mean levels were less.

Given the small sample size of pingers measured (3), it might be useful to test a larger number of pingers to achieve a better statistical representation of output levels. It would also be useful to measure at what time into a deployment battery power sinks below a level were sufficient output is achieved, in order to advise on recovery times.

Based on the measured levels and a sound propagation model for the Gold Coast and ambient noise at the Gold Coast, the number of pingers currently deployed per net is adequate for humpback whales and dugong and for dolphins swimming at normal travelling speeds. The pinger spacing, or alternatively the pinger output level, was insufficient only for the scenario of a dolphin swimming straight at a net at high speed.

While F10 pingers are deployed year-round, F3 pingers are seasonal and are only deployed during the humpback migration season. Modelled detection ranges were based on the currently available information on marine mammal hearing and numerous assumptions. There are no useful audiogram and critical ratio data for humpback whales, dugong and some of the dolphin species occurring along the Gold Coast. Detection ranges and optimal pinger spacing should be remodelled once better data on hearing by the resident populations is available.

This study was undertaken with the goal to produce reliable noise maps, or sound footprints, of the different types of pinger. The variance encountered in the source properties and the directivity of sound emission, however, could cause the propagation and detection ranges to vary by several fold, a conclusion also drawn by Shapiro *et al*. (2009). Future studies aimed at characterising marine mammal behaviour around nets equipped with pingers should consider real-time recording of received pinger levels rather than rely on mean modelled values.

While our acoustic measurements and models indicate that the current pinger design, the sound emission characteristics and the arrangement of pingers on shark nets adequately highlight a net to all target species, the question whether or not this bycatch mitigation solution works is best answered by *in situ* studies of animal behaviour and by long-term monitoring of bycatch rates (in relation to changing population numbers).

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Appendix A. Glossary

Pressure

Hydrostatic pressure at any given depth in a *static* liquid is the result of the weight of the liquid acting on a unit area at that depth, plus any pressure acting on the surface of the liquid.

Acoustic pressure is due to a deviation from the ambient hydrostatic pressure caused by a sound wave.

Pressure is measured with a *microphone* in air, and with a *hydrophone* underwater.

The common symbol and units are: P [1 bar = 10^5 Pa = 10^6 dyn/cm^2].

Peak Pressure

Peak pressure is the maximum absolute value of the amplitude of a pressure time series $P(t)$. It is also called the zero-to-peak amplitude.

Peak Pressure Level

The *peak sound pressure level* (SPL_{Pk}) is the logarithmic ratio of peak pressure to reference pressure:

$$SPL_{Pk} = 20\log_{10}\left(\max(|P(t)|/P_{ref})\right)$$

The *peak sound pressure level* is expressed in *decibels*: dB re 1 µPa. The *reference pressure* underwater is $P_{ref} = 1$ µPa.

Peak-to-peak Pressure Level

The *peak-to-peak sound pressure level* ($SPL_{Pk\text{-}Pk}$) is the difference (expressed in dB) between the maximum and minimum of the recorded pressure time series [dB re 1 µPa].

$$SPL_{Pk-Pk} = 20\log_{10}\left(\left(\max(P(t)) - \min(P(t))\right)/P_{ref}\right)$$

RMS Sound Pressure

The *rms sound pressure* is the root-mean-square of the time series $P(t)$. This quantity is useful for continuous sound (as opposed to pulsed).

RMS Sound Pressure Level

The *rms sound pressure level* (SPL_{rms}) is the logarithmic ratio of *rms pressure* to *reference pressure* [dB re 1 µPa]:

$$SPL_{rms} = 20\log_{10}\left(\sqrt{\frac{1}{T}\int_T P(t)^2\,dt}\,/\,P_{ref}\right)$$

Sound Exposure Level

The *sound exposure level* (*SEL*) is a measure of the total *energy* of a signal [dB re 1 μPa^{2}s]. For plane waves,

$$SEL = 10\log_{10}\left(\int_T P(t)^2\, dt\right)$$

In the presence of significant ambient noise $P_n(t)$, noise energy must be subtracted to compute *sound exposure* from the signal alone. In praxis, the noise energy is computed from a time section preceding or succeeding the signal:

$$SEL = 10\log_{10}\left(\int_0^T P(t)^2\, dt - \int_{Tn}^{Tn+T} P_n(t)^2\, dt\right)$$

Source Level

The acoustic *source level* is the level referenced to a distance of 1 m from a point source. For sources that are larger than a few cm (e.g., ship propellers and drillrigs), the spectrum is measured at some range, and a sound propagation model applied to compute what the spectrum would have been at 1 m range if the source could have been collapsed into a point-source. The *source level* can be expressed in terms of pressure [dB re 1 μPa at 1 m] or sound exposure [dB re 1 μPa^{2}s].

Power Spectrum Density

Power spectrum density describes how the power of a signal is distributed with *frequency*.

Power Spectrum Density Level

The p*ower spectrum density level* is computed as $10\log_{10}$ of the squared *sound pressure* in 1-Hz bands [dB re 1 μPa^2/Hz].

Band Levels

Band levels are computed by integrating the *power spectrum density* over frequency bands. In the case of proportional frequency bands, the ratio of upper to lower band-edge frequency remains constant. Common examples are 1/3-octave bands, octave bands and decade bands. In decade bands, the upper frequency is 10 times the lower frequency. The bandwidth is the difference between upper and lower frequency and increases with frequency. Therefore, band levels are higher than *spectrum density levels*, and the level difference increases with frequency. Band levels are measured in dB re 1 μPa.

Appendix B. Monthly Sound Spectrograms

Monthly sound spectrograms are shown for the entire deployment period.

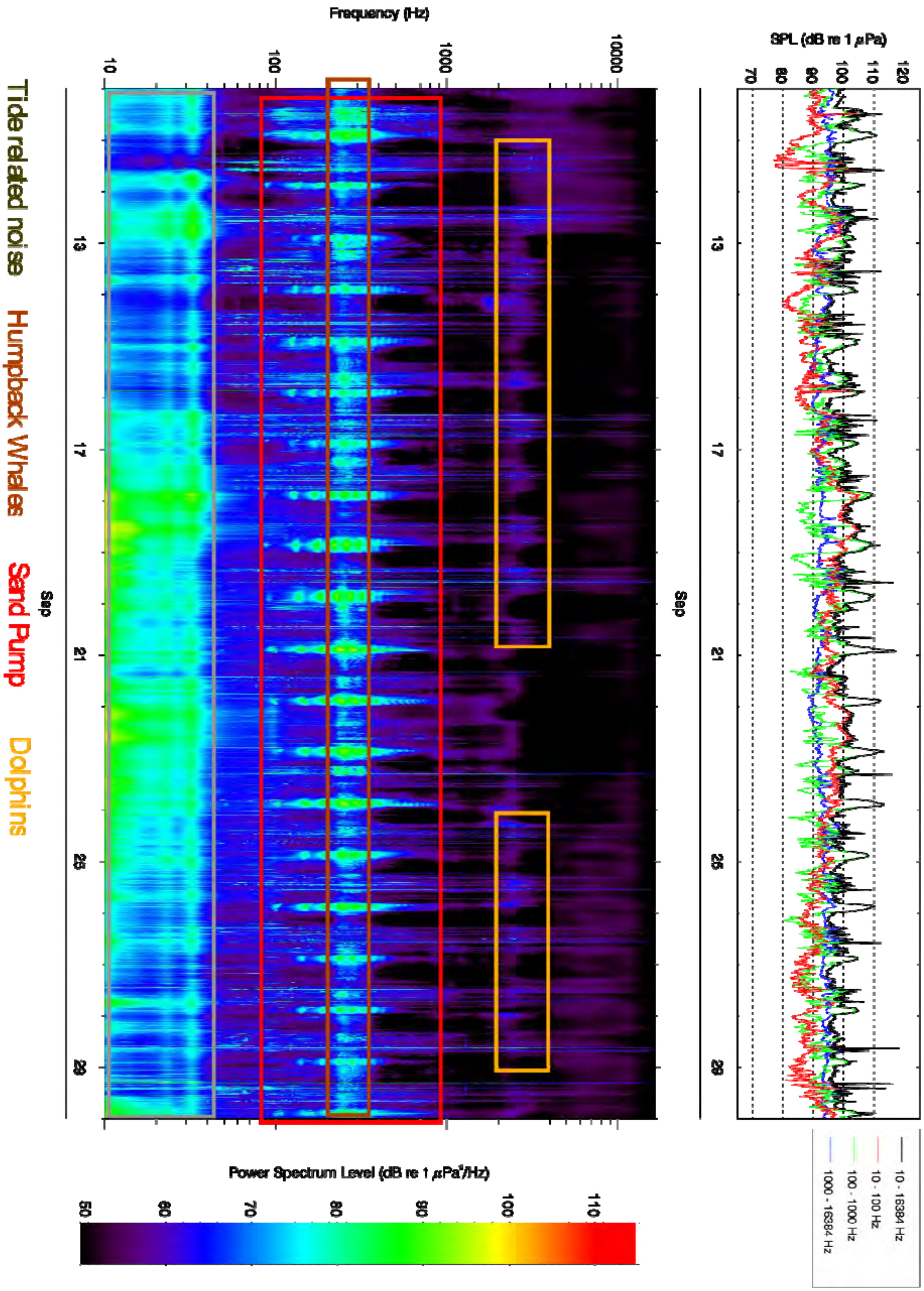

Figure 51: September spectrogram.

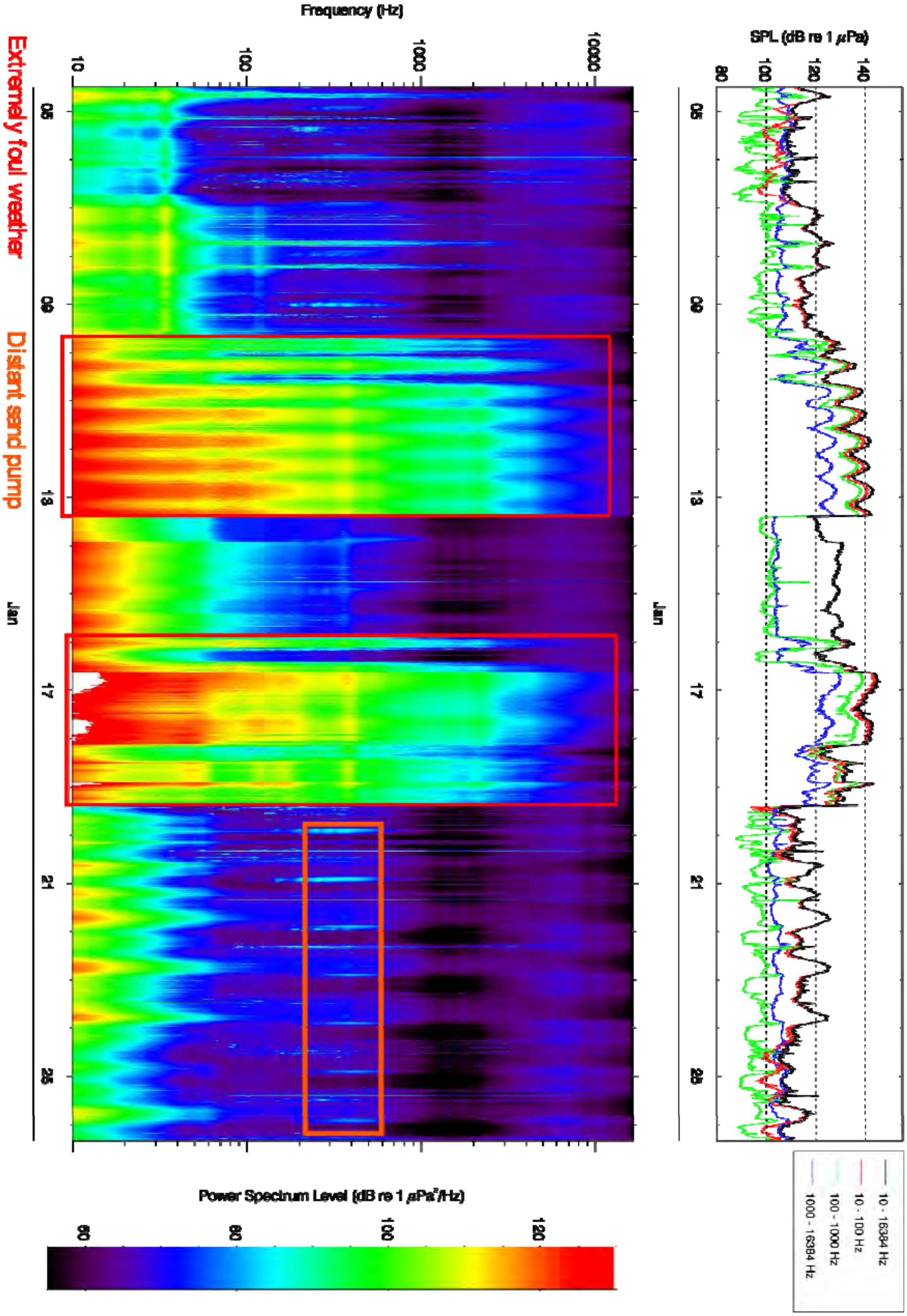

Figure 52: January spectrogram.

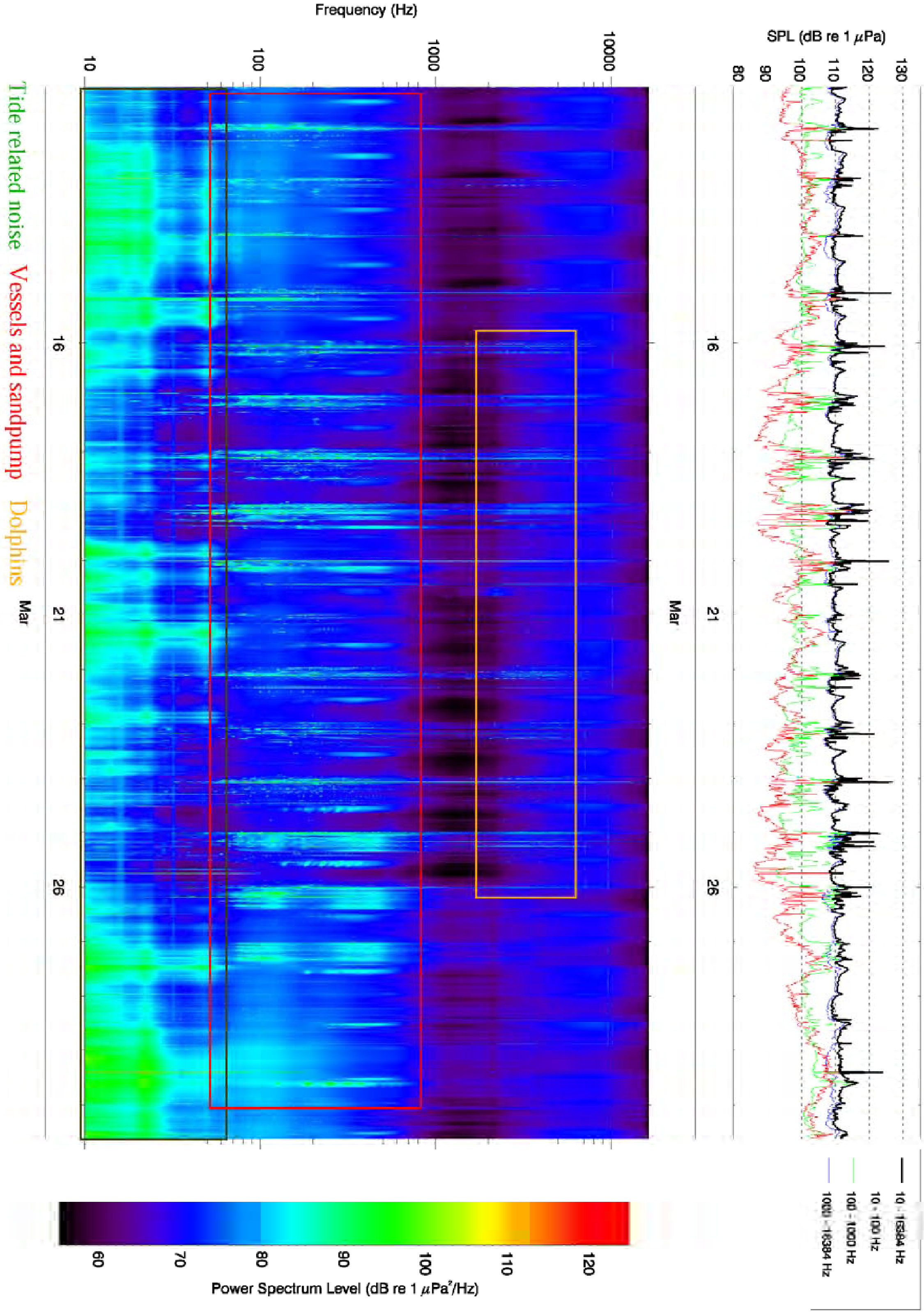

Figure 53: March spectrogram.

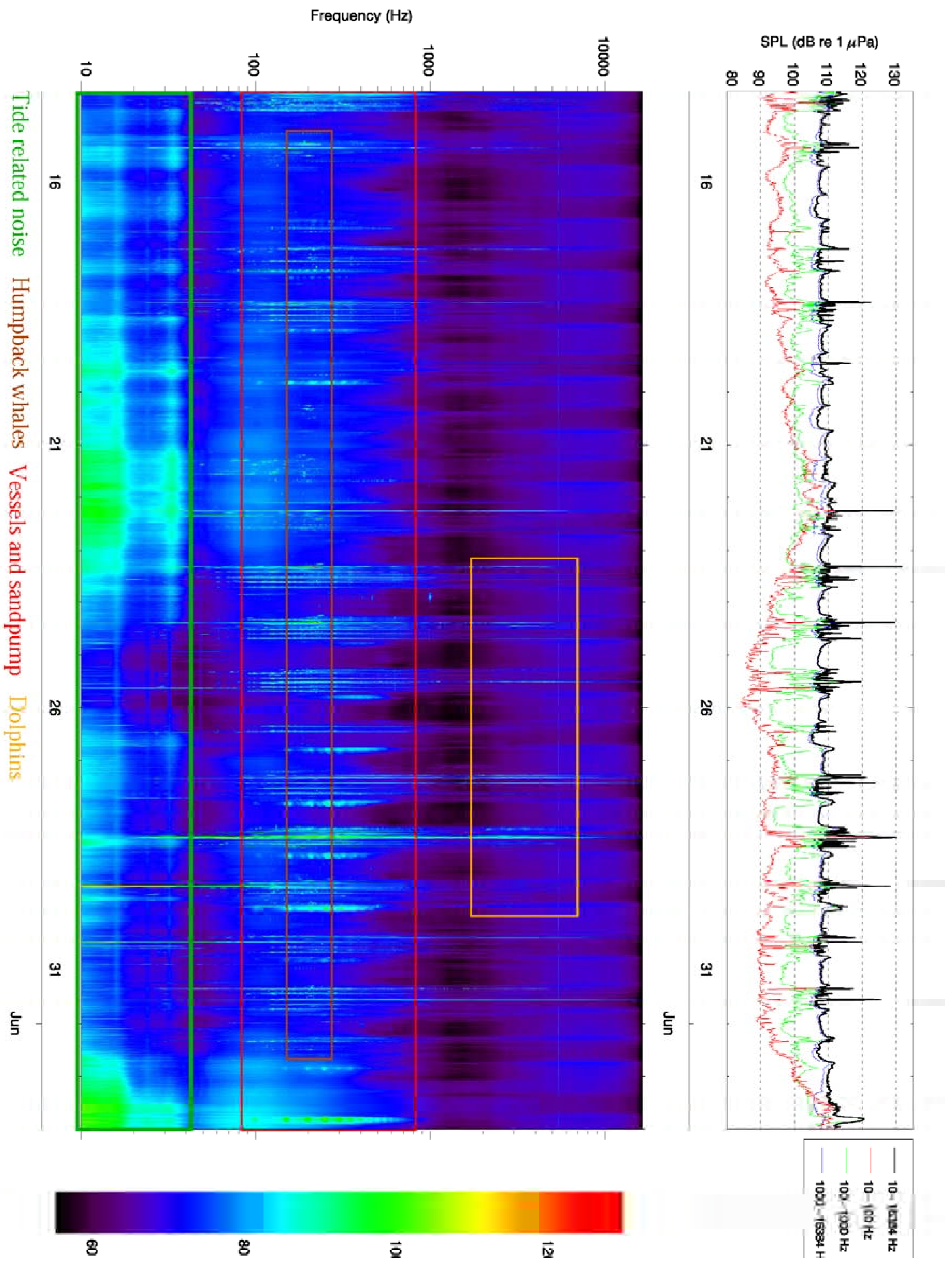

Figure 54: May spectrogram.