Centre for Marine Science and Technology

Offshore Irish noise logger program (March to September 2014): analysis of cetacean presence, and ambient and anthropogenic noise sources

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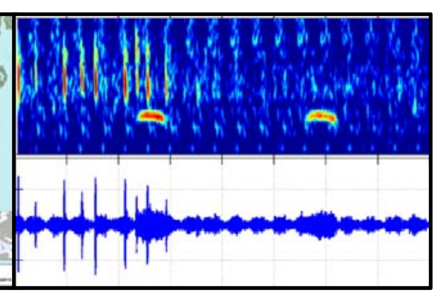

Research Partners:

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Executive summary

Six sea noise receivers were set over 18-May-2014 to 20-Sep-2014 west of Ireland on the eastern and northern sides of the Porcupine Basin and on the south western flank of Porcupine Bank (North, East and Southwest Porcupine Bank). The receivers detected: nearby vessel noise; natural ambient sea noise sources; exploration seismic survey signals; fin and blue whale calling; whistling signals from smaller toothed whales; sperm whale clicks; and unidentified echo-location signals from toothed whales.

Ambient noise was dominated by vessels, natural sources and fin whales at all sites up until early Jul-2014. During this period ambient noise levels in the band > 7 Hz averaged at 107 - 109 dB re 1µPa, with most energy in the frequency band up to 100 Hz. Vessel noise was considered to arrive at the receivers in two forms: 1) a recognisable vessel passage where the ship noise became apparent, increased in level as it passed abeam somewhere, then decreased in level as it steamed away; and 2) traffic noise comprised of energy ducted over long range in the deep sound channel which was apparent as almost continual tonal energy in the frequency band 5-100 Hz and not recognisable as from a nearby ship. The time taken for recognisable nearby ships to pass and the maximum levels reached as they passed was quantified for periods without seismic signals present and ranged at ~ 3-4 hours and 108-112 dB re 1µPa.

In early July seismic survey signals appeared at moderate to high levels at all sites and dominated sea noise at frequencies up to 300 Hz. Three seismic vessels were present. Seismic surveys signals up to 145 dB re 1µPa^2.s (SEL) were common. When averaged across the full recording period and including seismic signals, time averaged ambient sea noise increased to 113 - 115 dB re 1µPa (SPL) with most energy in the band 5 -100 Hz, believed due to deep sound channel ducted seismic signal energy. The seismic signals displayed clear examples of sound transmission phenomena. Seismic signals of < 0.5 s length at the source sometimes appeared as 10 s long signals at modest to long range, displaying strong modal structure with dispersion. Long range transmission of seismic signals highlighted seabed slope as an important factor in determining coupling of energy into the deep sound channel. Only short range seismic signals at < 58 km had energy above that ducted in the deep sound channel (~ > 100 Hz). From July onwards the proportion of time seismic signals were present in the recording period sat around 20-30% of the total recording time, although this reached 30-50% of the total time for protracted periods.

Calling from fin whales was common. The signals comprised sets of pulses over the frequency band 19-40 Hz (3 dB down points) with a mean spectral peak at 21.5 ± 0.30 Hz (± 95%), averaging 2.25 ± 0.007 s length (± 95%), spaced 14.74 ± 0.206 s apart with on occasion higher frequency 30-80 Hz pulses following the lower frequency pulses. High signal to noise ratio (SNR) 'pulses' comprised a single tone burst. Lower SNR signals had multipath distortion and appeared as a series of overlapping tone bursts, most likely multipath arrivals. The higher SNR fin whale signals always swept downwards in frequency with increasing time, although this was not consistent for lower SNR signals. There was no easily identifiable constant sized 'packet' of pulses (or number of pulses repeated), implying there was no defined packet size for the pulses. Pulses were typically produced in groups of from one to nine, although individual animals could produce more on occasion and had variable time spacing's before repeating another set of pulses. There was a slight indication of greater calling overnight time periods and after sunrise and before sunset but these trends were not significant. Fin whales were present across the full recoding period (including times of seismic surveys) at all sites but were highest at SW Porcupine Bank and East Porcupine and increased in call rates from mid-July. Average numbers of calling fin whales at any point in time was 0.333, 0.602 and 0.103 at North, SW Porcupine Bank and East Porcupine respectively. The calculated number of calling individuals gave the maximum number of calling fin whales as three at each site and the median 1-2. The listening range for fin whales was calculated under various combinations of source level and ambient noise. Listening ranges and areas were highly variable depending on the bathymetry path taken from the receiver location (i.e. heading about receiver), the animal source level and the ambient noise regime. The calculated detection range along different headings and associated listening area using low ambient noise for North, SW Porcupine Bank and East Porcupine respectively were: 60-148 km for 23,200 km^2; 59-90 km for 16,800 km^2; and 53-186 km for 40,600 km^2. Changing ambient noise levels had relatively constant impacts on listening area at North and East Porcupine with the change in listening area roughly linearly proportional to the increase in ambient noise in dB. At SW Porcupine Bank listening area increased dramatically as ambient levels fell below 95 dB re 1µPa, due to the increase in available listening area from deep water to the west.

Blue whale calls were only detected at SW Porcupine Bank in comparatively low numbers (compared to fin whale calls). Detections of blue whales increased across the sampling period, from the first single detection in June to the greatest number of animals detected in August and September 2014. The maximum number of animals calling detected was two and the median one. The detection range of blue whale calls was similar to fin whales with the same trends.

Dolphin whistles and a large number of toothed whale echolocation clicks (1.4 million) were found in the data sets. Clicks were differentiated into groups of: sperm whales, dolphin whistling; dolphin whistling plus low frequency echolocation clicks; tentative beaked whales and unknown high frequency echolocation clicks. While sperm whales were detected at all sites, their presence decreased at North Porcupine through May, then was consistently less than half the presence compared with SW Porcupine Bank and East Porcupine. At SW Porcupine Bank and East Porcupine sperm whale presence increased through mid-July to September with an oscillating tendency. A median sperm whale calling bout lasted 1.7 hours with bouts separated by a median period of no calling of 12 hours. Many bouts of sperm whale calling also had correlating dolphin whistling, at North Porcupine 17% of samples with sperm whales also had dolphins present, this 32% at SW Porcupine Bank and 52% at East Porcupine. This suggested dolphins often followed sperm whales. Tentative beaked whale clicks were rarely present and sporadic at North Porcupine but were common at SW Porcupine Bank (< 20% of time overall) with an increasing occurrence up to 40-60% of the time post late July. There appeared to be a 3-10 day periodicity in tentative beaked whale click presence at SW Porcupine Bank and East Porcupine. There was a general trend for an increase of sperm whale, beaked whale, smaller toothed whale and HF clicks post late July at SW Porcupine Bank and East Porcupine. All toothed whale categories had oscillating trends in presence, with periodicity in the 3-15 day period.

No minke, humpback or sei whales vocalisations were detected during the study. The period sampled was not when humpback whales were expected in the area so the lack of humpback detections was as expected.

The sea noise data sets have an enormous amount of information inherent in them with the analysis presented here a fraction of what is present and what can be extracted.

Acknowledgments

The field work was supported by the Irish Marine Institute and the crew of the RV Celtic Voyager and Celtic Explorer, RPS Metocean staff, Galway-Mayo Institute of Technology (GMIT) researchers and members of the Irish Whale and Dolphin Group. Mal Perry and Dave Minchin at Curtin University were instrumental in preparing and calibrating all sea logger hardware. Thanks to Aodhan Fitzgerald at the Marine Institute for the design and fabrication of the sea logger moorings. Thanks to Luke Smith and Gareth Parry from Woodside Energy Ltd. for their support and input into the study. This research was jointly support by the Joint Venture (JV) partners in Frontier Exploration Licenses (FELs) 5/14, 3/14 and 4/14; Woodside Energy (Ireland) Pty Ltd, Azeire Petroleum and Petrel Resources. The September 2014 recovery cruise was run as the sixth Cetaceans on the Frontier Cruise (COTF) to train marine science students in seagoing marine research. The ship-time for this integrated recovery cruise was part funded under the Irish National Development Plan Marine research Sub-Programme through the Marine Institute.

It is also of note that the JV partners supported Birdwatch Ireland research staff sailing on both the deployment and recovery cruises. On Monday 19-May-2014 observers Niall T. Keogh, Ryan Wilson-Parr, Simon Berrow & Rossa Meade sighted the first ever Bermuda Petrel (aka Cahow) off west Ireland. The Bermuda Petrel is one of the rarest birds in the world and has been the subject of an intensive conservation program which has seen it go from a low of 18 breeding pairs to 105 breeding pairs as of last year.

Thanks also to SeaBird Exploration and Geopartners for providing the navigation and source signature data for their 2014 south Porcupine Basin seismic survey.

While various parties have contributed to the formulation of this document, for which the author is highly appreciative, the author takes sole responsibility for any errors herein plus the views and opinions expressed in this document may not necessarily reflect those of the partners.

Table of Key Findings

A table of the key project findings, cross referenced to the appropriate chapter, is given in Table 1, followed by a summary table of findings by monitoring site (Table 2).

Table 1: Project key findings and text reference.

Category	Key findings	Document reference
Ambient noise	Ambient noise levels recorded were dominated by: wind noise; vessel traffic; seismic survey signals; and by calling whales. When seismic survey signals were not present, broadband sea noise levels across the band 7-2828 Hz (between 8 and 2500 centre frequency 1/3 octave band limits) fell between 74-141 dB re 1µPa. Mean and median noise levels displayed relatively normal distributions between 107-109 dB re 1µPa. The highest recorded ambient noise during period of non-seismic activity were due to either nearby vessels or whale calling.	3.1
Seismic surveys	At least three sets of simultaneous seismic survey signals were recorded. Seismic signals were present at south western Porcupine Bank ('SW Porcupine Bank') early in the sampling period (25-27 May and > 20-Jun) while absent at eastern Porcupine Bank ('east Porcupine') and northern Porcupine Basin ('north Porcupine') sites over this time frame. From ~ 03-Jul to 15-Sep exploration seismic signals dominated the low frequency sea noise (< 1 kHz) at the east and north Porcupine Basin sites but were of lower level at the SW Porcupine Bank. From 16-Aug to 14-Sep seismic surveys appeared close to the east and north Porcupine sites with another distant survey also recorded.	3.2
Vessel noise	The passage of ships was evident at all sites, particularly at east Porcupine which had the highest number of ships/day at the highest received levels. Background tones produced by passing and distant ships were recorded at all sites, particularly over May to June when seismic survey signals were lowest. The tones were evident over approximately 20-100 Hz, occasionally reaching up to 1 kHz when a ship passed nearby. The passage of nearby individual ships involved a rise in noise level over 4-6 hour periods with ship frequencies normally < 1 kHz but on occasion slightly higher in frequency.	3.3
Fin whale	Fin whale calls where recorded throughout the survey with calling becoming increasingly dominant later in the recording period, notably at the receivers to the west (SW Porcupine Bank site). The energy of many distant fin whales arriving via deep sound channel ducting increased toward the latter part of the recording period such that the frequency band over the range 18-26 Hz was dominated by fin whale energy.	4.1
Blue whale	Blue whales were only present at the far western site (SW Porcupine Bank) in this study, with the vast majority (96%) recorded in August and September. These whales were likely to be on their migration southwards. The number of blue whales detected was relatively low compared to other species such as fin whales, with only 27 individuals recorded over the study period, indicating either low populations numbers, low percentage of singers or the peak migration occurred after the loggers were retrieved.	4.2
Sperm whale	Sperm whale clicks were detected at all monitoring sites, particularly at the SW Porcupine Bank site. Patterns in the sperm whale presence across the study area revealed: • A decrease in sperm whale presence at the north Porcupine through the month of May, with less than half the presence at the north Porcupine compared with SW Porcupine Bank or east Porcupine sites. Sperm whale presence at the north Porcupine was consistently low post May; • An increase in sperm whale presence at the SW Porcupine Bank and east Porcupine was observed through mid-July to September; • An oscillating tendency for sperm whale presence at all sites on a 15-40 day periodicity, roughly coupled to the moon phase; and A large spike in sperm whale presence from mid-July to mid- August at SW	4.4

	Porcupine Bank, with similar trends at east Porcupine.	
Beaked whales	• Echolocation clicks tentatively identified as produced by Beaked whale were located in 1% of samples at north Porcupine and 12-13% of samples at SW Porcupine Bank and the east Porcupine, with number increasing later in the sampling period at SW Porcupine Bank and East Porcupine but not at North Porcupine.	4.5

Table 2: Summary of findings for each monitoring site.

Location	**Fin Whales**	**Blue Whales**	**Dolphins**	**Sperm Whales**	**Beak Whales** ***(Tentative)***	**Minke, Humpback and Sei whales**
Northern Porcupine Basin	Moderate – with two small peaks during study	No recorded vocalisations	Low – higher in Aug/ Sept	Low – periodicity in abundance	Low – intermittent during deployment	No signals detected
East Porcupine Basin	Low – no seasonality	No recorded vocalisations	High – higher in Aug/ Sept	Moderate – periodicity in abundance	Moderate – some increase in Aug/ Sept	No signals detected
Southwest Porcupine Bank	High – major increase during Aug/ Sept	High – more in Aug/ Sept	High – higher in Aug/ Sept	High – periodicity in abundance	Moderate – some increase in Aug/Sept	No signals detected

Contents

1. Introduction

In May-2014 RPS Metocean in conjunction with the Irish Marine Institute (MI) and the Galway-Mayo Institute of technology (GMIT), deployed six sea noise loggers supplied by the Centre for Marine Science and Technology (CMST) on three moorings west of Ireland. The loggers were deployed off the MI's Research Vessel, *Celtic Voyager.*

The program was sponsored by the Joint Venture (JV) participants in Frontier Exploration Licenses (FELs) 5/14, 3/14 and 4/14; Woodside Energy (Ireland) Pty Ltd, Azeire Petroleum and Petrel Resources, with the aim of:

- quantifying the presence of vocalising whales and dolphins (where possible);
- quantifying vessel visitation throughout the area;
- describing the local ambient noise regime; and
- describing any other major biological sources detected.

Moorings were deployed as shown in Figure 1 at the sites listed in Table 3, with sites labelled from north to south, northern Porcupine Basin ('North Porcupine'), south west Porcupine Bank ('SW Porcupine bank') and eastern Porcupine Basin ('East Porcupine'). Locations were chosen to represent waters likely to have high levels of biological activity, due to either the presence of canyon systems (i.e. SW Porcupine Bank) or situated along ridges with steep bathymetry. Noise loggers were set relatively deep in the water column but not on the seabed. They were deliberately sited within Special Areas of Conservation (SACs), away from discrete protected features, to reduce the risk of fouling by trawling activity. Their mid-water position also optimised their placement for the detection of toothed and baleen whale signals (near their foraging depths or deep sound channel respectively).

Table 3 Location and depth of the mooring locations.

Site	Water Depth	Location	
East Porcupine Basin	538m	51° 22.904' N	11° 37.446' W
North Porcupine Basin	596m	52° 22.775' N	52° 22.775' N
SW Porcupine Bank	767m	51° 52.660' N	15° 01.344' W

The moorings were recovered by RPS Metocean, GMIT and MI from the RV *Celtic Explorer* in September 2014. All six sea noise loggers functioned as planned. Each deployed mooring had a noise logger specialised for Low Frequencies (LF, 1 Hz to 3 kHz useable range) and High Frequencies (HF, 1 kHz to 96 kHz). Noise loggers sampled between 18-19 May-2014 to 19-20 Sep-2014 (slightly different start / end dates as they were deployed / recovered).

All species of cetaceans vocalise to some degree. These vocalisations can be detected by sea noise recorders either fixed or towed and are used to infer whale presence, behaviour and relative abundance. In some cases vocalisation patterns can allow estimates of absolute abundance. Fixed sea noise loggers (used in this study) are particularly powerful at elucidating habits, long term trends and rhythms in marine fauna presence, given their high relatively high duty cycle and long sampling duration.

Baleen whales emit powerful vocalisations or 'songs' commonly produced by mature males which are believed to be part of breeding displays (Payne, 1971). Assuming males produce these breeding songs (McDonald et al., 2001, Croll et al. 2002), the songs will only be produced by a fraction of the whale population. Typically the fraction of male singers is less than ~ 30% of the total whales in the population (or the proportion of breeding males in the population). In practice, the proportion of whales singing will be less as mature males must breathe and feed, only sing whilst on the breeding grounds and then at variable rates. As a result the non-detection of vocalising baleen whales or song detection does not mean whales' are not present in an area. Given the number of idiosyncrasies involved with song structure variability and the differences between the propensities for different individuals to sing, direct measures of call rates per unit time are not necessarily an immediate reflection of whale abundance.

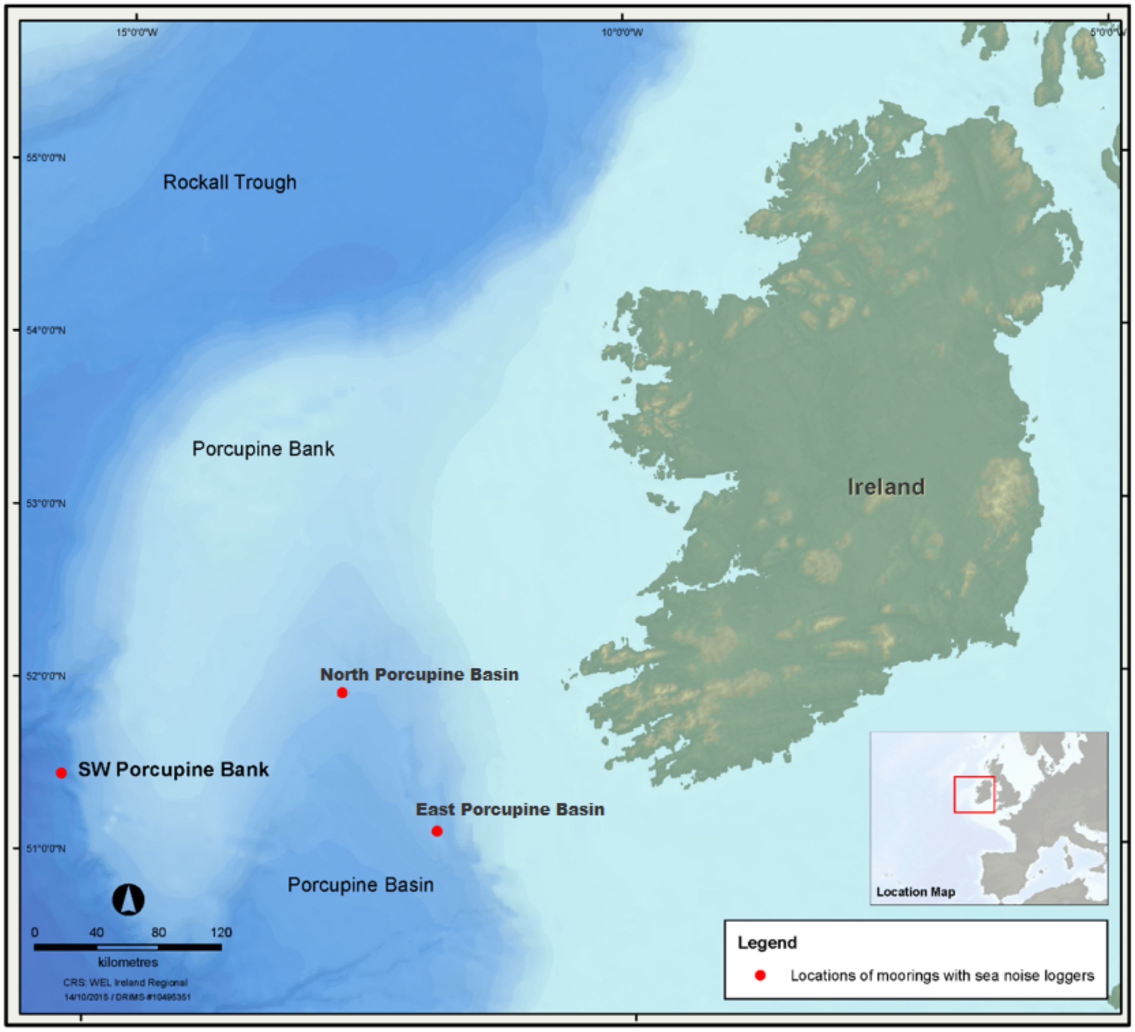

Figure 1: Sea noise logger mooring locations. Each mooring was assigned an identification number as followed: north Porcupine 3301 (LF and 3303 (HF); SW Porcupine Bank - 3302 (LF) and 3304 (HF); east Porcupine 3307 (LF) and 3305 (HF).

There is much we do not know about the singing behaviour of baleen and toothed whales. In addition, for some baleen whales species, it is not known if females also sing and without dedicated studies this cannot be assumed. There are many signals in the world's oceans most likely produced by baleen whales, which cannot yet be attributed to a particular species. The baleen whale song types are typically designed to travel long distances in the open ocean, retaining a recognisable structure for tens and perhaps hundreds of km. When produced in the open ocean, energy from baleen whales trapped in the deep sound channel can travel ocean-scale distances. The deep sound channel is a duct created by the vertical sound speed temperature minimum at near 1000 m depth where a certain band of frequencies become 'trapped' by refraction ('bending' towards the minimum sound speed) and so do not interact with the seabed or sea surface. For low frequencies (say < 200 Hz) absorption loss due to interaction of the sound wave and sea water is negligible. The lack of sea-surface or sea-bed interaction with the travelling sound wave and the negligible absorption loss leads to only 2 dimensional spreading loss and so allows long range energy transmission of baleen whale calls. But, at long ranges in the open ocean (hundreds of km or greater) the baleen whale signals have degraded and are typically not recognisable as individual whale calls, but instead act to increase the noise level in the call frequency band. Thus while it is true that baleen whale signals can travel ocean scale distances they are no recognisable as coherent signals beyond a few hundred km from the source. Ocean scale transmission in the deep sound channel is limited to a frequency band between 5-100 Hz hence is only available to baleen whales with their powerful, low frequency signals. In addition to the more commonly known songs produced by baleen whales, they often produce other sound types used in socialisation contexts (Dunlop et al. 2007). For most species these socialisation signals are less well known and are usually recorded at lower source levels than the 'song' signals, thus tend not to travel as far. Only the more powerful 'song' type signals are analysed here.

As opposed to the baleen whales, toothed whales routinely vocalise, using either echolocation for foraging aids or in a social context. Echolocation signals are a form of active acoustics where the whale images a target using sound. The echolocation clicks are short (milliseconds to tens of milliseconds in length) and wide band (spanning a wide frequency range), generally at higher frequencies (2-100 kHz). The signals are short so the animal can identify the reflection. If the signals were longer in length the reflection would arrive during the outgoing signal and would not be discernible. The signals are at higher frequencies to gain resolution of the target. As frequency increases so does its absorption loss, or energy dissipation due to molecular scale interaction of the sound wave, the water and dissolved salts. This loss becomes substantial above a few kHz, resulting in even the highest level echolocation clicks produced by smaller toothed whales not travelling further than a few km at best (tens km in the sperm whale case). Toothed whale echolocation clicks vary enormously according to what function the animal is using them for, and may be greatly distorted by sound transmission phenomena. The socialisation signals of toothed whales are varied, but dominated by whistles of various sorts. Socialisation whistles tend to be greater than a few kHz in frequency content and at comparatively low source levels, thus do not travel more than a few km also. Like echolocation clicks, the toothed whale whistle structure may be extremely variable amongst individuals of the same species, and amongst different species, making discerning species by whistle structure difficult. While individuals of both sexes of toothed whales will vocalise consistently, their signals are generally only heard within several kilometres and may not be easily distinguishable to a species level.

Two studies previously carried out on the acoustic presence of whales in Irish waters are discussed. Charif and Clark (2009) analysed whale detection data across 1996-2005 using underwater acoustic arrays set up during the cold war to track submarines in the north eastern Atlantic (SOSUS system) across a large area which partly sampled the study region here (which is approximately 50^{o}-53^{o} N and 10^{o}-16^{o} W). The SOSUS system data was classified but Charif and Clark (2009) were able to access raw signals of whales and bearings from receiver arrays' to whales. Using this data the songs of fin, blue and humpback whales were detected and tracked, with relative abundance of song detected in that order. In the defined study area here (Charif and Clark's areas D2 and E2), the fin whale songs were present year round, with lowest numbers during April to June, numbers increasing during July to September and reaching a plateau at a high level over September to February of the following year. In this study region blue whale detections reported by Charif and Clark (2009) were rare during May and June, increased in number through July to November and peaked over the November-December period. Humpback whales detected in the study region by Charif and Clark (2009) were rarely observed over the May to September sampling period of this study. Humpback whale songs detected by Charif and Clark (2009) were predominant in the region over January to March with the majority of the calls in the northern section. Given the results of Charif and Clark (2009), this study should have detected blue and fin whales, with detection rates increasing in the latter period of sampling and would have had a low probability of detecting humpback whales as the sampling carried out here was outside of the time humpbacks were historically detected in the area. This is what transpired.

Anon (2011) carried out visual and acoustic surveys using a towed array in the Rockall Trench during September to October 2011 and again in March 2011, determining the presence of whales. Their study region focussed along the western slope of the deep continental shelf west of Ireland, along the 1000 m depth contour as depicted in Figure 1. The southern end of the survey overlapped with the SW Porcupine Bank site. Sperm whales, bottlenose and common dolphins were the only cetaceans visually sighted in the study area sampled here. Only sperm whales were detected acoustically in the study region sampled here, with a few beaked whale detections along the ridge well north of the SW Porcupine Bank site.

A major part of this report has been focussed on defining whale calls and patterns in these calls, for various species detected. This information has been used to give an indication of the presence of whales in the study region in 2014 and the time and space patterns observed. In order to make this data more accessible, many of the technical aspects underlying the analysis have been moved to appendixes in the latter half of the report. This has invariably led to a small amount of duplication and discontinuity in the order of the presentation of results, in order to present the 'summary' data up front. The main report body focuses on the biological findings of the study. The technical aspects of: methods; detailed analysis for each species group; the ambient noise regime; vessel presence; and seismic survey signals measured are presented in the appendixes.

2. Summary Methods

Six sea noise loggers were set on three moorings between 18-20 May-2014 to 19-20 Sep-2014 west of Ireland (see Figure 1). Each mooring had two noise recorders, one designed to collect fully calibrated sea noise from 2 Hz to 3 kHz (termed Low Frequency or LF, 6 kHz sample rate, 369 s samples every 15 minutes) and one focussing on higher frequency sea noise from 1 kHz to 98 kHz (termed High Frequency or HF, 196 kHz sample rate, 400-500 s samples every 90 minutes). Details of how and where moorings were deployed, instrument depths, the time instruments were in the water and hardware used, are listed in Appendix 4. The project was designed to capture signals produced by the great whales (including baleen and sperm whales) and toothed whales, with the frequency range of species of interest listed in Table 4.

Recovered data were given arbitrary numbers which tied to the CMST meta-data system (the set numbers were listed in the caption of Figure 1 and are referred to throughout this report). All sea noise loggers worked, although: 1) there were instances of mooring noise making analysis more difficult; 2) the HF loggers (a common commercial make) were not capable of being calibrated directly below ~ 200 Hz although they were able to be checked against the LF noise logger measures in-situ; 3) one of the LF loggers suffered a temporary loss of sensitivity due to a faulty underwater connector; and 4) seismic signals made searching for whale signals difficult in the latter sampling period. None of these issues compromised the ability to analyse data for the project aims, although they added complexity to the analysis.

Various search routines were utilised during analysis to locate: air gun signals; fin whale downsweeps; blue whale signals; dolphin whistles; sperm whale clicks; beaked whale clicks; and other toothed whale echolocation clicks. These search algorithms returned time stamps of 'hits'. For fin whale and blue whales, where the dominant frequency of their calls overlapped seismic survey signals, the search algorithm outputs were manually corrected to remove false or missed detections, primarily due to the algorithm mistakenly triggering on air gun signals. As a result all fin and blue whale call detections were manually checked to ensure the detections were correct. The toothed whale echolocation clicks and whistles were not fully broken down into species groups, as this would require considerably more analysis time. Instead, the toothed whales have been broken down into groups of: sperm whales; smaller toothed whales (dolphins and possibly killer whales based on whistles and echolocation clicks up to 30 kHz); and beaked whales. A summary of the manual checking of recordings is presented in Table 18, Appendix 9. Various metrics have been used to describe presence or relative abundance of a whale species as derived from the acoustic counts. Measures of samples with call presence per 24 hours, calls per unit time or units derived from the number of instantaneously calling individual whales have been used.

For periods of seismic survey operations, all air gun signals detected by the LF noise loggers which had the air gun array source location and time of signal generation supplied by the contractors (one of three seismic programs), could be ascribed to a specific source / receiver location and fire / receive time. For these signals an accurate source location, receiver range and orientation of receiver to array tow direction were available for the suite of parameters measured describing the signal character.

All analysis has been carried out using in-house software programs designed at Curtin University and tailored for idiosyncrasies and inherent complexities in the data sets.

Table 4: The acoustic frequency range for various species encountered during this study.

Analytical group	Species included in each group	Acoustic signature range
Baleen Whales	Fin Whales	18-80 Hz
	Blue Whales	10-100 Hz
Toothed Whales	Sperm Whales	1-20 kHz
Beaked Whales	Sowerby's beaked whale	30-96 kHz
	Cuviers beaked whale	
	Gervais beaked whale (vagrant)	
	Harbour porpoise (shelf)	
	Northern bottlenose whale	
	True's beaked whale (vagrant)	
Dolphins	Atlantic white-sided dolphin	1.5-20 Hz
	Bottlenose dolphin	
	White-beaked dolphin	
	Risso's dolphin (shelf)	
	Short-beaked common dolphin	
	Striped dolphin	
	White-beaked dolphin	

3. Ambient and Anthropogenic Noise Results

3.1. Ambient Noise

Natural noise levels in the ocean are termed ambient noise and are produced by physical factors such as wind, ice or a myriad of natural physical process. There are base levels of noise in the world's oceans produced by thermal noise, natural ocean noise levels cannot go below these limits. The ocean transmits sound better than in air and in some instances, such as the deep sound channel, which can trap energy within narrow frequency bands, allows sound transmission across ocean scale distances. This large scale transmission of sound energy in the ocean also means that the listening area for noise from natural or non-natural sources is larger than in air, which has the effect of increasing natural noise levels, dramatically in some instances. In some cases, increases in wind or biological noise routinely cause 10-30 dB fluctuations in the background noise levels. While the deep oceans are coupled to the deep sound channel and so have relatively high natural noise levels across the frequency band ~ 5-100 Hz, shallower water such as on the worlds continental shelves are not coupled to the deep sound channel so have lower noise levels across this band, again dramatically (i.e. 30 dB, McCauley et al. 2015). The point needs to be made that one cannot translate trends of ocean noise in the worlds deep oceans to waters on the continental shelves as they are decoupled, especially in the low frequencies (~ < 200 Hz).

Ambient noise levels recorded here were dominated by: wind noise; vessel traffic; seismic survey signals; and in specific frequency bands, by calling whales. When seismic survey signals were not present, time averaged (a sample, or ~ 370 s) broadband sea noise levels across the band 7 to 2,828 Hz (between 8 and 2500 centre frequency 1/3 octave band limits) fell between 74-141 dB re 1µPa (minimum and maximum levels encountered) with mean and median levels at around 107-109 dB re 1µPa and relatively normal distributions of levels. The periods of highest ambient noise, in periods of no seismic activity, were due to nearby vessels or whale calling. All sites were in the deep ocean, therefore coupled to the deep sound channel. The deep sound channel played a significant role in the transmission of air gun signals. Vessel tones transmitted in the deep sound channel were consistent at all sites in the frequency band 5-100 Hz. These tones were not able to be attributed to specific vessels. Averaged ambient noise levels for each month have been plotted in Appendix 8, Figure 32 and tabulated in Table 16 and Table 17.

3.2. Seismic Survey Signal

Three seismic surveys' were run during the deployment and were dominant in the sea noise records from early July to the end of the recording period in September although they were present across the full recording period at lower levels. Seismic surveys use intense impulse signals to image below the ocean seafloor, with signals repeated every 10-15 s while a vessel steams along a long transect. The signals produced at the source are short, perhaps tens of milliseconds long and intense, of the order of 100 dB above ambient levels. Seismic signals have most energy at low frequencies, over the band 5-150 Hz, with little energy above 1 kHz transmitting beyond one km. Signals were ducted in the deep sound channel so were audible and distinct, albeit at lower levels, at long ranges out to ~ 340 km. During periods of sustained air gun operations levels of individual air gun pulses were received consistently at 90-135 dB re 1µPa^2.s (Sound Exposure Level or SEL) at the North, SW Porcupine Bank and East Porcupine sites although during periods of nearby operations levels were consistently around 138-142 dB re 1µPa^2.s SEL (i.e. mid-June at East Porcupine or mid-August to mid-September at North Porcupine). Many of the long range seismic signals (> 50 km) showed strong levels of distortion due to sound transmission phenomena. For example signals recorded at North Porcupine had '*stretched*' in length via dispersion of slightly different frequencies transmitted in the dominant modes, from likely several tens of ms long at the source to up to 8 s long (time for 90% energy to pass) at 255-310 km. During periods of seismic survey activity, air gun signals were typically present for 20-30% of the time in most samples but this increased to 30-

35% of the time when multiple seismic sources where present or when strong signal '*stretching*' occurred.

Detailed navigation data was supplied for several of the seismic surveys. Seismic signals along several lines were analysed for received signal level parameters from the North and East Porcupine sites. It was not possible to analyse all signals as: 1) the seismic signal level was close to the background noise level around 340 km so a signal was not easily differentiated from the noise when it was at this range or further; or 2) the presence of multiple air gun signals overlapping made it impossible to discriminate levels or determine which survey a signal was from.

Signals were analysed from one survey at 58-340 km from North East Porcupine. Large increases in received seismic signal noise level were seen for the source when it was beam on to the receiver relative to when the receiver was forwards or aft of the array tow direction. Although air gun arrays are configured to focus sound energy downwards the greatest sound levels in the horizontal plane area typically measured abeam of the array.

Transmission of the air gun signals was influenced by the bathymetry between source and receiver. Signals which were along relatively flat bathymetry paths between source and receiver travelled well. If the bathymetry at the source sloped downwards towards the receiver then transmission was good to the receiver (low transmission loss) while if the bathymetry at the source sloped upwards towards the receiver then transmission was poor (high transmission loss). At comparative ranges the seabed slope at the source made up to a 10 dB difference in received level at several hundred km, when comparing worst cases of downward vs. upward seabed slopes towards the receiver. The reason for this difference was believed to be coupling of the shallow source into the deep sound channel. For a shallow source in the deep ocean only a small fraction of the direct path energy produced will enter the deep sound channel duct at shallow enough angles (close to horizontal) to be trapped within the duct. Energy at steeper angles is lost in surface-bottom bounces and does not travel far horizontally. If a reflective seabed which slopes downward towards the receiver is present then a large fraction of reflected energy from the first seabed bounce is available to be trapped within the sound channel duct, increasing the signal energy transmitted within the duct. The effect can be pronounced for an air gun vessel operating in continental shelf slope waters and was clearly evident here.

3.3. Vessel Noise

Noise is produced by vessels primarily from cavitation bubbles produced on propellers, or by machinery noise transmitted through the ships' hull. In the deep ocean the noise produced by vessels can be roughly differentiated into two types: 1) traffic noise, which is the contribution of many distant ships via energy ducted in the deep sound channel and which is not easily attributed to a specific ship; or 2) the nearby noise of a passing ship, where a distinct vessel signature is recognisable with the level increasing then decreasing as the ship passes by. For receivers on the continental shelf (within the 200 m depth contour) traffic noise is lost and only the noise signatures produced by passing ships is present. At the sites sampled here in the deep ocean, both types of vessel noise were present.

At all sites there were always tonal signals produced by ships' machinery present in the frequency band which transmits in the deep sound channel duct, 5-100 Hz plus tonal signals at distinct frequencies, up to 1 kHz on occasions. These tonal signals could be up to 10 dB above the background ambient noise. They were consistent across recordings, although not at constant frequencies. The signals in the frequency band 5-100 Hz were considered a part of the 'traffic noise', while the higher frequency tones were often associated with recognisable ship passage. It is not possible to establish the direct contribution of energy produced by ship noise signals to the deep sound channel ducted energy as there is no North Atlantic reference location which is coupled to the deep sound channel and free of ships.

The time taken for recognisable nearby ships to pass and the maximum levels reached as they passed was quantified for periods without seismic signals present. North Porcupine had 1.6 ships/day pass, SW Porcupine Bank 1.1 ships/day and East Porcupine the most at 1.8 ships/day. Ships were present for 27%, 31% and 36% of the time at North Porcupine, SW Porcupine Bank and East Porcupine respectively. The median time for a ship to pass was highest at East Porcupine (4.2 hours, mean 4.9 ± 0.68, ± 95% confidence limits), lowest at SW Porcupine Bank (median 3.0 hours, mean 4.0 ± 1.00) and 3.1 hours at North Porcupine (mean 4.17 ± 0.84). Using data from all sites the mean time a passing ship was clearly evident was 4.5 ± 0.47 hours (median 3.6 hours). The maximum level reached during ship passage was highest at East Porcupine at 112 dB re 1µPa and lowest at North and SW Porcupine Bank (107-108 dB re 1µPa). The East Porcupine site had the highest numbers and levels of ship passage, indicating it was perhaps closer to a shipping lane than the other sites.

4. Cetacean Acoustic Signals

A number of whale signal types were identified including signals from: fin whales; blue whales; sperm whales; beaked whales; dolphin whistles; and toothed whale echolocation clicks which could not be attributed to a species. Attempts were made to separate out the 1.4 million toothed whale echolocation clicks detected into species groups. The sperm whale clicks were relatively easy to separate out, whereas deciding if a high frequency echolocation click was from a beaked whale was less clear. These clicks have been pulled out here and termed as '*tentative beaked whale*' clicks.

Signals were not detected from humpback, minke or sei whales. The period sampled was not when humpback whales were expected in the area (Charif and Clark, 2009) so the lack of detections was as expected.

Whale signals for each species groups have been presented in separate sections below.

4.1. Fin Whales

4.1.1. Background

Fin whales are a baleen whale (Family Balaenopteridae) and are the second largest baleen species, ranging from 17.5 to 20.5 m long (Reid, et al. 2003). Fin whales have a dorsal fin situated two-thirds of the way along the back and commonly display a distinctive rostrum in front of the blowhole and a single central ridge along a v-shaped head (Reid, et al. 2003; Wall, et al. 2013). Often used as an identifying feature, the fin whale also presents an asymmetric patch of white around the mouth, which begins on the right side of the lower lip, extending into the mouth cavity and covering the front baleen plates (Reid, et al. 2003; Wall, et al. 2013). Fin whales can be seen breaching occasionally, producing a blow up to 6 m tall, which is often columnar in shape (Reid, et al. 2003; Wall, et al. 2013).

4.1.1.1. Behaviour and Vocalisations

The low frequency 'calls' produced by male fin whales have been recorded as downward sweeps in frequency between 15-30 Hz repeated every 7-26 s (Watkins et al. 1987). Despite being such a low frequency these vocalizations can reach an intensity of between 184-186 dB re 1µPa (rms), (Watkins et al. 1987). Research undertaken in the Gulf of California in Mexico has revealed that only the male produces vocalisations and sounds can mostly be attributed to male mating displays used to attract females from large distances (Charif et al., 2002; Croll et al. 2002; Watkins et al. 1987).

4.1.1.2. Global Distribution

The fin whale is distributed globally, but is found mainly in higher latitude temperate and polar waters and is often sighted in areas of high topographic gradient where zooplankton aggregations may occur (Reid, et al. 2003). Although north Atlantic migration routes are not currently clear, the fin whale is believed to breed and calve in warmer waters in the winter and migrate to polar regions during the summer months to feed. However, some populations of fin whales are known to remain in polar regions throughout the year (Jefferson et al., 2008; Reid, et al. 2003). The North Atlantic, Mediterranean, Pacific and Southern Oceans have been recognised by Shirihai and Jarret, (2006) to be home to separate populations of the fin whale.

4.1.1.3. Regional Irish Distribution

Fin whales are rarely sighted in Irish waters during winter and early spring, however there appears to be several individuals that remain foraging in the inshore waters off the southeast coast of Ireland (IWDG, 2013). Current knowledge indicates fin whale abundance increases on the Irish Shelf and Rockall Trough in summer and the highest numbers in the region are recorded off the south coast and the northwest shelf slopes in late summer and autumn.

Analysis of a long-term offshore SOSUS acoustic array suggests fin whales migrate southward through the Rockall Trough to the south-western North Atlantic in March and April and return northwards in July and August (Clark and Gagnon 2002, Charif and Clark 2009). Currently there is no evidence of fin whales using Irish waters to calve, which is believed to occur at lower latitudes. Fin whales within the Rockall Trough are thought to be primarily migrating, however opportunistic foraging along the shelf slopes has been observed (Wall et al. 2009).

4.1.2. Fin Whale Detection Methods

Fin whales were searched for by running an algorithm across each sea noise sample which:

1. checked that the sample was a real signal and was not dominated by a noise spike, if so rejecting this sample;
2. downsampling the waveform to 500 Hz sample rate;
3. bandpass filtering the signal (15-45 Hz);
4. calibrating the signal in the time domain;
5. normalising the signal to the range -1 to 1;
6. cross correlating the sample with a high level, similarly normalised fin whale pulse;
7. finding cross correlations > a threshold value (hit-1);
8. rejecting the next 'hit' if it was < 2 s after a previous one;
9. checking noise from the 'hit' (calibrated rms) with noise before the 'hit' and accepting the hit if it was > 5 dB above the noise level;
10. checking noise from the 'hit' (from spectrogram) and comparing it with noise from immediately above and below the 'hit' and accepting if > 5 dB above the noise; and
11. carrying out further checks to see if the sample was dominated by air gun signals (standard deviation of hit time < 2 s) and rejecting the entire sample if it was.

All algorithm detections were manually checked. The search algorithm output and the manual checking process gave time stamps for each fin whale signal > 5 dB above the ambient noise level.

The technique was good at locating fin whale calls but the enormous variety of air gun signal multipath arrivals made filtering air gun 'hits' extremely difficult. Since air gun signals dominated at least half of the recording period this made searching for fin whales difficult. The methodology to identify fin whale calls from air gun signals is fully outlined in Appendix 6.

4.1.3. Fin Whale Results

4.1.3.1. Fin Whale Listening Range

Estimation of the listening ranges for fin whales was made from each location (Figure 2). Details of the generics of how this was carried out are presented in Appendix 5. Given the ambient noise regime at the locations varied over the sampling period, an estimated listening area for fin whales at each site (Figure 2), was modelled for background noise levels; 90 dB re 1µPa and 96 dB re 1µPa. Listening range models assumed fin whale source level of 183 or 186 dB re 1µPa.

The calculated listening range for fin whales and areas are listed in Table 5 and Table 6 respectively. While the listening area for fin whales could be quite large, and was many tens of thousands of km^2 under low ambient noise regimes it was also highly variable depending on the bathymetry path taken from the receiver location (i.e. heading about receiver), the animal source level and the ambient noise regime. Features evident in these calculations were:

- The detection range for fin whale calls varied enormously around each site with heading, source level and ambient noise. For example at a background noise level of 96 dB re 1µPa in the fin whale bandwidth (approximately the average noise level measured) and a fin whale source level of 186 dB re 1µPa then the detection range at East, SW Porcupine Bank and North Porcupine depending on heading ranged from: 53-186 km; 59-90 km; or 60-148 km (respectively). Under these conditions the listening area at East, SW Porcupine Bank and North Porcupine was: 40.6 x 1000 km^2; 16.8 x 1000 km^2; and 23.2 x 1000 km^2 (respectively).
- Fin whale call transmission was worse when the source was in shallow water (i.e. inshore of East Porcupine);
- Fin whale call transmission was worse when the source was over a seabed sloping upwards towards the receiver (i.e. animal west of East Porcupine, animal west of SW, Porcupine);
- Fin whale call transmission was better when the seabed depth between source and receiver was comparatively uniform (i.e. to the south of East Porcupine);
- Fin whale call transmission was better when the seabed sloped downwards from the source towards the receiver (i.e. North Porcupine to SW, or East Porcupine to NE);
- For an ambient noise level of 96 dB re 1µPa the listening areas for fin whales overlapped between the North and East Porcupine sites but not for the SW Porcupine Bank site;
- At high ambient noise levels (110 dB re 1µPa) listening areas dropped to 1-2 x 1,000 km^2 (186 dB re 1µPa source level) at low ambient noise levels (86 dB re 1µPa) listening areas increased to 72, 85 & 46 x 1,000 km^2 (186 dB re 1µPa source level, East, SW Porcupine Bank and North Porcupine respectively) or up to 80 times difference (worst case, comparing 86 and 110 dB re 1µPa ambient noise at Porcupine);
- At low ambient noise levels SW Porcupine Bank had a much greater listening area than the other two sites while at high ambient noise levels East Porcupine had the greatest listening area;
- Ambient noise levels had relatively constant impacts on listening area at North and East Porcupine (that is the change in listening area was roughly linearly proportional to the increase in ambient noise in dB) but at SW Porcupine Bank listening area increased dramatically as ambient levels fell below 95 dB re 1µPa, due to the increase in available area in deep water to the west.

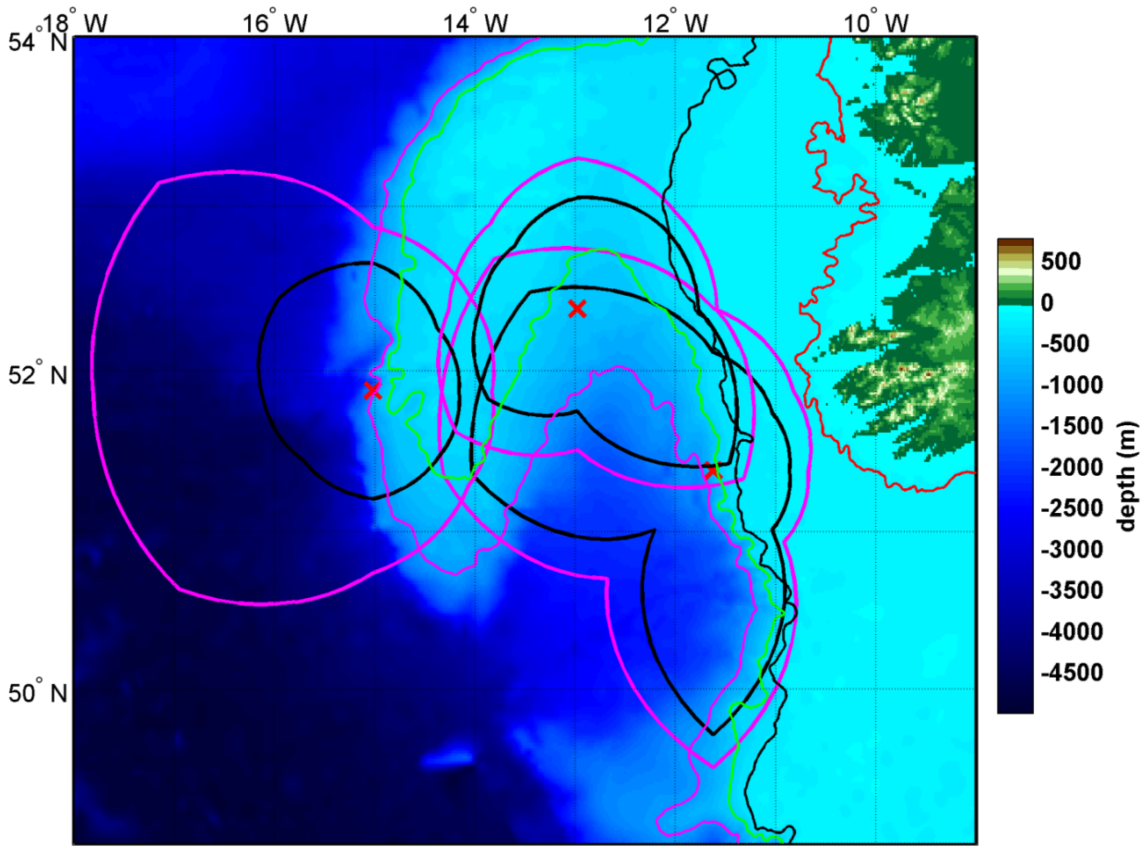

Figure 2: Estimated listening area for fin whales at each site for background noise levels of 90 dB re 1μPa (black curves) and 96 dB re 1μPa (magenta curves) and an assumed fin whale source level of 186 dB re 1μPa.

Table 5: Estimated detection range for fin whale signals (km) at each site for source levels 183 & 186 dB re 1μPa and two background noise levels (96 / 100 dB re 1μPa). E = East Porcupine, S = SW Porcupine Bank and N = North Porcupine.

Site	0°	45°	90°	135°	180°	225°	270°	315°
E. 183 dB	68.9/ 55.5	44.5/ 38.5	39.5/ 34.5	46.3/ 42.3	36.1/ 32.7	37.1/ 32.1	156.7/ 42.1	150.5/ 33.9
E. 186 dB	81.3/ 63.1	57.1/ 42.7	52.7/ 37.9	58.1/ 44.1	186.3/ 34.7	57.3/ 36.3	166.9/149.3	175.1/112.9
S. 183 dB	77.3/ 60.1	49.3/ 35.7	52.1/ 44.3	53.5/ 33.1	53.5/ 31.5	41.3/ 26.7	54.5/ 37.9	48.3/ 41.1
S. 186 dB	86.7/ 70.7	61.3/ 44.7	58.9/ 50.1	64.1/ 51.9	74.5/ 49.1	67.7/ 41.5	76.3/ 53.1	89.7/ 46.3
N. 183 dB	68.5/ 44.5	69.9/ 55.9	77.3/ 63.3	140.5/ 47.9	53.7/ 43.1	69.5/ 53.1	58.7/ 43.5	52.1/ 40.9
N. 186 dB	74.7/ 61.7	79.5/ 67.3	81.9/ 73.9	148.5/ 99.3	69.7/ 51.9	86.5/ 65.5	66.3/ 52.7	59.9/ 50.3

Table 6: Estimated detection areas (in units of 1000 km^2) for fin whale detections at the three sites with differing ambient noise regimes and call source levels.

Back (dB re 1μPa)	**East Porcupine (1000 km^2)**		**SW Porcupine Bank (1000 km^2)**		**North Porcupine (1000 km^2)**	
	183 dB SL	186 dB SL	183 dB SL	186 dB SL	183 dB SL	186 dB SL
85	67.2	75.8	77.0	89.2	41.2	49.5
90	51.5	60.0	32.6	64.4	29.0	35.3
95	25.8	43.3	11.3	18.9	20.4	24.6
96	22.2	40.6	9.2	16.8	18.5	23.2
100	4.9	17.2	4.9	8.3	7.7	13.9

4.1.3.2. Fin Whale Acoustic Detection Results and Discussion

Signals from fin whales were common in the data sets. The signals comprised sets of pulses mostly over 18-30 Hz although with on occasion higher frequency pulses over 30-80 Hz present following the lower frequency pulses. Examples of pulses are shown on Figure 3 with a single pulse waveform shown on Figure 4. High signal to noise ratio (SNR) 'pulses' comprised a single tone burst of around 1.5-2.5 s in length which dropped in frequency with time. Lower SNR signals had multipath distortion and often appeared as a series of overlapping tone bursts which were multipath arrivals. The higher SNR fin whale signals always swept downwards in frequency with increasing time, although for low signal to noise ratio calls where the signal degenerated into a series of multipath tone bursts, this shift in frequency became vague and the pulse could even appear to sweep upwards with time, as the slightly lower frequency components dropped out or dispersion altered the signal time structure for the different frequency components. The high SNR, higher frequency pulses (30-80 Hz) also always swept downwards in frequency with increasing time.

The search algorithm output and the manual checking process gave time stamps for each fin whale signal > 5 dB above the ambient noise level. These time stamps were analysed to give a mean pulse to pulse interval of 14.74 ± 0.206 s (± 95% confidence limits). There was no easily identifiable constant sized 'packet' of pulses (or number of pulses repeated), implying there was no defined packet size for the pulses. Pulses were typically produced in groups of from one to nine, although individual animals could produce more on occasion and had variable time spacing's before repeating another set of pulses.

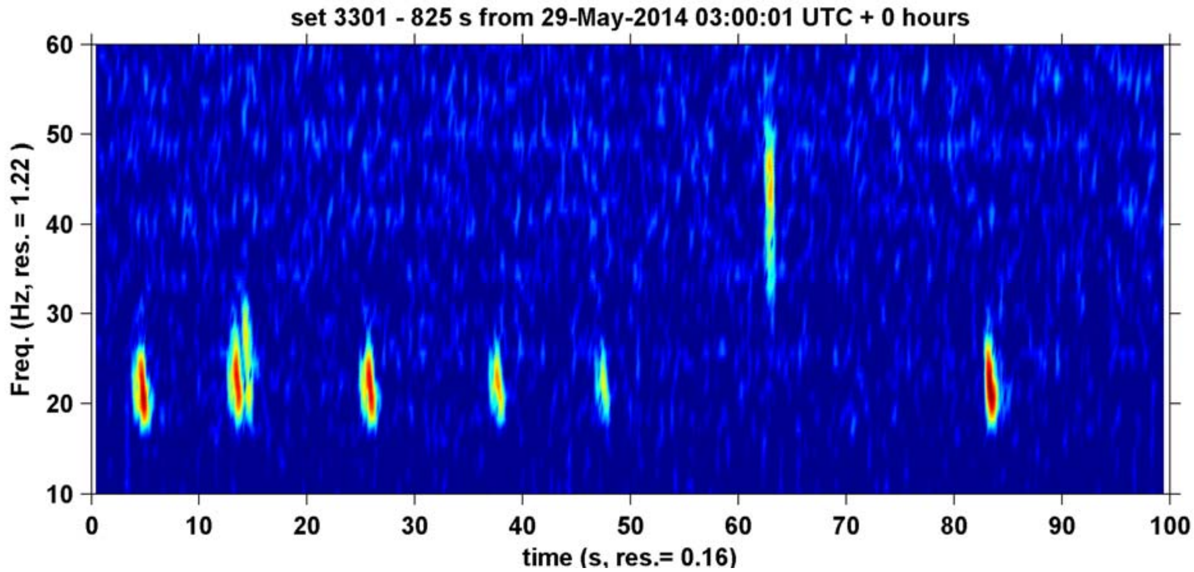

Figure 3: Spectrogram of fin whale calls from North Porcupine.

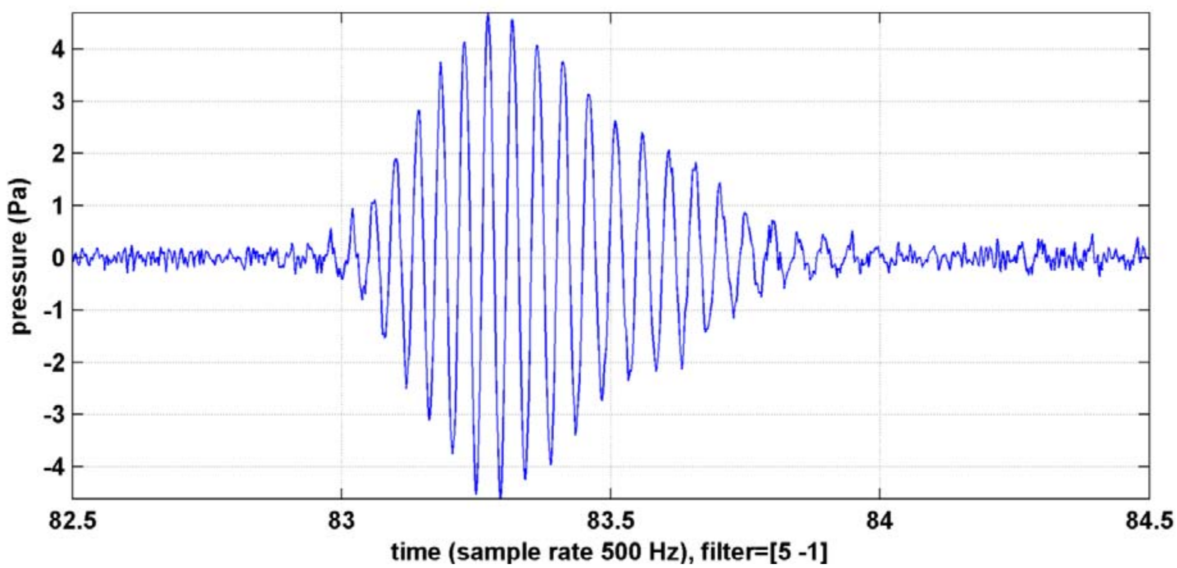

Figure 4: Waveform of fin whale pulse seen on Figure 50 over 82.5 - 84.5 s.

At the North and East Porcupine sites most of the fin whale calls were received at relatively low levels with only a few calls received at moderate to high levels, with these two sites having similar distributions of received call levels. This indicated that animals were mostly at moderate ranges from the receivers (probably many tens of km). The data sets have a sharp drop off in fin whale call detections for low level calls which was indicative of the signals falling into the ambient noise (noting signals were only detected if they were > 4-5 dB above the ambient noise in the fin whale frequency band).

Using the time taken for 90% of the signal energy to pass to define pulse length, then we measured a mean fin whale pulse length of 2.25 ± 0.007 s (95% confidence limits), median =2.18, sd. 0.723, N=36,028. The calculated pulse lengths were normally distributed. The fin whale pulses were consistent in their frequency content with 201 of the highest level common pulses having 3 dB down points over 19.5 - 39.6 Hz, a mean spectral frequency peak at 21.5 ± 0.30 Hz (± 95% confidence limits) and a median spectral frequency peak at 21.0 Hz.

The detections of fin whale calls were used to determine trends in calling at the three sites using two metrics: a) the number of call detections / 200 s; and b) the estimated number of individual whales calling within a sample. The two metrics were correlated. The call detection rates and number of calling individuals were used to look for changes in propensity to call related to time of day. There was a slight indication of greater calling during overnight time periods and after sunrise and sunset but these trends were not significant. The time series of numbers of calling fin whales across the full sample period from all sites is shown on Figure 5 using the smoothed trend of calls/200 s, averaged across a 24 hour period.

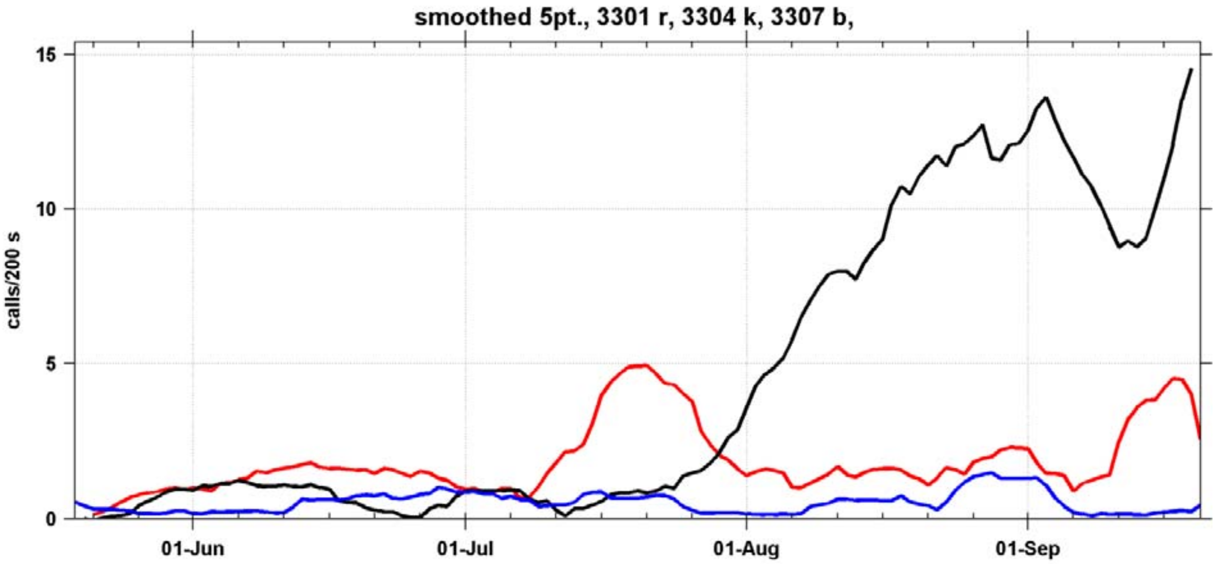

Figure 5: Smoothed trends of fin whale calls/200s averaged across a 24 hour period from: SW Porcupine Bank (3304, black curve); North Porcupine (3301, red curve); and East Porcupine (3307, blue curve).

The time trends in fin whale calling showed:

- Fin whales were present across the full recoding period (including times of seismic surveys) at all sites;
- At North Porcupine two small peaks of calling occurred in mid-July and mid-September;
- A consistent trend for constant, low numbers of calls at East Porcupine;
- A major increase in calls detected through late July and August at SW Porcupine Bank; and
- Around five times as much calling at SW Porcupine Bank as at East and North Porcupine in September.

The total numbers of calling fin whales detected at the three sites was quantified using the curves of calling individuals through time integrated across each site then normalised to the full sampling period (divided by number of days sampled) to give the mean number of calling individual fin whales in each data set. This gave average numbers of calling fin whales at any point in time as:

- North Porcupine 0.333
- SW Porcupine Bank 0.602
- East Porcupine 0.103

The call rates when averaged across May-Sep 2014 showed almost three times as many calling fin whales at North Porcupine than at East Porcupine and roughly twice as many calling individuals at SW Porcupine Bank than at North Porcupine. This suggests that fin whales were found preferentially at the offshore and northern sites and increased in numbers post August offshore but did not increase inshore at the most eastern site.

The calculated number of calling individuals gave the maximum number of calling fin whales as three at each site and the median number 1-2.

As a further view of the trends in fin whale calling across the season the time averaged sea noise spectra was followed across time. While the trends were confounded by long periods of high seismic survey noise raising background noise levels in the fin whale frequency band, they reinforced that fin whale calling rates increased across the sampling period and were highest in late September at the end of the recording period.

4.2. Blue Whales

4.2.1. Background

Blue whales are members of the family Balaenopteridae (suborder Mysticeti; order Cetacea). There are thought to be four sub-species globally, with only a single species known from the northern Atlantic Ocean (*B. musculus musculus*). The blue whale is the largest animal in the world and has been known to reach up to 28 metres in length in the northern Atlantic Ocean, and can weigh up to 150 tons. Blue whale males are 1.5 metres longer than their female counterparts which are believed to calve every 2-3 years. Blue whales live for 80-90 years and were severely depleted by whaling in the late 1800's to early 1900's. In the central northern Atlantic over 15,000 blue whales were caught during this period (OSPAR 2010). In Irish waters Norwegian owned whaling stations caught 124 blue whales between 1908 and cessation of Irish whaling in 1922 (Wall et al. 2009; Fairley 1981).

4.2.1.1. Behaviour and Vocalisation

Blue whales are usually seen alone or in pairs. However in areas of high productivity, up to 50 individuals have been observed together. It is believed that some blue whales can be resident in areas of year-round high productivity while others appear to migrate between high latitudes in summer and warmer lower latitudes in winter (Charif and Clark 2000, 2009). Blue whales feed almost exclusively on euphausiids or krill.

Blue whales produced long structured sequences of vocalisations, often called songs. The north Atlantic blue whale produces a tonal sequence of two parts (A and B) with most energy in the range 15-20 Hz and totalling 15-20 s in length (Mellinger and Clark, 2003). It is believed these songs are produced by males and have a reproduction function (Oleson et al 2007). In addition to these songs, both males and females produce a downsweep, which seems to be common amongst many blue whale subspecies.

4.2.1.2. Regional Irish Distribution

The study of Charif and Clark (2009) using the SOSUS acoustic arrays have indicated migration of blue whales, south from northern waters during late summer, with the migration pathway to the west of the Irish Shelf (the northern migration appears to occur in late autumn/ early winter). From this study and that of Clark and Charif (1998) it appears there are few blue whales in the broad Irish waters in spring and early summer.

Visual sightings of blue whales are rare in Irish waters, only three sightings from dedicated cetacean surveys in Irish waters between 2005 and 2012 are listed in the literature and all were recorded during August or September (Wall et al 2013). The lack of visual sightings is likely to be a reflection of relatively low levels of offshore sampling, the impacts of poor sea state and visibility during times in which blue whales may be present (autumn through winter and into spring) and comparatively low numbers of blue whales.

Based on the acoustic data and sightings recorded during the SOSUS studies, it is predicted that blue whales are most likely to be recorded late in this study sampling window (May to September), on their migration south. In addition, blue whales are more likely to be recorded on the most western logger (SW Porcupine Bank) as they migrate in the deeper contiguous waters to the west of the Irish Shelf (Charif and Clarke 2009).

4.2.2. Blue Whale Detection Methods

For blue whales a relatively simple detector was used which looked for consecutive peaks in spectrograms > 5 dB above surrounding noise over the frequency range 5-20 Hz, with sets of consecutive suitable spectral peaks spanning > 3.5 s and < 25 s in length. The detector missed only low SNR calls but provided several false detections, thus all algorithm outputs were manually corrected.

This detector:

1. Down sampled the sample waveform to 250 Hz;
2. Calculated a spectrogram of each sample using the down sampled waveform at a desired 0.5 Hz resolution with an 0.8 overlap;
3. At each time point of the spectrogram looked for spectral peaks within the frequency band 10-20 Hz, > 5 dB above the 'noise'. The 'noise' was calculated as the mean of frequency bands above and below the searched band;
4. Found sets of consecutive time points which met the spectral peak criteria and were between 3 and 25 s long; and
5. Checked that the mean value for the sequences of points meeting these criteria within 1 frequency resolution of the frequency band around 16.8 Hz, was > 5 dB above the mean value of points 5-9 frequency values below 16.8 Hz and spanning the same time frame (i.e. this step checked that signal was a sharp tone).

The detector missed several detections but recorded a considerable number of false detections so all algorithm outputs were manually checked and time stamps of hits corrected as required (removed or added). As the number of blue whale detections was low overall, the manual checking process included a further step where samples with positive detections were bracketed by three samples (only samples not previously manually checked used), and checked, with time stamps added for blue whale signals as required. This process was iterated until no new bracketing samples were identified (i.e. every sample within 3 samples of one with a blue whale call present had been checked). This manual checking step ensured that were no blue whale calls were missed.

4.2.3. Blue Whale Results

4.2.3.1. Blue Whale Listening Range

The calculations of blue whale detection ranges were similar to those for fin whales and are discussed in Appendix 5. At an average background noise level of 96 dB re 1μPa and assuming a source level of 186 dB re 1μPa then listening ranges at East, SW Porcupine Bank and North, Porcupine were: 46-198 km; 56-85 km; and 58-147 km (respectively). A table of listening areas at different ambient noise regimes (Table 7) and a plot of calculated detection areas are included for blue whales on Figure 6.

Table 7: Estimated detection areas (in units of 1,000 km^2) for blue whale detections at the three sites with differing ambient noise regimes and call source levels.

Back noise (dB re 1µPa)	**East Porcupine (1,000 km^2)**		**SW Porcupine Bank (1,000 km^2)**		**North Porcupine (1,000 km^2)**	
	183 dB SL	186 dB SL	183 dB SL	186 dB SL	183 dB SL	186 dB SL
85	69.6	75.7	69.8	86.7	38.7	47.1
90	51.1	60.3	27.5	62.2	27.3	33.6
95	34.1	45.9	10.6	21.3	19.7	24.0
96	23.2	42.8	8.0	15.7	16.6	22.3
100	4.5	20.5	4.5	7.1	7.1	12.0

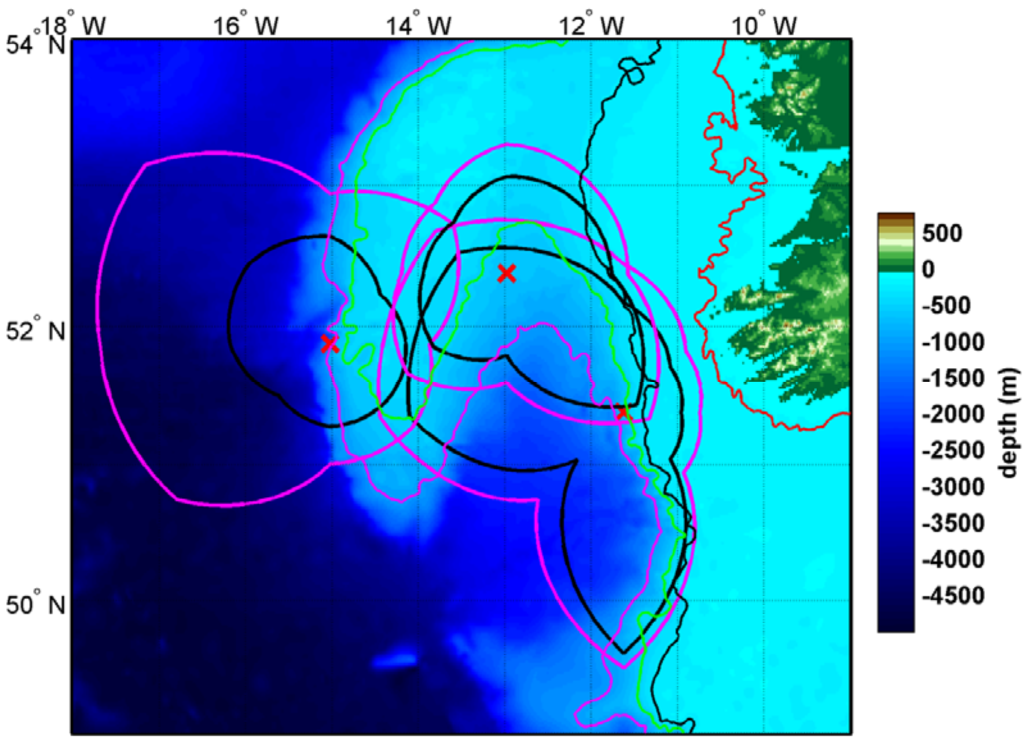

Figure 6: Estimated listening area for blue whales at each site for background noise levels of 90 dB re 1µPa (black curves) and 96 dB re 1µPa (magenta curves) and an assumed fin whale source level of 186 dB re 1µPa.

4.2.3.2. Blue Whale Acoustic Detection Results

A signal type described from north Atlantic blue whales (i.e. Mellinger and Clark, 2003) was detected from the Porcupine site, with an example signal shown on Figure 7. This signal was similar to the part A-B call shown by Mellinger and Clark (2013). There were comparatively few blue whale calls detected, all of these at the Porcupine site and almost all detected in the presence of fin whale calls and / or air gun signals. As fin whale and air gun signal energy overlapped with the blue whale call frequency content this made establishing call parameters for the blue whales difficult. The call frequency content of 27 calls was analysed, with the median frequency for the part A call 16.9 Hz.

The blue whale call detector was run across the HF and LF loggers at SW Porcupine Bank and the LF loggers at North and East Porcupine. Blue whale calls were only detected at SW Porcupine Bank in comparatively low numbers (compared to fin whale calls). There were sufficient calls from the HF logger at SW Porcupine Bank (data set 3304) to establish call-call increments, which was approximately 71 s between consecutive calls. Using a call separation time of 68 s to count for the number of callers (all detections within a 68 s window must have been different individuals) then the trend in number of calling individuals observed across the sampling period from SW Porcupine Bank is shown on Figure 8. Detections of blue whales increased across the sampling period, from the first single detection in June to the greatest number of animals detected in August and September 2014. The maximum number of animals calling detected was two and the median one.

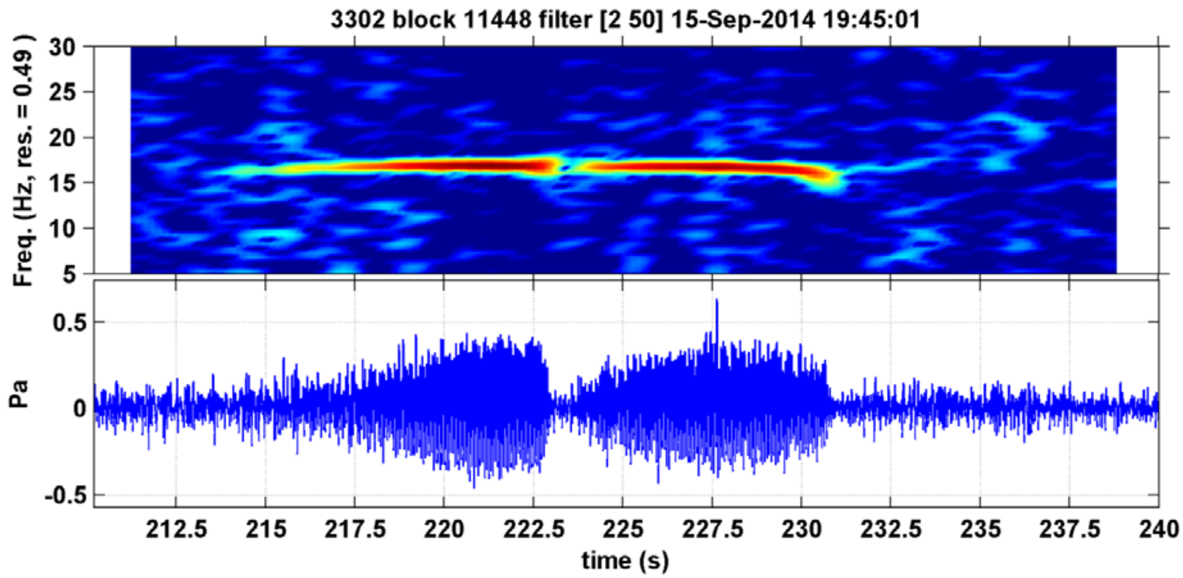

Figure 7: Example of part-A and B of a blue whale call detected from SW Porcupine Bank. This call had most energy at 16.8 Hz.

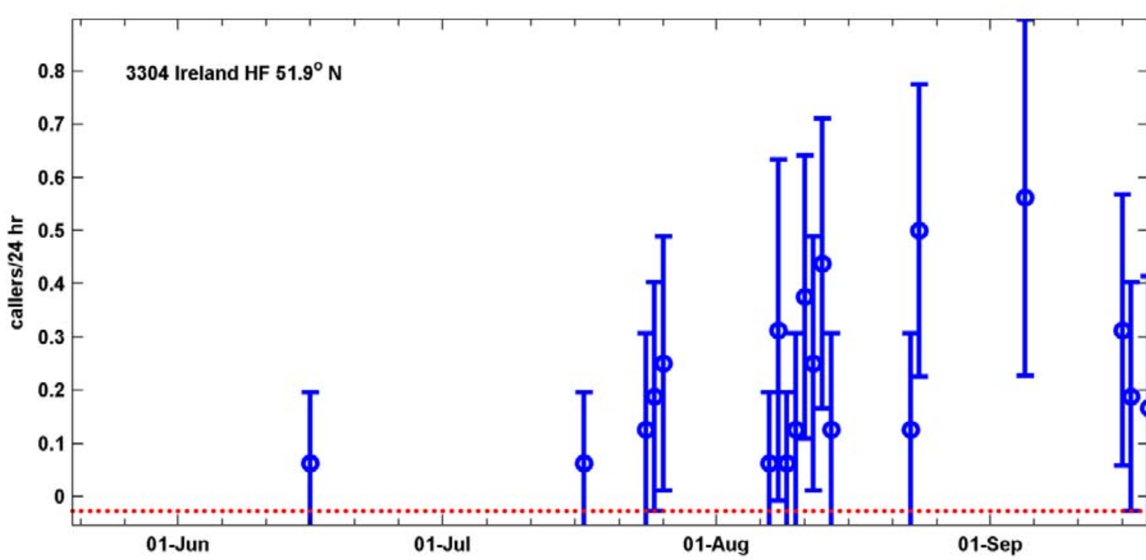

Figure 8: Number of calling blue whales averaged over 24 hour periods (12:00 to 12:00 UTC) shown with 95% confidence limits s error bars from data set 3304 (HF logger) at SW Porcupine Bank.

4.2.4. Blue Whale Discussion

Blue whales were only present at the far western site (SW Porcupine Bank) in this study with the vast majority (96%) recorded in August and September. These whales are likely to be on their migration southwards. The number of blue whale calls detected was relatively low compared to other species such as fin whales with only 27 individuals recorded over the study period indicating either low populations numbers, low percentage of singers or the peak migration occurred after the loggers were retrieved. Charif and Clarke (2009) showed peak numbers of blue whales in late November early December in the vicinity of our SW Porcupine Bank site, indicating that this study concluded prior to the peak southern migration numbers.

The northern migration period which is in late summer was not detected in this study, as the study only commenced in May. However, a single blue whale was recorded in June, which falls between the predicted southern and northern migrations. Charif and Clarke (2009) indicated that blue whales are found throughout the year in the Porcupine region but in low numbers between March and July. The individual detected in June was likely to be an early southern migrating animal.

Blue whales have been shown to migrate along the western edge of Irish Shelf (Charif and Clarke 2009). This study detected no blue whales at the two Porcupine Basin inner locations; North and East Porcupine indicating that migration pathways are likely to be located in contiguous deepwater areas off the shelf edge. Given the large listening ranges of the acoustic receivers, there is no evidence that blue whales migrate through the shelf areas between May and September.

4.3. Dolphins

4.3.1. Background

The Short-beaked common dolphin, striped dolphin, the white-beaked dolphin, Atlantic white-sided dolphin, the common bottlenose and the Risso's dolphin are all found in the waters around Ireland. They vary in range from 1.9 to 3.8 m in length, with the common bottlenose dolphin being the largest species in the area (Well et al., 2013; NPWS, 2009).

Short-beaked common dolphins are often sighted bow riding vessels and commonly breach clear of the water. The sleek body of a short-beaked common dolphin can be identified by the dark brown or black back and white underbelly, with yellow patches along the front flank. The side flanks have grey streaks along them. A distinct black ring surrounds their eyes which continues in a line forward along the melon. Half-way along the back is a curved dorsal fin and at the front of the torso sits a striking black beak (Well et al., 2013; NPWS, 2009).

Like the short-beaked common dolphin the striped dolphin has a small sleek body with a slender beak. A dark grey dorsal fin sits half way along the back and the torso is covered in a dark grey cape. The flank of the species is light grey with a light pink underside and a dark band runs from under the dorsal fin, along the flank to just above the pectoral fin (Wall et al., 2013). Like the Short-beaked common dolphin the eyes are surrounded by a black ring which extends in a line to the melon and along the flank (Wall et al., 2013).

The common bottlenose dolphin and Risso's dolphin are larger in size and more robust than the striped and short-beaked common, white-beaked and Atlantic white-sided dolphins. The common bottlenose dolphin is grey with a white underside, a short round beak and softly curved mouth. They have a tall dorsal fin and a moderately keeled tail (Wall et al., 2013; NPWS, 2009). The features of the white-beaked dolphin are a large prominent black dorsal fin a distinctive white or grey saddle and two white patches on the flank of the body.

The juveniles of the Risso's dolphin species starts youth as dark grey with a paler underside and due to tooth rake marks gained during social engagement, the Risso's dolphin becomes paler in colour with age, often appearing pale grey or white (Wall et al. 2012). Risso's dolphins also have a white anchor shaped patch on their chests and a blunt bulbous heads with a vertical cleft at the front of the melon. The dorsal fin is tall and dark and seated half-way along the back and the pectoral fins are long and crescent-shaped (Wall et al., 2012).

4.3.1.1. Behaviour and Vocalisations

Studies have indicated that dolphin whistles have a social communication function (Sayigh, 1990; Herzing, 1996; Janik and Slater, 1998; Cook et al., 2004; Quick and Janik, 2008; 2012). Whistles are tonal signals which fluctuate regularly in time, usually with fundamental frequencies between 5 kHz and 15 kHz, although fundamental frequencies as low as 800 Hz and as high as 28.5 kHz have been reported (Schultz and Corkeron, 1994; May-ColladoGlobal and Wartzok, 2008) and harmonics can extend higher still (e.g., 80 kHz: Lammers and Au; 2003; Branstetter et al., 2012). Whistles are only somewhat directional at low frequencies; however, higher frequency harmonics can be directional (Branstetter et al., 2012). At this point in time discriminating the whistles and echolocation clicks of different dolphin species is not clear cut. Risso's dolphins have been reported to have short ($< \sim 0.5$ s) whistles with a somewhat flat frequency response near 2 kHz and echolocation clicks > 20 kHz (Lyne pers. comm.) but the signal types produced by all dolphin species need better characterisation.

4.3.1.2. Global Distribution

The short-beaked common dolphin along with the common bottlenose dolphin inhabits warm temperate and sub-tropical waters (NPWS, 2009). The short-beaked species is absent from the Indian Ocean however the common bottlenose dolphin can be found in coastal, oceanic, inshore waters and areas along the continental shelf (Wall et al., 2013; NPWS, 2009).

The striped dolphin also has a large range, stretching through the Atlantic, Indian and Pacific Oceans. Although there have been sightings of this species recorded in Greenland and the Faroe Islands, there range has been recorded to be generally limited to 50^0 North and 40^0 South (Wall et al., 2013).

The range of the Atlantic white-sided dolphin is limited to the North Atlantic along with the range of the white-beaked dolphin, spreading through the North Atlantic, from Cape Cod and France through to Greenland, Svaldbard and east to Novaya Zemlya, off the coast of Russia (NPWS, 2009).

The waters over the continental shelf are known to be home to the Rissos's dolphin, especially those areas where the slope gradient is steep. This trend applies to both hemispheres from the tropics to more temperate regions (Wall et al., 2012).

4.3.1.3. Regional Irish Distribution

The Short-beaked common dolphin has been recorded in high abundance all along the Irish coastline, with an average group size of 36 and groups as large as 3,000 individuals recorded off the Pembroke coast (Wall et al., 2013; Berrow et al., 2010). Inshore sightings have historically peaked in August suggesting an eastward movement along the south coast during autumn and winter. The species is spread across a vast range and it has been suggested that there are two geographically and genetically distinct populations that inhabit the North Atlantic (Berrow et al., 2010).

Sightings of the striped dolphin in Irish waters are rare as the species is commonly pelagic. Fishing bycatch studies have suggested a range far to the south west of the Irish mainland (Wall et al. 2013;

Berrow et al., 2010). Both of the two striped dolphin sightings recorded in Irish waters, were over the Porcupine Bank, which could be a reflection of the similarity of their physical features to those of the common bottlenose dolphin (Wall et al. 2013; Berrow et al., 2010). Both sightings were also recorded over summer, yet stranding records reveal habitation of Irish waters year round.

Sightings of the White-beaked dolphin are rare in Irish waters and have become increasingly so over the last decade. There are concerns numbers may be declining in the region (Wall et al. 2013; Berrow et al., 2010). Rare sightings of this pelagic species suggest the northward movement of the species range over the past decade, as no sightings have been recorded along the south or southwest coastlines during this time.

Restricted to the North Atlantic, the Atlantic-white sided dolphin is found primarily in the cool, deep (> 200 m) waters along Ireland's continental shelf and over the offshore banks (Wall et al. 2013; Berrow et al., 2010). Over the Rockall Trough and Porcupine Banks in 2000, sightings have been recorded of groups of approximately 5,500 individuals. Sightings of this size have been recorded on several occasions. This species is often viewed in large groups with an average size of 14 individuals. Sighting data shows a peak over the summer months. This may reflect the relative ease of offshore access during the more benign Atlantic summer (Berrow et al., 2010).

Common bottlenose dolphins are sighted off all Irish coasts in groups averaging 11 individuals (Berrow et al., 2010). Despite the species having been sighted off all Irish coastlines, the majority of sightings have been in waters inshore along the western seaboard. Offshore sightings have revealed that groups of this species appear to prefer the slopes of the Irish Shelf and offshore banks. Offshore sightings are commonly limited to Porcupine Bank, Porcupine Seabight and Rockall Trough. Resident and semi-resident populations have also been found in the protected waters of the Shannon Estuary and Cork Harbour respectively. Seasonal movements may have been influenced by summer sighting conditions and effort, as sightings are greatest between May and September, with low densities recorded through autumn and spring and minimal sightings over the winter (Wall et al., 2013).

In Irish waters the Risso's dolphin is the sixth most frequently sighted cetacean with most sightings occurring between May and July, but with sightings recorded in all months (Wall et al. 2013; Berrow et al., 2010). The groups sighted were of an average size of five individuals. Risso's dolphins have been sighted from coastal locations all around the island of Ireland with Wicklow and Wexford counties recording the highest percentage of sightings from 2000-2009 (Wall et al., 2013; Wall et al., 2012). Reduced sightings during winter and autumn months could be a factor of low survey effort and poor visibility. The presence of young calves in some groups indicates that calving and breeding may occur in Irish waters (Wall et al. 2013; Wall et al., 2012; Berrow et al., 2010).

4.3.2. Whistle Detection Methods

Dolphin sounds are generally categorized as whistles, echolocation and burst pulses. Dolphin whistles are used for social communication while clicks are used for echolocation of prey or prey location and imaging.

All samples of the HF noise loggers were searched for dolphin whistles. This was achieved by:

1. A sample was down-sampled from 192 to 48 kHz;
2. The frequency band 4-18 kHz was selected and a spectrogram at 48.88 Hz resolution (1,024 points) with no overlap made across the sample;

3. The spectrogram was divided into 10 s segments;
4. The spectrogram of each panel was normalised for slope with frequency by finding the median spectral value at each frequency across the 10 s segment then subtracting this from each respective frequency - this acted to 'flatten' the spectral shape and so normalise the spectrogram;
5. The median value of the normalised spectrogram found (should now have been zero);
6. Individual values in the spectrogram > 8 dB above the median value found;
7. Values > 8 dB above background with a neighbour > 8 dB above background within 2 points away (time and frequency) were scored as 1 on a matrix of zeros the same size as the spectrogram matrix;
8. Within the 10 s spectrogram panel, values > 0 on the logic matrix from 7) were followed individually and potential whistles tagged (time and frequency values kept) where a value had a neighbour > 0 within ± 2 frequency and 0-3 time divisions later. This process continued to follow the 'whistle' until no more suitable neighbours were found. The followed whistle time-frequency points were stored independently then set to zero in the master-matrix and the process iterated until all points in the 10 s panel were set to zero. This gave a series of X-Y (time-frequency) values for potential whistles within the panel;
9. If a panel had whistles present and these were > 0.45 s long then the sample was deemed to have whistles present and the process stopped. If no whistles were present > 0.45 s long the next 10 s panel was processed as for 3) above onwards, until either whistles were found or were not found (implying the full sample was searched); and
10. For samples with whistles found the process was re-run and all whistles within the full sample located.

This technique, locating whistles of any shape in a defined frequency band (4-18 kHz) that exceeded a set time limit (length of whistle) worked extremely well. The algorithm had no false detections and detected all samples with whistles in 300 manually checked HF samples. This algorithm was tailored for whistles and set a limit on the time/frequency rate of change allowed, so did not capture short duration pulses or echolocation clicks.

4.3.3. Dolphin Results

4.3.3.1. Echolocation click detection

Echolocations clicks produced by dolphins or sperm whales were found in the HF logger data by:

1. Extracting HF logger sample data (volts, 192 kHz sample rate) in consecutive 10 s panels;
2. Band pass filtering the waveform over 2 - 30 kHz and 25-96 kHz;
3. Removing a small number of points each end of the waveform to account for filter artefacts;
4. Calibrating the signal (assuming a flat recording system frequency response);
5. Setting a threshold (T) defined as 80 x the panels median squared pressure (different frequency bands treated separately from here on);
6. Locating hits within the panel of $Pa^2 > T$ and excluding signals within 4 ms after any defined hits;
7. Extracting each 'hit' using 2048 samples with 1 ms before the hit time and the remaining points after (9.67 ms);
8. Using the magnitude of the Hilbert transform for the hit to locate any clicks in the waveform of length L (ms), such that $0.1 < L < 1.5$;
9. Calculating the spectral peak of the hit;
10. Calculating the peak pressure values (dB re 1µPa);
11. Locating any signals within the hit likely to be an internal reflection (sperm whales); and
12. Saving the hit data and waveforms for post processing.

The algorithm was excellent at returning clicks, with no false detections found in approximately 2,000 manually checked clicks. Discerning which toothed whale species produced the clicks was far more difficult and beyond the scope of work here. Sperm whale clicks were identified by the presence of the internally reflected clicks and a spectral peak within the frequency band > 2 kHz and < 15 kHz, but all other signals derived in this frequency band (apart from beaked whales, dealt with below) were placed under the category 'toothed whale echolocation clicks'.

To assess the minimum number of individual dolphins whistling during each whistling period, the whistling dataset was re-processed and all dolphin whistles within a whistling period identified (the initial algorithm pass stopped after it had identified a whistle as being present). This allowed a minimum estimate of the number of dolphins to be made, by:

1. Stepping through each time point within each identified whistle within a sample;
2. Locating all other whistles which had this time point but a different frequency value at this time point and saving the number of other whistles overlapping this time; and
3. Obtaining the minimum and maximum count of different whistles across a sample to give a measure of the number of different dolphins whistling simultaneously in this sample.

4.3.3.2. Dolphin Acoustic Detection Results and Discussion

Multiple periods of dolphin whistles of various types were heard from all sites on the HF loggers. An example of 10 s of whistles from SW Porcupine Bank and the east Porcupine are shown on Figure 9 and Figure 10 respectively. Multiple periods of dolphin whistles of various types were heard from all sites on the HF loggers. Dolphin whistling occurred in 1.5 - 6 hour bouts across all locations (see Appendix 11 for bout length analysis).

Figures of whistle presence at each site are given in Figure 11 below. The whistles have not been attributed to species and are referred to as dolphin whistles only. The study of Anon (2011) along the Rockall trench reported common dolphins as the most prevalent species sighted, but also sightings of striped dolphins and pilot whales in the offshore areas. It is probable that most of the whistles detected here where from common bottlenose dolphins as these were the most prevalent previously recorded. However other dolphin signals could include those from; striped; North-Atlantic white sided; Risso's; and the short-beaked common dolphin, plus pilot whales, potentially in high numbers.

To compare dolphin whistles at each location and between day and night time, whistle presence per 24 hours was integrated across a season, normalised to the respective data set length with night and day counts differentiated as shown on Figure 12. The day and night -time periods were delineated using sunset and sunrise times for each location using the Matlab astrophysics package of Ofek. There were more dolphin whistles recorded at the east Porcupine and SW Porcupine Bank locations than the north Porcupine location between May and September (Figure 12). There was no clear pattern in the level of dolphin whistles between night and day. There were more whistles at night at SW Porcupine Bank and the east Porcupine locations, while the north Porcupine location had similar level of whistles recorded during night and day.

There appeared to be a greater number of whistles later in the deployment, during the months of August and September (Figure 11). However, as previously stated, the whistle data is likely to be from numerous species including striped dolphin, North-Atlantic white-sided dolphin, common bottlenose dolphin, Risso's dolphin and the short-beaked common dolphin. Currently there is insufficient knowledge to acoustically analyse individual dolphin species' whistles. Consequently, the abundance of dolphin whistles over the study period is likely to mask varying seasonality in individual species' abundance at individual locations.

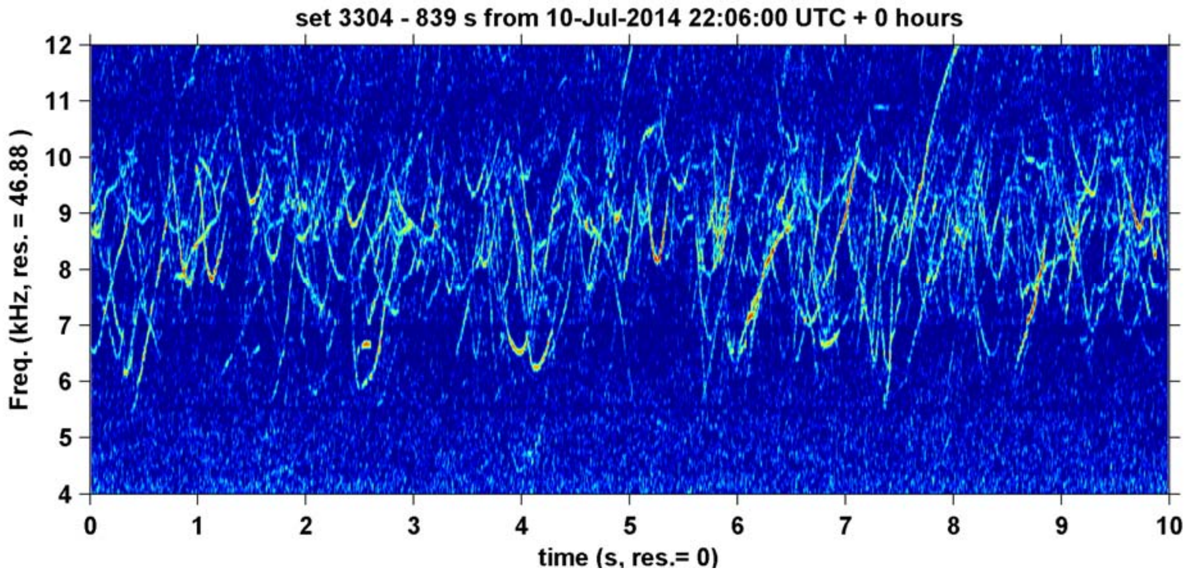

Figure 9: Example of multiple dolphin whistles overlapping from SW Porcupine Bank.

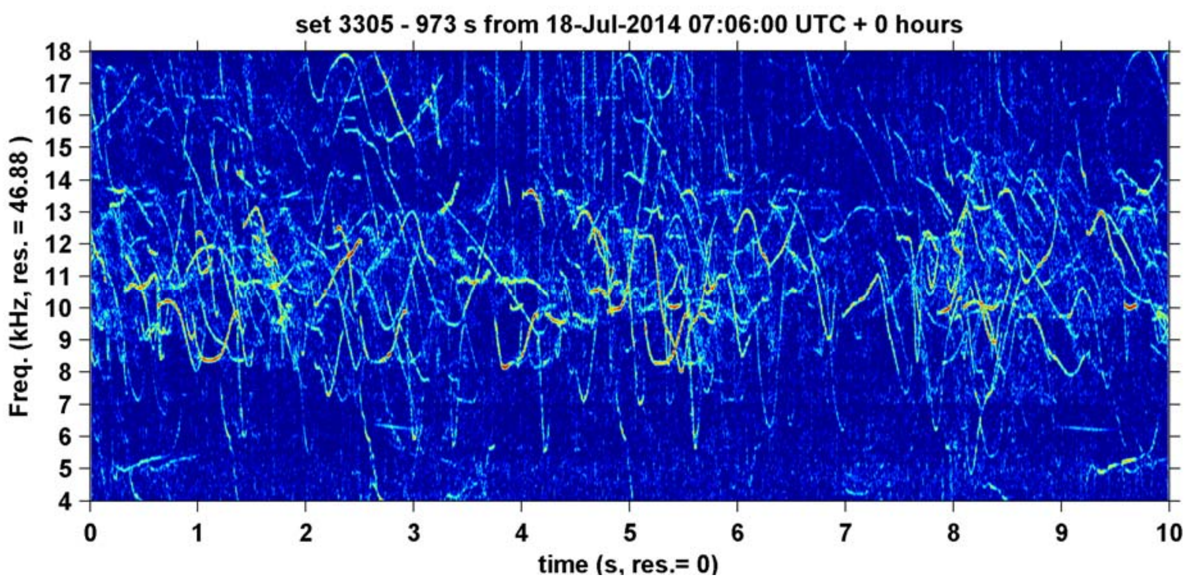

Figure 10: Example of dolphin whistling from the east Porcupine.

Dolphin whistle bout lengths, or the length of time given by the number of samples whistling was consecutively heard, was found to range from 1.5 hours (this was the minimum resolution given by the HF noise logger sample increment) to 18 hours with a median value of 3 hours and a skewed distribution towards shorter bout lengths (Figure 13). By counting the number of whistles at different frequencies within a sample, estimates of the number of whistling dolphins were made. Most of the dolphin whistling bouts had a single animal whistling, but this was often higher with a highly skewed distribution towards one. In one instance 17 animals were detected whistling.

In many instances, dolphin whistling appeared to correlate with sperm whale calls, suggesting dolphins were following the sperm whales. At the North Porcupine site 17% of samples with sperm whales also had dolphins present, this doubled at the SW Porcupine Bank to 32% of samples and roughly doubled again at the East Porcupine site to 52% of samples. Future analysis could further assess the dataset to look at the links between dolphin and sperm whales pods in offshore Ireland.

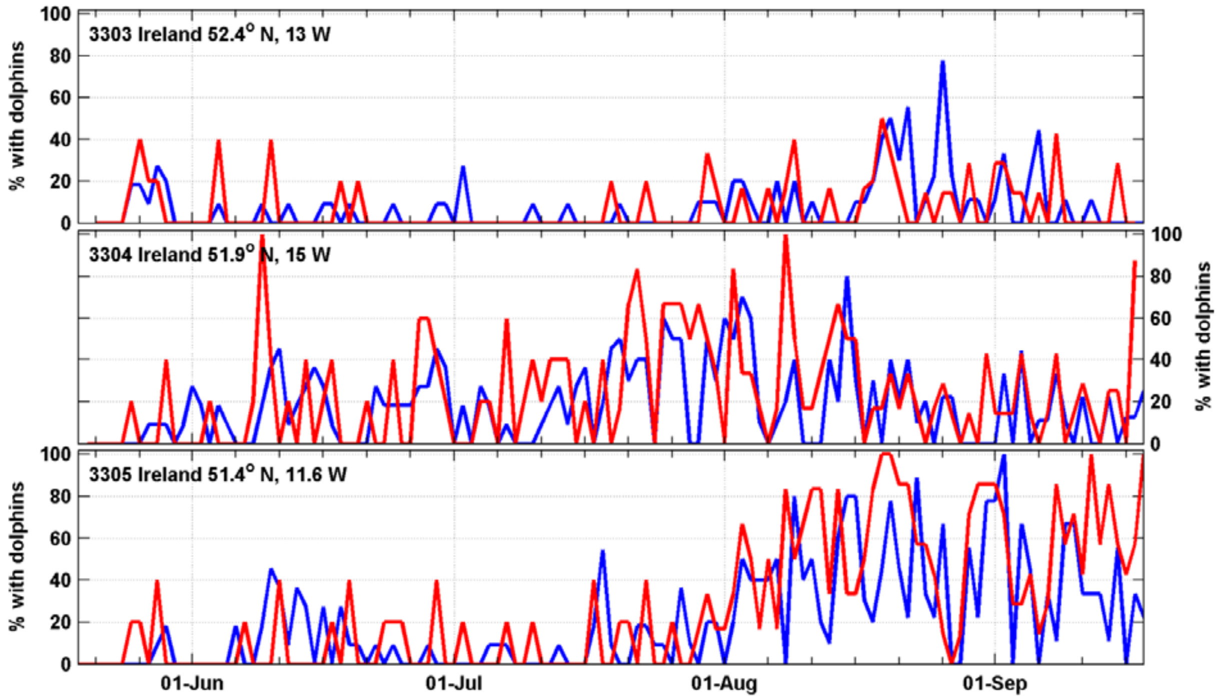

Figure 11: Percentage of samples with dolphin like whistles present from the north Porcupine, SW Porcupine Bank and east Porcupine (top to bottom), shown split by day (blue, sunrise to sunset) and night (red, sunset to sunrise). The raw data is shown.

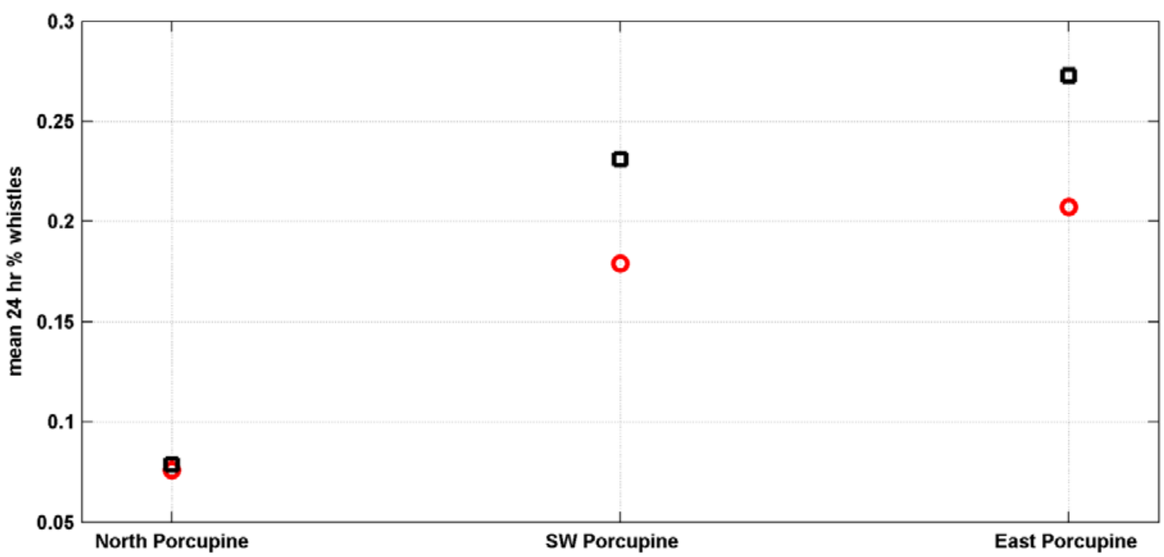

Figure 12: The presence of dolphin whistles at all sites as given by the integral of the % of samples/24 hour with whistling, normalised for the respective data set lengths. The black squares represent periods of darkness, the red circle daylight.

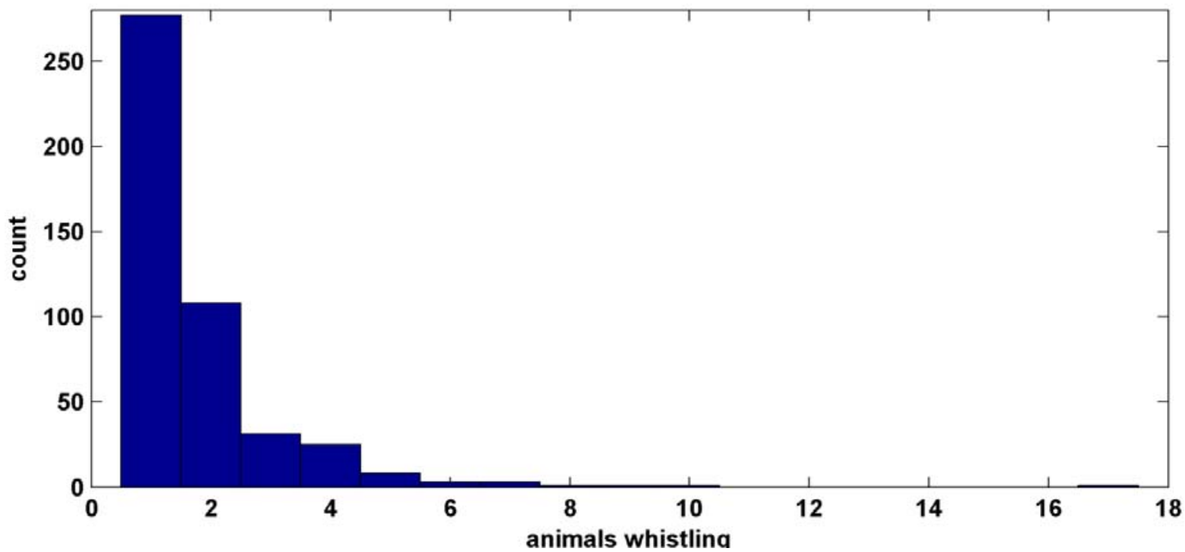

Figure 13: Distribution of the number of dolphins whistling using data from all sites.

4.4. Sperm Whales

4.4.1. Background

The largest of the toothed whales, the sperm whale, has a long dark brown back with no fin, but has a triangular dorsal hump in front of a spinal ridge and skin corrugations (Wall, et al. 2013; Reid, et al. 2003). The male of the species can grow to lengths of 18 m and females to 13 m, and both sexes display a large square head with a low-set jaw (Reid, et al. 2003). When diving, the triangular, deeply notched tail fluke is often thrown into the air and the bushy blow may reach 1-1.5 m high. Individuals and commonly juveniles can breach clear of the surface and dive to depths up to 2,000-3,000 m (Wall, et al. 2013; Reid, et al. 2003).

4.4.1.1. Behaviour and vocalisations

The Sperm whale is organised into matrilineal groups comprised of mature females and their offspring. On reaching sexual maturity the males of the group will leave to join bachelor groups, while the females will remain in the natal group (Reid, et al. 2003). The female groups are generally found in low latitudes while the males are found from polar to temperate waters. Often spread over large areas the group size of the sperm whale ranges in the tens of animals, although only a proportion may be visible at the surface (Wall, et al. 2013; Reid, et al. 2003). The natal and bachelor groups commonly come together to breed and socialise. The occurrence of high relief features is known to influence the spatial distribution of groups over large distances (Reid, et al. 2003).

Sperm whale vocalisations are produced as a series of impulsive clicks that are displayed in a well-defined click train ranging in frequency from 100 Hz to at least 32 kHz and in duration between 2 to 24 ms (Morrissey et al., 2006). These clicks have been identified as 'usual' clicks (0.4-1.0 s period), slow clicks (5-8 s period), codas (patterned clicks) and creaks (rapid clicks) (Barlow & Taylor, 2005). It is hypothesised that sperm whales use clicks and creaks for echolocation and a very slow click for communication purposes (Morrissey et al., 2006).

4.4.1.2. Global distribution

Sperm whales can be found in all oceans in depths of between 500 and 2,000 m from the equator to the poles (Taylor, et al. 2008). Common sightings of sperm whales occur over mid-ocean and submarine canyons at the edges of the continental shelf and they have also been seen in deep water around oceanic islands and volcanic coastlines (Reid, et al. 2003).

4.4.1.3. Regional Irish Distribution

The sperm whale can be found through the northeast Atlantic particularly in deep waters to the west of the continental shelf and over submarine canyons and near volcanic landmasses (Berrow et al. 2010). Historically sightings around the UK and Ireland have been recorded between July and December however there is evidence to support the theory that there are small groups remaining at high latitudes during winter months (Reid, et al. 2003). There have been relatively few sperm whale sightings in inshore shelf waters around Ireland. Offshore acoustic and visual surveys have revealed the presence of sperm whales in the Rockall Trough and the Porcupine Bank subsea canyons along the shelf (Berrow et al. 2010).

4.4.2. Sperm Whale Detection Methods

Sperm whale clicks were differentiated within the 1-30 kHz filtered clicks retrieved as described above, if the clicks: 1) had a spectral frequency peak in the range 2-15 kHz (the signals used had been bandpass filtered over the range 2-30 kHz); and 2) had an internal reflection present (i.e. Goold 1999, where a replicate signal arrives after the initial arrival and within 1-4 ms of the original arrival). Within a sample the presence of one click which met the criteria set the entire sample as having Sperm whales present.

The Sperm whale presence data was used to estimate calling bout length. To do this a bout was recognised as a period with sperm whale calling present in samples which were not separated by a period of 6 hours or more (4 samples) with no sperm whales present. That is a period of at least six hours of no sperm whale calling differentiated a calling bout. Using this definition the median sperm whale calling bout lasted 1.7 hours with bouts separated by a median period of no calling of 12 hours.

4.4.3. Sperm Whales Acoustic Detection Results and Discussion

Previous studies have found most sperm whales in offshore Ireland are in the Rockall Trough during winter with low numbers found in spring (Wall et al 2012). However sampling effort has been very low or non-existent in some locations. In addition sperm whales spend 95% of their lives beneath the surface making visual observations of their presence/absence and behaviour challenging using traditional surveys. Consequently, passive acoustic monitoring is an effective way of understanding the seasonal presence of these deep-diving whales. Within this acoustic study, sperm whales were found across all sampled locations throughout the deployment period (May to September). An example spectrogram of sperm whale clicks is shown on Figure 14 for the North Porcupine site. Four sperm whale click waveforms from the North Porcupine and SW Porcupine Bank, showing the internal reflected signals are included in Figure 15, with their power spectra shown on Figure 16. The multiple pulses produced by sperm whales are clear on Figure 18. The frequency content of the sperm whale click pulses can be seen to vary on Figure 16 with the spectral peak of the lower amplitude pulses shifted downwards in frequency, possibly as the lower frequencies propagate better than the higher frequencies, thus range becomes a predictor of received click frequency.

Peak presence of sperm whales was observed to be between mid-July and mid-August. The lowest number of detections were recorded at North Porcupine with the greatest numbers recorded at SW Porcupine Bank. Given the depths that sperm whale forage to, most individuals are likely to favour the steep shelf-break slopes and potentially the canyons and channels that are prevalent along the Rockall Basin margin. However, sperm whale abundance is highly variable from day to day, and week to week (Figure 17 & Figure 18). Sperm whales have the ability to move over 100 km in a single day (Jaquet and Whitehead 1999) and consequently their localised daily abundance can change quickly around an acoustic receiver as they respond to prey availability and social cues. There were several interesting observations within the sperm whale dataset. Firstly, an oscillating tendency for sperm whale presence at all sites on a 15-40 day periodicity. Currently, there is no firm explanation for this periodicity but preliminary comparisons seem to indicate there may be a link to moon phase. Secondly, median sperm whale calling bouts lasted 1.7 hours with bouts separated by a median period of no calling of 12 hours. Finally many bouts of sperm whale calling also correlated with dolphin whistling, suggesting dolphins were following sperm whale groups. At the north Porcupine site 17% of samples with sperm whales also had dolphins present, this doubled at the SW Porcupine Bank to 32% of samples and roughly doubled again at the east Porcupine location to 52% of samples. These data observations require a more thorough assessment of the dataset that was not possible with the time scope of this report.

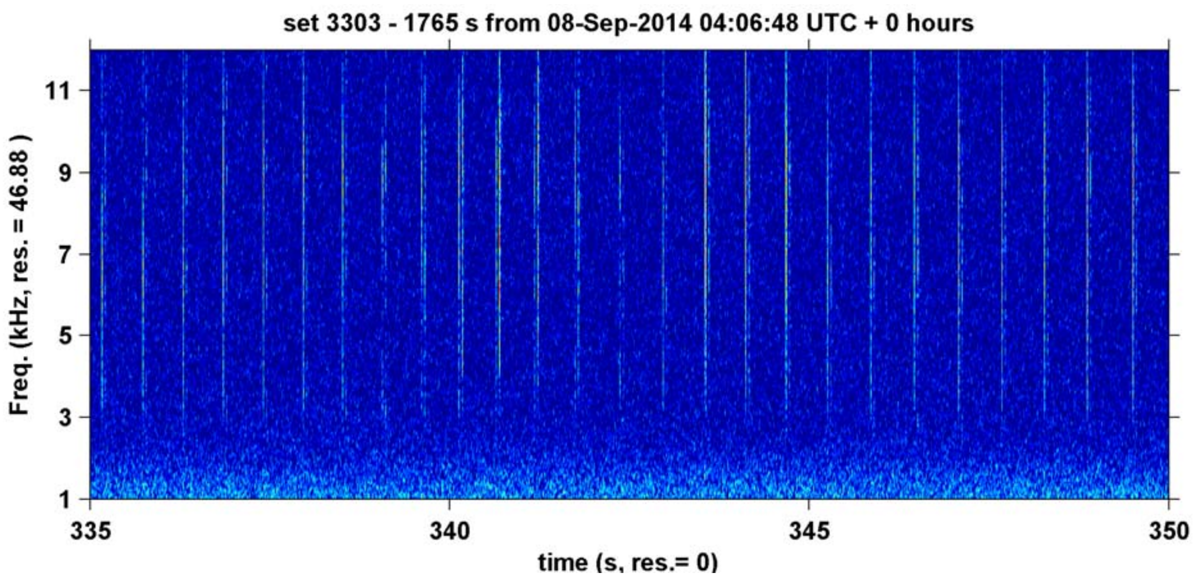

Figure 14: Example spectrogram of sperm whale clicks recorded from the north Porcupine location (4096 point FFT, time resolution 0.00427 s).

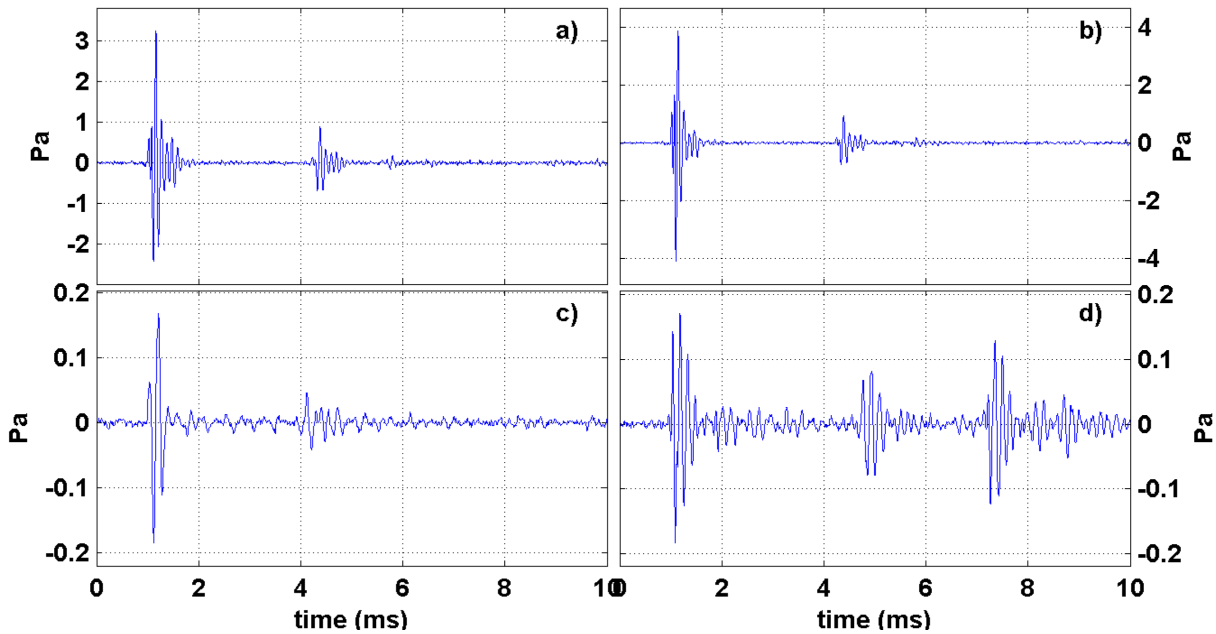

Figure 15: Waveforms of sperm whale clicks showing the internally reflected signals around 3-4 ms after the initial arrival. The signals are from: a) and b) north Porcupine sample 1765, 08-Sep-2014 04:06; and c) and d) from SW Porcupine Bank sample 85 starts at 24-May-2014 20:06. Multipath reflections are evident in all signals.

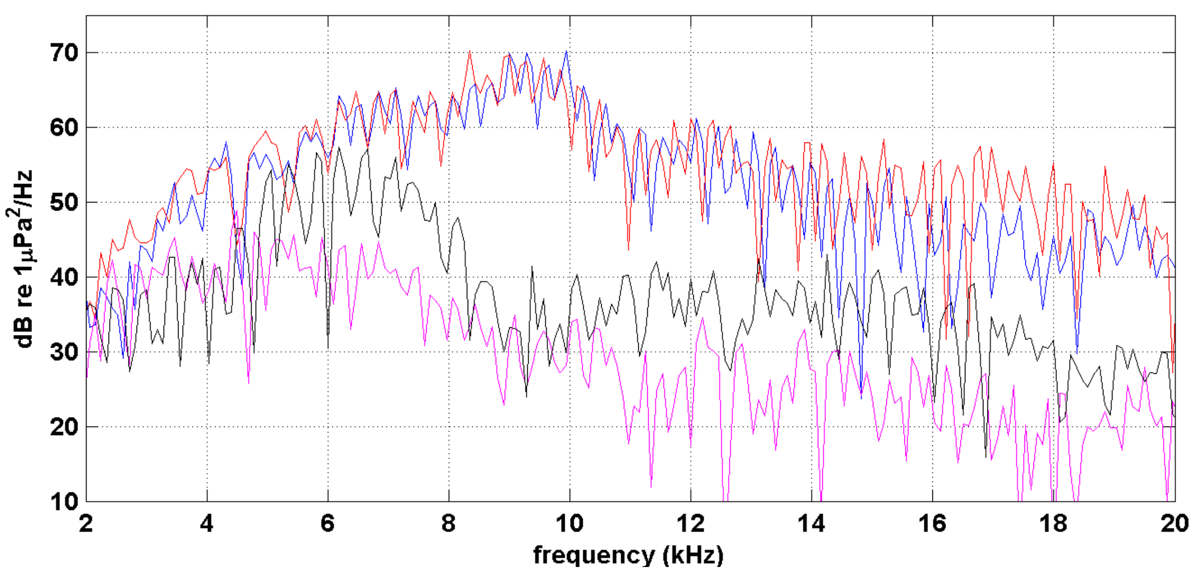

Figure 16: Power spectra of the four waveforms shown with the red and blue curves from waveforms a) & b) and the black and magenta curves from waveforms c) & d). Power spectra made with sample rate 192 kHz, 2048 points, hanning window, 93.75 Hz resolution.

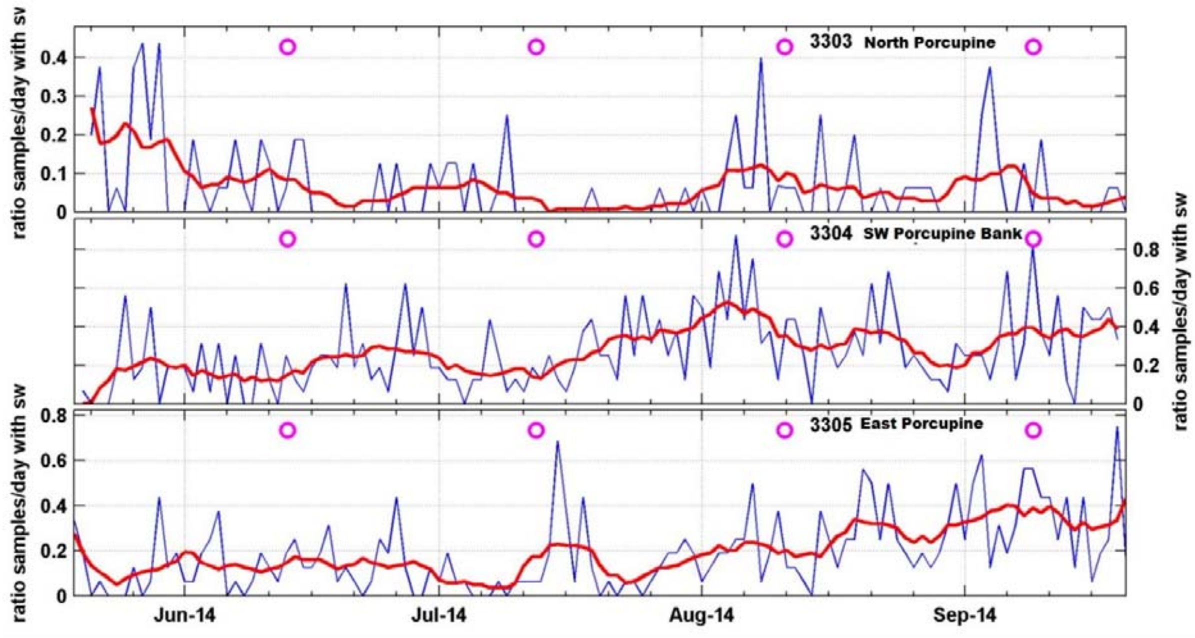

Figure 17: Presence of sperm whales at each site as given by the number of samples per 24 hour period (12:00 one day to 12:00 the next) with sperm whales present. The blue lines are raw data, the red lines are smoothed curves using a 4 day running linear fit. Note that the y-axis ranges are not the same between plots. The magenta circles are the days with full moons. The x-axis tick increments are at five days.

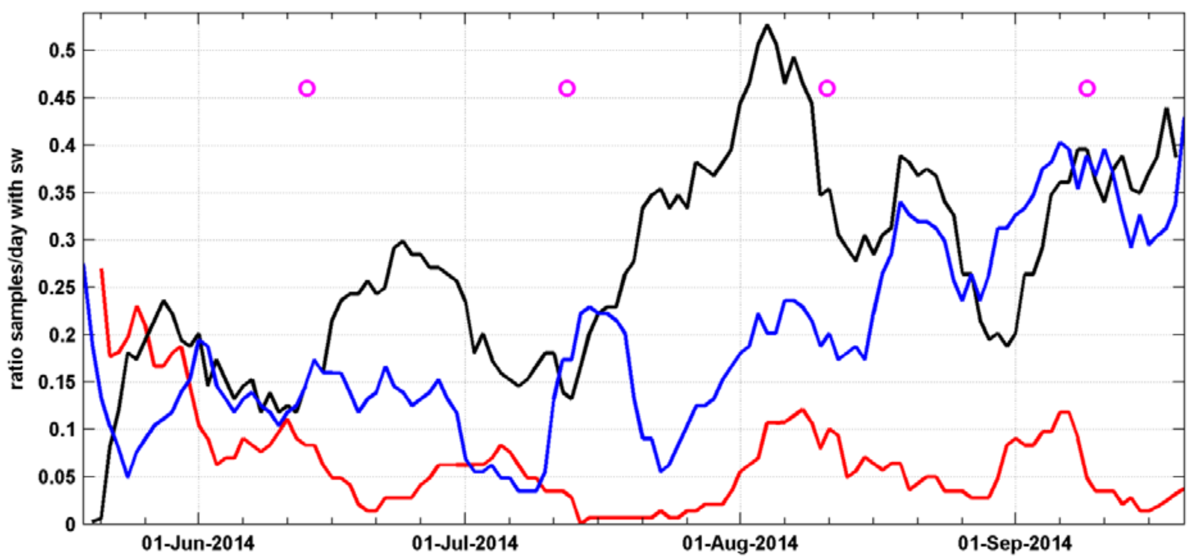

Figure 18: Smoothed curves of sperm whale presence at each site, give as ratio samples per 24 hour period with sperm whales. The sites are: red – North Porcupine; black – SW Porcupine Bank; blue – East Porcupine. The magenta circles are dates of full moons. Minor tick increments are five days.

4.5. Beaked Whales

4.5.1. Background

There are six species of Beaked whales, with five recorded in Irish waters to date (Lyne, pers.comm.). The distinguishing feature of all the Beaked whales is the size and position of a single pair of triangular flattened teeth, which are protruded only in the males. All the beaked whales are known to breach clear of the water, often in synchronised displays.

The four species in the *Mesoplodon* genus (of which three occur in Irish waters) display very similar physical attributes, reach an average maximum size of 5.5 m with a more slender body than the other species, more like that of a dolphin. On all four M*esoplodon* species a small triangular dorsal fin protrudes two-thirds along the back, however they differ in beak shape, teeth placement and body colour (Reid, et al. 2003; Wall, et al. 2013).

The Sowerby's beaked whale has a long slender beak with an arched lower jawline and as in all *Mesoplodonts* one pair of triangular teeth that sit behind the mid-point of the gape. The True's beaked whale has a short beak sloping into the bulbous forehead and a single pair of teeth that sit at the far point of the lower jaw (Reid, et al. 2003; Wall, et al. 2013). The beak of the Gervais beaked whale is also short, with a straight mouthline and one pair of teeth in the lower jaw and another along the gape from tip to snout. The teeth of the Blainville's beaked whale are exposed by the tip of a high arching mouth and unlike the other three grey coloured *Mesoplodonts* the Blainville's' beaked whales back is patterned by light blotches. The flattened head and a slender protruding beak are also features of the Blainville's beak whale (Reid, et al. 2003; Wall, et al. 2013).

The Northern Bottlenose and the Curvier's Beaked whale are more distinctive than the *Mesoplodon* species and therefore more easily identified. The Northern bottlenose whales have a large robust body (reaching 9.8 m length) with a bulbous forehead and beak and the Curvier's beaked whale have a similar shape, however the bulbous forehead is much reduced and the beak more subtle (Wall, et al. 2013; Jefferson et al. 2008; Reid, et al. 2003;). The Northern bottlenose whale is a brown/olive colour with the dorsal fin situated two thirds of the way along the back and paddle-shaped pectoral fin sunken into grooves on the flank of the body. This is similar to that of the Curvier's beaked whale attributes, however the head of the Curvier's beaked whale is usually paler that the rest of the body and the dorsal fin is a stronger triangular shape than that of the Northern bottlenose whale (Wall, et al. 2013; NPWS, 2009).

4.5.1.1. Behaviour and Vocalisations

Little is known of the beaked whales of the genus *Mesoplodon*. They have been observed tail-slapping, breaching and porpoising, however commonly they are quite passive when visible on or near the surface and therefore little is known of their behaviour (NPWS, 2009; Reid, et al. 2003). It is known that the *Mesoplodon* and other species of the family Ziphiidae spend time at depth, feeding on squid and fish. The Northern bottlenose and the Curvier's beaked whale can be found in groups from two to seven individuals and at times in large groups of up 35 individuals (Wall, et al. 2013; Berrow et al., 2010; NPWS, 2009; Reid, et al. 2003). The social organisation of these species has been studied, but appears to be variable, with mixed sex groups more commonly sighted from June to August each year (Berrow et al., 2010; NPWS, 2009; Reid, et al. 2003). The beaked whales have historically been difficult to study as much of what is known about these species are from strandings, however beaked whales are known to produce pulsed sounds (clicks) and whistles ranging from 13 kHz to 40 kHz (Barlow et al. 2006).

A 2004 echolocation study by Johnson et al, revealed that some beaked whales only clicked at depths greater than 200 m and down to a maximum depth of approximately 1,200 m. Short repeated clicks were made by two species of beaked whale (*Mosoplodon densirostris* and *Ziphius cavirostris*) (Barlow et al. 2006). The larger beaked whales *Berardius* and *Hyperoodon* are known to produce more consistent vocalisations at depth than have been detected when an animal is near the surface. The Curvier's beaked and Northern bottlenose whales produce a pattern of clicks that can be clearly distinguished from the other species in the family (Barlow et al. 2006).

4.5.1.2. Global distribution

The species of the Ziphiidae family have a distribution spreading from cold temperate zones to the tropics in both hemispheres. The Northern bottlenose whale resides in the cold and temperate waters of the North Atlantic from the Canary Islands, Gulf of St Laurence to the Davis Strait and the Barents Sea (Wall, et al. 2013; Berrow et al., 2010; NPWS, 2009; Reid, et al. 2003). The Sowerby's beaked whale inhabits temperate waters from the Canaries through to Labrador and the Norwegian Sea in the north. The Curvier's beaked whale has a larger range stretching through temperate areas, sub-tropical and tropical zones across the Atlantic, from Tierra Del Fuego to the UK and Ireland. The Gervais' and Blainville's beaked whale both inhabit temperate and tropical waters with the Gervais' beaked whale's range stretching north to Ireland and the Blainville's whale found in areas from Iceland, Japan the Bahamas and the South Pacific (NPWS, 2009). The Blainville's beaked whale is thought to have the largest range of the six species although strandings in Britain and Iceland are believed to be extralimital (Reid, et al. 2003) and this species is not commonly found in the northern, eastern Atlantic. Little is known of the True's beaked whale distribution, however it is known that they occur in the waters of the North Atlantic including the coastal waters of Ireland and the coasts of South Africa and South Australia (Wall, et al. 2013; Reid, et al. 2003).

4.5.1.3. Regional Irish Distribution

Beaked whales have been recorded in the Irish waters through the year and the Northern bottlenose whale is known to migrate south during summer to more temperate waters. Information on the movements of the other species in the family is limited (Oudejans, 2014; Wall et al., 2013). The distribution of the beaked whale family in the waters of Ireland is focused around the west coast with sampling to date potentially indicating a preference for the areas around the shelf-break. Reflecting this trend, both visual and passive acoustic 'sightings' have been made at the Porcupine Bank, the Northwest Shelf slopes and the Rockall Trough (Wall et al. 2013). Little is known about the True's Beaked, Gervais' beaked and Sowerby's beaked whale in Irish waters as records of these species have been attained through limited stranding records and in the case of the True's beaked whale there is yet to be a live sighting (IWDG, 2013).

In 1995 there were a reported 40,000 Northern bottlenose whales in the eastern North Atlantic, however population estimates of the other Beaked whale species are poorly known (Taylor et al. 2008).

4.5.2. Beaked Whale Detection Method

Deciding if a high frequency echolocation click (extracted as described above) was from a beaked whale was not clear cut. Clicks have been pulled out here and termed as *'tentative beaked whale'* clicks. The hits derived by the click extraction process for the signals with a high frequency spectral peak process were checked by looking for the frequency upsweep throughout the click which is characteristic of beaked whales. This was done as per:

- The click in question (calibrated waveform) was excised by taking samples from 250 to 750 µs before and after the leading edge of the click;
- The magnitude of the Hilbert transform of the signal was found to give the signal positive envelope (S_{ah}) and the leading and trailing edge of the click (t_1 and t_2) within this envelope found by finding consecutive points where the envelope values bracketed the leading edge of the click and were > median(S_{ah}). Many clicks were rejected at this point usually due to other clicks confounding this analysis;
- The inflection points of the click waveform within the bounds t_1 to t_2 were found and used to give the frequency of each full cycle within the time bounds; and
- Clicks with an increasing frequency across the time bounds and where the correlation coefficient (r^2) of the linear fit of cycle-step with frequency exceeded 0.6, were deemed to be from beaked whales (ie. they had a consistent FM upsweep through the click waveform).

This gave an estimate of samples with beaked whale clicks - any click within a sample which met the above criteria, which was not deemed to be a sperm whale click, set the sample as containing beaked whale signals. All sample with clicks analysed in this frequency band which did not meet the beaked whale or sperm whale criteria where aggregated in the category "*toothed whale echolocation*" clicks. Thus the "*tentative beaked whale*" click discriminator were deemed to be from beaked whales if they had a spectral peak > 35 kHz and had a definitive increase in frequency throughout the waveform (FM upsweep).

4.5.3. Beaked Whale Acoustic Detection Results and Discussion

Any sample which had one or more believed beaked whale clicks was set to contain beaked whales. All samples which had 30-96 kHz clicks and no beaked whale clicks was set as *'toothed whale echolocation clicks, 30-96 kHz'*. An example of four click waveforms which met the parameters are shown on Figure 19. These clicks were located in 1% of samples at the North Porcupine and 12-13% of samples at SW Porcupine Bank and the East Porcupine (Figure 20). However there was an increased occurrence up to 40-60% of the time post late July at the two latter sites. There appeared to be a 3-10 day periodicity in the presence of this click type at SW Porcupine Bank and east Porcupine.

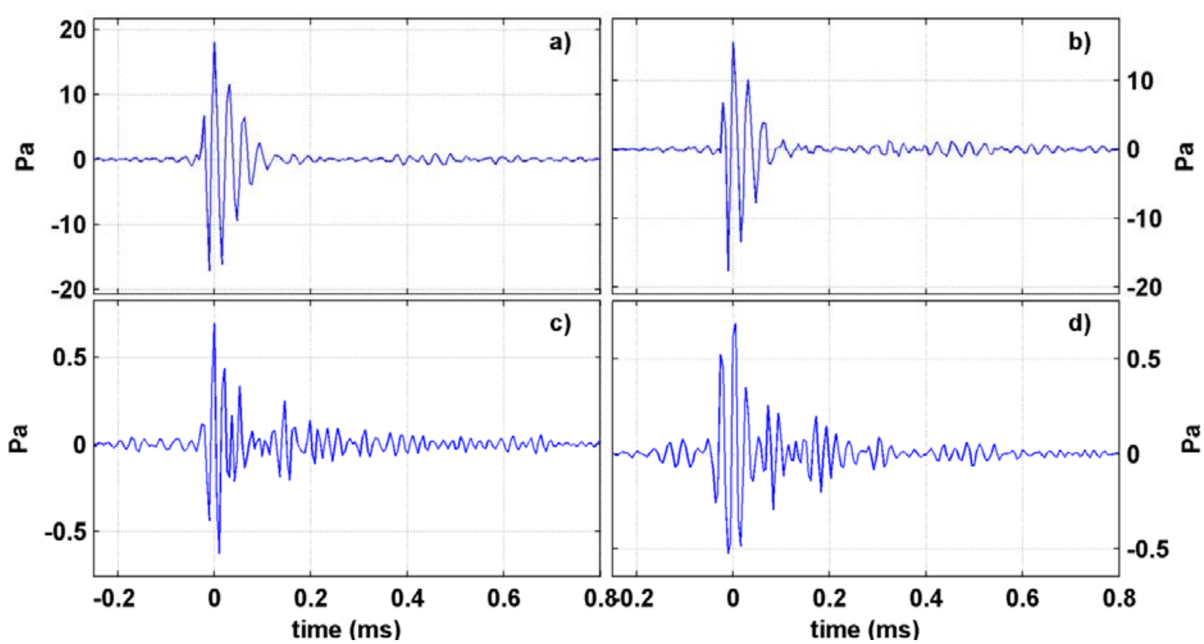

Figure 19: Four example waveforms of signals deemed to be beaked whale clicks, which had spectral peaks > 30 kHz and a consistently increasing upward frequency sweep through the click. Multipath reflections are apparent in all signals. Plot a) and b) from north Porcupine 24-May 05:06, plot c) from SW Porcupine Bank 14-Aug 12:36 and plot d) from the east Porcupine 19-Sep 14:06.

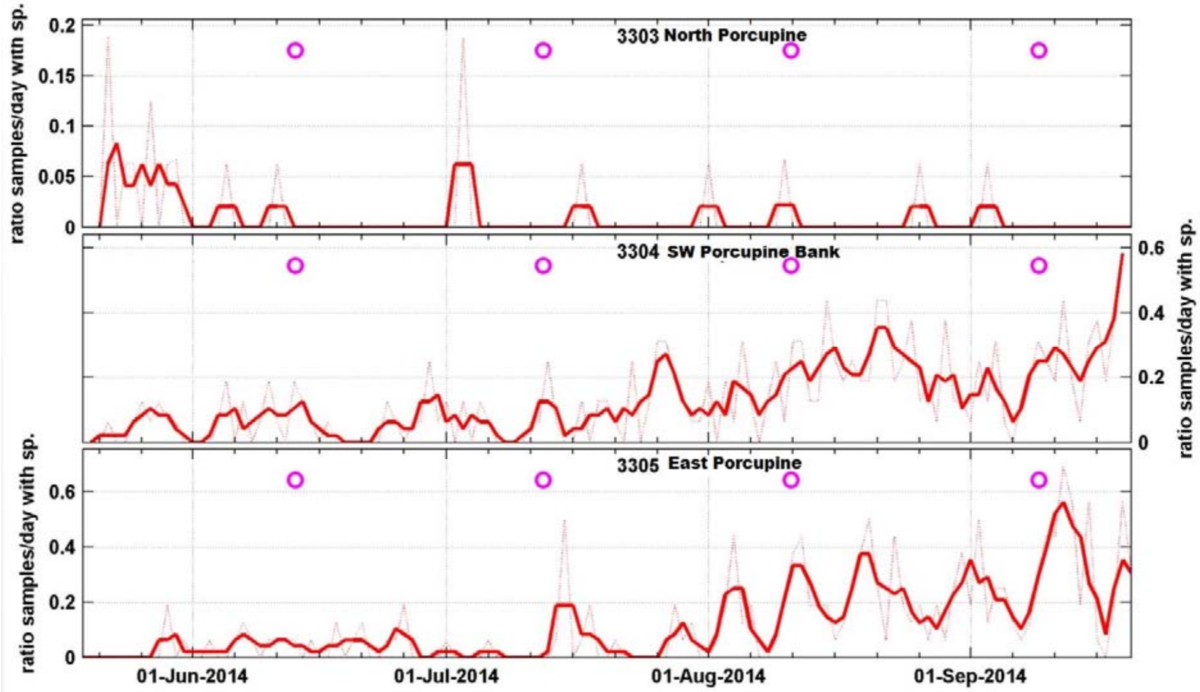

Figure 20: Trend of *'tentative beaked whale clicks'* for each site. The dotted curves are the ratio of samples / 24 hours with clicks, the solid curves are smoothed trend (one day running, linear fit).

5. Discussion

Six sea noise receivers were set over May to September 2014 at three locations, North Porcupine, SW Porcupine Bank and East Porcupine in deep water west of Ireland in the eastern Atlantic. These receivers showed signal types of: nearby vessel noise; natural ambient sea noise sources, primarily wind noise; petroleum seismic survey signals; fin and blue whale calling; whistling signals from smaller toothed whales; sperm and beaked whale clicks; a variety of echo-location signals from toothed whales which were split into those with spectral peaks at 2-30 kHz or 30-96 kHz; plus military sonar signals. The levels of seismic signals received at two sites and the presence of whales at all locations across the recording period is shown on Figure 21.

Up until early July-2014 background noise levels were dominated by natural sources and fin whales at all sites. During this period ambient noise levels in the band > 7 Hz averaged at around 107 - 109 dB re 1µPa, with most energy in the frequency band up to 100 Hz. Few periods of high level ambient noise occurred across this period and where these did occur they were primarily due to vessel passage. Vessel noise was considered to arrive at the receivers in two forms: 1) a recognisable vessel passage where the ship noise became apparent, increased in level as it passed abeam somewhere, then decreased in level as it steamed away; and 2) traffic noise comprised of energy ducted over long range in the deep sound channel which was apparent as almost continual tonal energy in the frequency band 5-100 Hz and not recognisable as from a nearby ship. While the contribution to the background noise level of a passing ship could be quantified the same could not be done for the traffic noise as there was no baseline measurements without traffic noise, to compare against. The time taken for recognisable nearby ships to pass and the maximum levels reached as they passed was quantified for periods without seismic signals present and ranged at ~ 3-4 hours and 108-112 dB re 1μPa.

In early July seismic survey signals began appearing at moderate to high levels at all sites and continued until the recording ceased in September. The energy from seismic surveys frequencies dominated up to 300 Hz. At least three seismic vessels were present in the sea noise, often with two present at moderate levels. Seismic surveys signals up to 145 dB re 1μPa^2.s (SEL) were common in the latter part of the recording period. When averaged across the full recording period and including seismic signals, time averaged ambient sea noise increased to 113 - 115 dB re 1μPa with most energy in the band 5 -10 Hz, which was believed due to deep sound channel ducted seismic signal energy. The seismic signals received displayed clear examples of sound transmission phenomena. Seismic signals of < 0.5 s length at the source at modest to long range appeared as 10 s long signals displaying strong modal structure with dispersion apparent, to look nothing like the transmitted signals. Long range transmission highlighted the seabed slope as an important factor in determining coupling of energy into the deep sound channel. In one seismic survey line, signals at 250-350 km range over a seabed sloping downwards towards the receiver were almost 10 dB higher than signals received from the same source over 150-250 km range operating over a flat seabed, highlighting the seabed reflected signal as an important component of deep sound channel ducted energy. Only short range seismic signals at < 58 km here, had energy at frequencies above those ducted in the deep sound channel (~ > 100 Hz). From July onwards the proportion of time seismic signals were present in the recording period sat around 20-30% of recording time, although this reached 30-50% of the time on occasion. These proportions were based on the time it took for 90% of a seismic pulse's energy to pass, with this time summed for all seismic signals in a sample and compared with the total sample length, then statistics calculated across the period of interest. This differs from other workers measurements of the amount of time seismic is present, which tend to give higher values as they typically do not quantify the actual seismic signal length but rather give total proportions of time seismic signals were present, including quiet periods between shots. During periods of sustained seismic operations, the multiple sources will have created masking of long range low frequency (< 200 Hz) whale communication signals.

Fin whale signals were common in the recordings from all sites. Fin whale calling was more prevalent at the offshore receiver, least prevalent at the site closest to Ireland and increased later in the recording period at the offshore site. A fin whale 'song' was composed of one to eight or nine 'pulses', each with most energy around 26 Hz, although this frequency varied somewhat and the signal frequency dropped with increasing time within a pulse. The individual pulses were comprised of one or several tone bursts. It was not known if the multiple tone bursts were multipath signals or derived from the animal repeatedly oscillating a lung space. For high signal to noise ratio calls the 'song' of groups of low frequency pulses were often followed by one or several higher frequency, short pulses ranging over 30-80 Hz. The fin whale song and these high frequency pulses all tended to decrease in frequency with increasing time. There was a slight tendency for fin whale calling to be more prevalent just after sunrise and sunset though this was not significant. Fin whale calling was present during the periods of seismic survey activity and steadily increased across this period at the offshore site. The ambient noise in the band of fin whale calling (18-26 Hz) increased concurrent with an increase in fin whale call detections.

A small number of blue whale signals, some at relatively high levels indicating the animals were at close range (< 10 km) were recorded from SW Porcupine Bank but not at North and East Porcupine. The numbers of blue whale detections was low, sporadic and increased post mid-July (Figure 21).

Whistles over 4-18 kHz from dolphins were relatively common at each site. The whistles have not at this point been attributed to a species but were most likely from common dolphins. Whistling was more prevalent at East Porcupine (closest to the Irish coast), intermediate at SW Porcupine Bank (offshore) and least prevalent at North Porcupine. The amount of whistling at each site increased across the sampling period. High frequency echolocation clicks with most spectral energy at frequencies > 35 kHz and which had an increasing frequency through the click were located in 1% of samples at North Porcupine and 12-13% of samples at SW Porcupine Bank and East Porcupine. These were considered to be *'tentative beaked whale clicks*'. There were few instances of these click types at North Porcupine where their presence was sporadic. At SW Porcupine Bank and East Porcupine there was a continual low level presence of be *'tentative beaked whale clicks*' (< 20% of time) with an increasing occurrence up to 40-60% of the time post late July.

As shown on Figure 21 there was a general increase in the detection of biological signals towards the latter part of the recording period. Fin whales had greater detection rates at the offshore Porcupine site, blue whales were only heard at Porcupine. The toothed whale signals had comparative rates of detection and increases in detections through time at SW Porcupine Bank and East with low level detections at the North Porcupine site only.

Looking at the different study locations; SW Porcupine Bank location had the highest level of cetacean vocalisations compared to the locations closer to Ireland; with the most vocalisations for fin, blue and sperm whales. This offshore location, with the steeper slopes of the shelf break, is likely to have high levels of productivity from upwelling events, which could support larger numbers of foraging cetaceans than the other locations. In addition, previous studies have found that migrating species, such as fin and blue whales migrate through the Rockall Trough, along the edge of the Irish shelf. Many of these species are migrating south to breed at low latitudes in the winter months. Consequently, vocalisations late in this study (August and September) increase significantly compared to earlier months adjacent to the SW Porcupine Bank location.

This study has generated an enormous volume of data on the ambient, biological and anthropogenic noise at three locations in the Irish Sea. This initial analysis has just began to unravel the complex biological signals of marine mammal vocalisations which include baleen whale "songs", feeding echolocation signals or whistles, and clicks of social interaction and communication. Future work could further analyse these datasets and deploy passive acoustic arrays to cover the periods outside the period of this study (October to April) to understand seasonality of species distribution throughout the year in offshore Ireland.

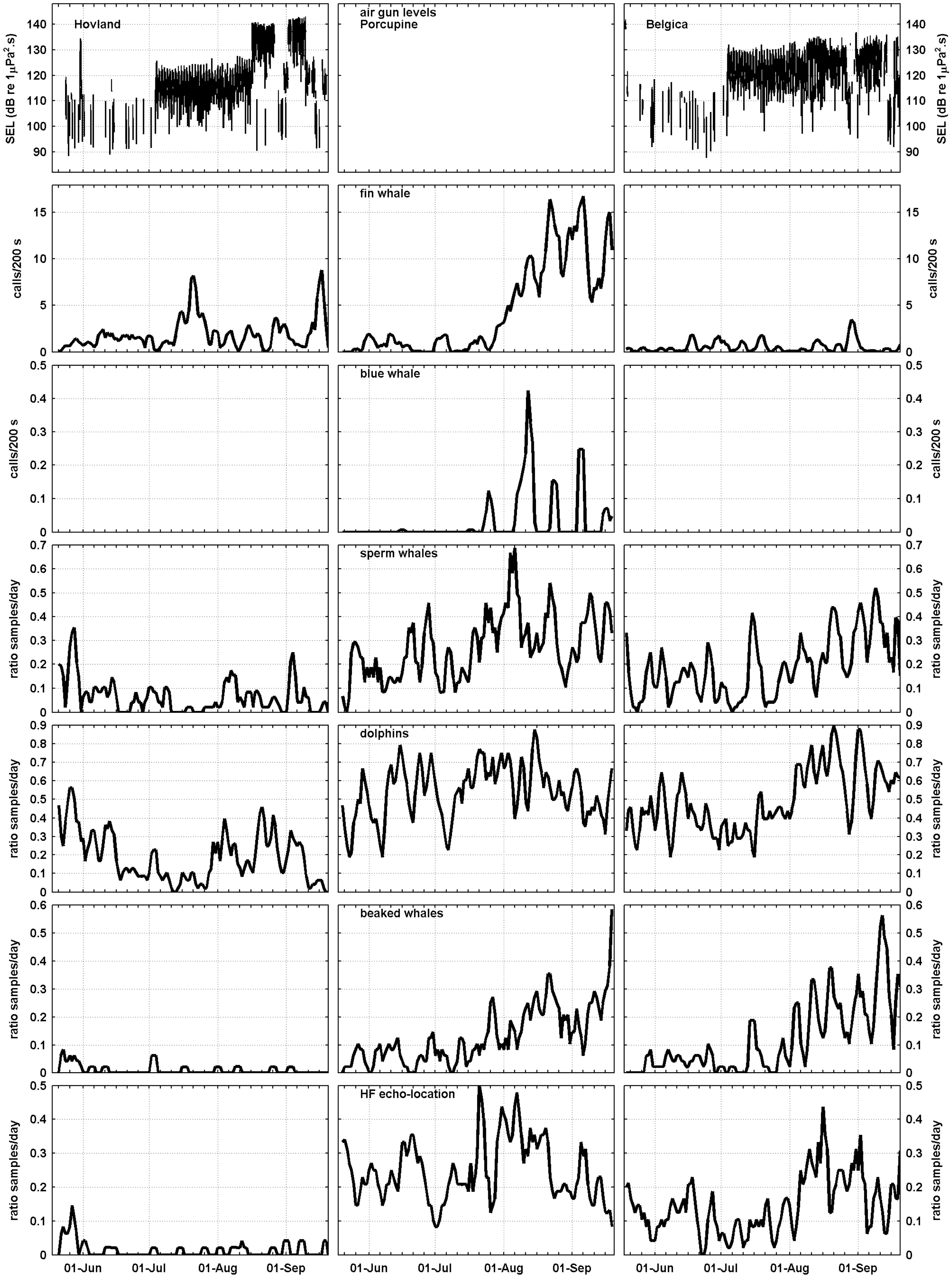

Figure 21: Air gun levels (top panels) and presence of: fin whale; blue whale; sperm whale; dolphins (whistling and echolocation clicks); beaked whales; and high frequency echolocation clicks from unidentified toothed whales, from North Porcupine (left), SW Porcupine Bank (centre) and East Porcupine (right). All biological detections are over 24 hour periods (12:00 to following day 12:00) and use a one day linear smoothing.

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Appendix 1: Acoustic units and definitions

- **dB re 1μPa²/Hz** – these are termed spectral level units. The value has been normalised so that the intensity is presented in the equivalent of a one Hz bandwidth, even if the actual bandwidth the measurement was calculated in was not one Hz. These units are used widely in underwater acoustics and are useful for comparing the energy content of different sources, as the units can be directly overlain, even if for example the power spectral frequency resolution differs.
- **dB re 1μPa –** this is the intensity across the measurement bandwidth, with the bandwidth potentially differing. The bandwidth may be across the power spectra frequency resolution or it may be across the source effective frequency (typically assumed as the default if a bandwidth is not stated), as discussed below
- **dB re 1μPa Broadband –** this is the integrated energy across the full frequency bandwidth of the source. Usually exact frequency bandwidths are not stated so it is assumed that the measurement encompasses the frequency range of dominant energy in the source (ie. the signal energy outside of this frequency range does not contribute to the overall source energy received).
- **dB re 1μPa across a 1/3 octave band –** 1/3 octaves are recognised logarithmically increasing frequency bands used in airborne acoustic studies. Each band has a defined lower frequency, centre frequency and upper frequency. The dB re 1μPa within a 1/3 octave band is the intensity summed across the band. The 1/3 octave bands are normally referenced by their centre frequency. The 1/3 octave scale was designed to mimic the frequency resolution of the human ear, which integrates energy in logarithmic frequency bands. It turns out that this is a trait common to all vertebrates, hence has wide application in studies into animal response to noise and hearing.
- **dB re 1μPa @ 1 m –** or source level – this is the intensity of a measured source at some range, which has been assumed to be a point source and which has had the transmission loss correction for that range and frequency applied. The source level is then the intensity at one m range the source would radiate if it were an infinitesimal point. Most real sources are not infinitesimal points so for large sources such as vessels and air gun arrays, where the radiated noise is actually the sum of many spatially separated sub-sources, source levels are never reached.
- **dB re 1μPa².s SEL & dB re 1μPa *msp* –** The first measure, SEL is widely termed as *sound exposure level*. It is a measurement which is approximately proportional to a signal's energy. This measurement is used to describe impulsive signals, such as air guns, which are short and sharp. For measuring long term noise the *mean squared pressure* (**MSP or *RMS***) units are commonly used. As the name suggests, *mean squared pressure* levels are simply the mean value of the squared pressure converted to appropriate dB values. To take a mean value implies an averaging time, which if the noise in question is stationary (ie. changes little over the time frame of averaging) is not of major consequence. Impulse signals are short, usually less than one second, thus the *mean squared pressure* level of an impulse measure may be critically dependant (or vary) according to the way the averaging time is defined. Since ***SEL*** measures are calculated in a way that accounts for time, they are independent of an averaging time. Given that ***SEL*** is also a closer match to the energy delivered by an impulse signal (noting that

it is not a correct energy measure itself) then the ***SEL*** value is now widely accepted as the best unit to define the approximate energy of an impulse signal. For signals of longer duration the ***MSP*** or *RMS* level is often quoted. The ***MSP*** values calculated here were averaged over the time taken for 90% of the impulse signals' energy to pass.

Appendix 2: Units, conventions, data sources

All times presented in this document are UTC. All spatial analysis has been carried out using the Matlab mapping toolbox in great circle distances. All analysis has been carried out using software developed at CMST in the Matlab environment. A definition of acoustic units is given in Appendix 1. Bathymetry was retrieved from the ETOPO1, 1 Arc-Minute Global Relief Model (http://www.ngdc.noaa.gov/mgg/global/global.html). Vertical sound speed profiles were calculated using data from the World Ocean Atlas 2005 (WOA05, see http://www.nodc.noaa.gov/OC5/WOA05/pubwoa05.html). Unless stated otherwise, all errors are ± 95% confidence limits.

Appendix 3: Data quality

There were some issues of mooring noise, believed primarily due to the vertical in-line mooring vibrating, moving the hydrophone and so producing noise artefacts. The mooring noise did not compromise the ability to analyse data, either spike rejection techniques were used to remove noise spikes or sections with high mooring noise were not included in the appropriate analysis. In sea noise recordings mooring noise is far too common, with the most robust technique to produce noise-free recordings in long term sea noise logger deployments being to lay hydrophones on the seabed, rather than as deployed here, as part of an in-line mooring.

The HF loggers (commercially purchased) were calibrated from frequencies above 1 kHz but as they were not able to be directly calibrated their response below 1 kHz was not known. Without directly calibrating them one cannot be sure of the impedance matches between hydrophone, pre-amplifier and digitising electronics which together act to change the system response in the low frequencies. As it transpired the HF systems were checked against the LF loggers at low frequencies using in-situ, time-matched samples and were found to have roll offs below around 100-300 Hz. The HF loggers also had sharp jumps in system response around 1 kHz. The clocks of the HF loggers were not corrected for drift (there was no accurate technique for doing this). None of these issues compromised data analysis, provided one was aware of the limitations of the system used.

One of the LF loggers (set 3302) suffered a temporary drop in sensitivity throughout the recording period (sensitivity in the low frequencies dropped then recovered). This was due to a faulty underwater connector changing the hydrophone capacitance 'seen' by the pre-amplifier (slight corrosion in the connector changed the hydrophone-cable-connector capacitance, which changed the system frequency response). This sea noise logger is the only one of the CMST pool with an underwater connector. We retain the connector as this hydrophone is massive, designed for low frequencies (General Instruments C32) and so cannot be left physically connected to the end cap when the system is not deployed. The hydrophone is very high capacitance and if correctly calibrated (as per here) is capable of recording sea noise down to 0.01 Hz. The drop in system sensitivity did not compromise data analysis as we worked around the problem.

A major problem with analysis was the sustained presence of air gun signals in the recordings, with at times signals from three seismic sources arriving. Various sound transmission phenomena acted to transform these signals at long range into a large variety of forms, with signals stretching to be many s long in some cases. The air gun signals caused large amounts of false detections in the biological signal search algorithms (the algorithms incorrectly triggered on an air gun signal) for the low frequency search routines. Various techniques to reduce air gun false detections were applied, but for some signal types manual checking was the only way to be sure false detections did not occur. This is documented below were appropriate.

Appendix 4: Hardware and moorings

The moorings were deployed in conventional oceanographic moorings where the instrument was bolted into a vertical riser, with floats above and acoustic releases (dual releases used) plus 200-300 kg of weight below. A schematic of the SW Porcupine Bank and East Porcupine moorings is shown on Figure 22. This mooring design is not optimal for obtaining artefact free sea noise recordings so techniques used to try and reduce mooring induced hydrophone movement were: use of 'hairy ropes' to break up turbulent flow along moorings lines and so reduce cable strum; hydrophones mounted on soft, suspended 'arms'; and vanes on instruments so as to align the hydrophones into any subsea currents. In general all recordings were of high quality although some had more noise artefacts than others.

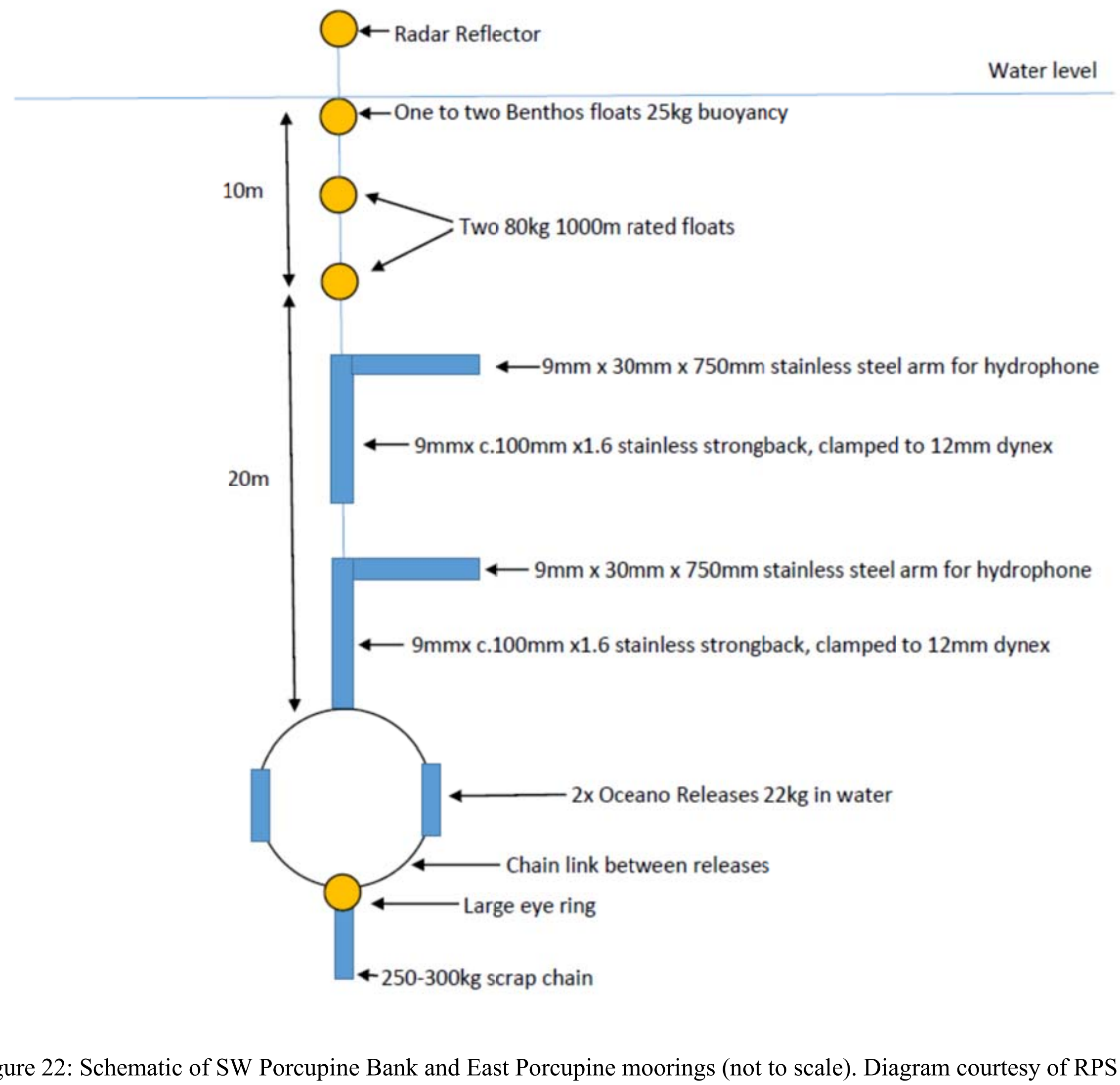

Figure 22: Schematic of SW Porcupine Bank and East Porcupine moorings (not to scale). Diagram courtesy of RPS Metocean.

Details of the deployments are listed in Table 8. The locations, depth of receivers, sampling regime with logger duty cycle plus electronics and hydrophones used are listed. The low frequency noise loggers were proven CMST-DSTO types made at Curtin University. These used a 360 s sample (the electronics adds a small time for settling of electronics so actual samples were 368-369 s long) made every 15 minutes at 5 kHz sample rate with a roll off applied to flatten the low frequency noise and so improve the system dynamic range. The loggers were calibrated by inputting white noise of known level in series with the hydrophone. This way the full system response was obtained including the impedance match of hydrophone to pre-amplifier, impedance match of pre-amplifier to recording electronics and the roll off applied. The system gain responses to the white noise are shown on Figure 23. The set 3302 system used the General Instruments C32 hydrophone which had a much higher capacitance than the HighTech U90 hydrophones used on the other instruments, hence its response in the low frequencies followed exactly the roll off deliberately applied while the U90 hydrophones began rolling off at a slightly higher frequency. The hydrophone sensitivity plus the system gain with frequency were used to calibrate input signals in the time or frequency domain as required. Note that just before the deployment we were advised that seismic survey activity would take place near several of the proposed mooring locations, with the exact range of closest approach not known but considered as 'close'. The authors experience is that the systems when run at full gain (40 dB as shown on Figure 23) may overload for a large air gun source (> 4000 cui) within 10 km range. Thus to avoid any potential overloading on the receivers all of the low frequency systems were set with split sampling at 20 and 40 dB gain, as shown on Figure 23 In this mode the system sampled at 10 kHz and applied x 1 gain after the A-D input (20 dB gain was applied at the pre-amplifier) to the odd samples (so total system gain was 20 dB) and x 10 gain to even number samples (so 40 dB gain). Thus two 5 kHz channels were sampled, with 20 and 40 dB gain respectively.

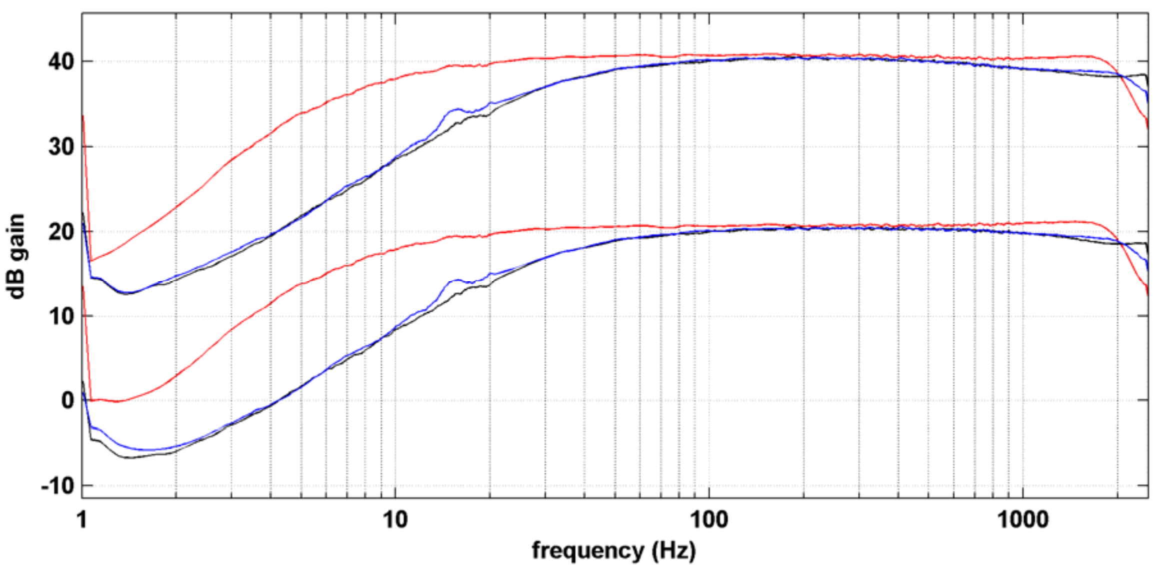

Figure 23 System gain with frequency calibrations for the low frequency CMST-DSTO sea noise loggers. The red curves were for SW Porcupine Bank (set 3302), the Black curves from the east Porcupine (set 3307) and the blue curves from the north Porcupine (set 3301).

The on-board clocks of the CMST-DSTO loggers were set to UTC time before deployment and the drift read after deployment using a GPS Genius and software/hardware modifications which interface the GPS to the instrument. Absolute timing accuracies of ± 250 ms were available at any point in the deployment for the LF loggers, noting the clocks are adjusted to within µs to the GPS but they jump when the gear is deployed and recovered due to the sudden temperature change, hence the larger time error.

The high frequency noise loggers used the Wildlife Acoustics SM2 bat recorder electronics. One system (north Porcupine, set 3303) used the SM2 electronics in a Curtin designed package with Curtin pre-amp, a Reson TC 4033 hydrophone set on a short flying lead (high quality and a high frequency response, hydrophone suspended on a soft pole away from the housing), separate pre-amplifier and SM2 power supplies, in a housing used for the CMST-DSTO noise loggers. This system was capable of being calibrated with white noise. The other two high frequency noise loggers were as purchased from Wildlife Acoustics using the SM2 electronics card with hydrophones built into the end caps of the instruments. These systems were not capable of being calibrated to check their frequency response so we can only assume the system calibrations as per the instrument settings and stated hydrophone sensitivities. All of the high frequency instruments were designed to collect data above 1 kHz. Because of limitations in the hardware, notably the relatively low hydrophone capacitance's, they were not accurate at frequencies below ~ 100 Hz. We did comparative measures of LF versus HF systems which shows the difference in sensitivity at low frequencies.

All high frequency noise loggers were set with the same sampling regime of a 500-700 s sample every 90 minutes at 192 kHz with 44 dB system gain (according to the system settings). The SM2 electronics tend to skip samples occasionally so not all samples were collected. The samples were set as reasonably long duration as the SM2 hardware / software version used gradually reduces the length of samples collected during a long deployment.

The software in the generation of SM2 Wildlife Acoustics cards used did not write the file start times into the saved *.wav files thus the sampling times are derived from the time stamps embedded in the file names. This is assumed to be the time the file was started (which will not be the same as the time sampling of the sea noise started). The clocks on the high frequency noise loggers could not be calibrated for drift across the recording period.

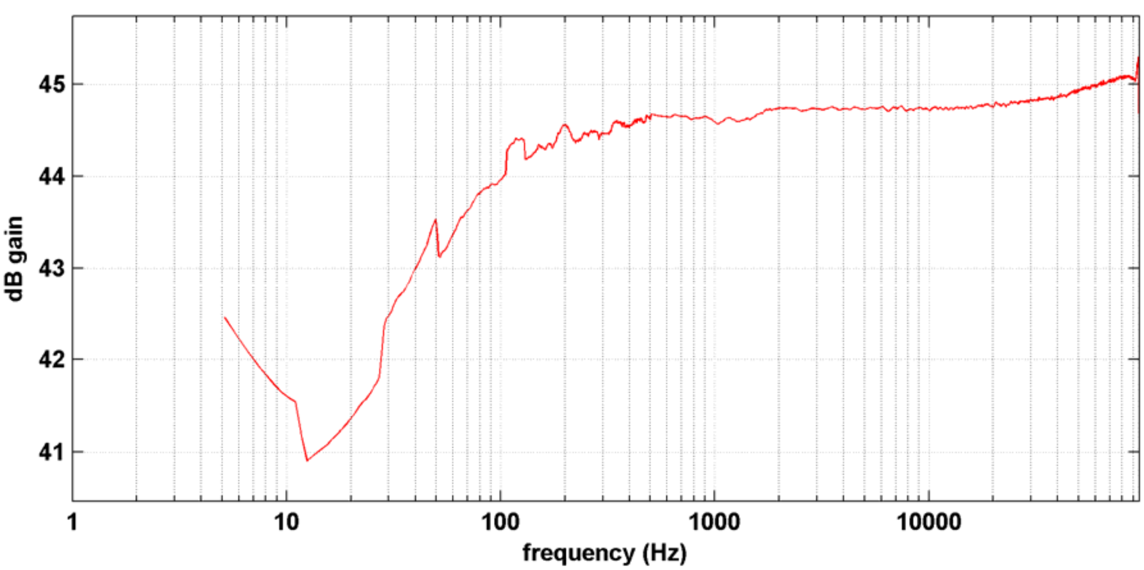

Figure 24: System gain with frequency for the high frequency sea noise recorder used at north Porcupine (data set 3303).

Table 8: Summary of sea noise logger deployments. The fields are: the location and Curtin set number; latitude; longitude; time of first record in-water (UTC); time of last record in water (UTC); number of days sampled (in-water); depth of receiver (m) / depth water (m, from ETOPO-1); sample numbers in-water; mean sample length; mean sample increment; the system electronics and hydrophone type (GI= General Instruments, HTI = HighTek, TC4033 = Reson) and serial number.

Set	**Latitude (N)**	**Longitude (W)**	**Time start sampling**	**Time end sampling**	**Days**	**Depth (m)**	**samples**	**Length (s)**	**Increment (min)**	**Electronics / hyd.**
North Porcupine 3301	52 22.775	12 58.842	20-May-2014 13:00	19-Sep-2014 17:45	122.2	596 / 610	1 - 11732	368.8	15	E28/ HTI U90 4540034
North Porcupine3303	52 22.775	12 58.842	20-May-2014 13:06	19-Sep-2014 16:06	122.1	596 / 610	1 - 1949	400	90	SM51/ TC4033 4512014
SW Porcupine Bank 3302	51 52.660	15 1.344	19-May-2014 13:00	19-Sep-2014 05:00	122.7	767 / 1257	1 - 11777	368.8	15	E35 / GI C32
SW Porcupine Bank 3304	51 52.660	15 1.344	19-May-2014 13:06	19-Sep-2014 04:06	122.6	767 / 1257	1 - 1963	500	90	SM1/ HTI-99-HF 681431
East Porcupine 3307	51 22.904	11 37.446	18-May-2014 13:00	20-Sep-2014 06:45	124.7	545 / 611	1 - 11941	368.8	15	E32/ HTI U90 4540002
East Porcupine 3305	51 22.904	11 37.446	18-May-2014 13:06	20-Sep-2014 05:36	124.7	545 / 611	1 - 1996	510	90	SM2/ HTI-99-HF 681429

Appendix 5: Estimation of logger listening ranges

Noise logger listening ranges were calculated to define the detection area of a noise logger for various whale calls. The noise logger listening area is species and site specific, dictated by: the frequency range of the call; the average call source level (energy radiated at an equivalent of 1 m range); the depth of the calling whale and receiver; the ambient noise; and sound transmission at the site. Listening ranges have been calculated for fin and blue whales. These listening ranges were calculated by:

1. Deciding on the frequency span of the call and dividing this into a number of discrete frequencies spanning the main energy output of the call (since sound transmission modelling runs at discrete frequencies);
2. Obtaining representative call source levels.
3. Obtaining representative caller source depths (the modelling requires a source depth and this depth may be critical in lateral sound transmission). The modelling carried out here assumes a range of caller source depths based on the literature.
4. Defining the bathymetry paths on radial headings run from the receiver location. The sound transmission models are then run along each heading accounting for variable topography.
5. Defining the seabed geo-acoustic properties and the water column sound speed profile along each heading. These have been assumed to be constant along each heading from the source.
6. Running a sound transmission model set up for each frequency and environment along each heading. This was done using the theory of reciprocity where the calculations were made with the source at the receiver location (hydrophone) and the receiver in the water column (where the real-source would be). The model runs allow the full water column vertical sound field to be calculated (usually around a one m vertical step) out to the range limit set (range resolutions of 10 m out to 220 km except where water depth was < 50 m). Using reciprocity a selection of source depths can then be chosen and the modelled source-receiver orientation switched with the real source-receiver orientation, so that the real-receiver becomes the hydrophone location and the real-source is in the water column. Using reciprocity in source and receiver location greatly reduces the number of runs of the sound transmission model required.
7. Along each heading the sound transmission modelling output was averaged across the frequency span of the call and the assumed source depths, to give an energy loss for the call with range from the receiver.
8. The call source level had the averaged sound transmission loss subtracted to give the estimated received level at the hydrophone, with range from the source.
9. This curve of estimated received call level with range was smoothed using a probability approach outlined in McCauley et al (2001), which defined the range at which the call was present at a prescribed received level, 95% or greater, of the time.
10. This curve was run down to the ambient noise level in the frequency band of the call, to determine the outside call detection range. This step was determining the outside range signals were detected at by the noise logger given the prevailing noise conditions. In the detection calculations to locate call types the appropriate search algorithm normally does not detect calls down to the background noise state (the algorithms have a threshold above ambient noise the signal must exceed before the detection threshold is tripped).
11. The call outside detection range for the defined conditions were interpolated between headings around the receiver to give a polygon of call listening area.
12. Where appropriate the influence of any blocking bathymetry was calculated and sections with shallow bathymetry removed from the listening area polygon. The depth profiles along a series of closely spaced headings around the receiver were retrieved from a bathymetry atlas for the area and ranges at which the seafloor became too shallow for a whale to be in, were tagged.

The polygon around the receiver location was then adjusted to the range limited locations along each heading.

The polygons of listening radii along multiple headings from the receiver location were then used to give search areas for different combinations of ambient noise, source calling depth and source levels. The details of source levels, calling depths and ambient noise levels used in calculations are given in the respective fin and blue whales results sections. The search areas were calculated from the polygons using the Matlab mapping function to build the latitude and longitude co-ordinates of the listening range boundaries then calculating the area defined assuming a spherical earth.

Note that in step 10 above the calculations did not consider the additive effect of the signal and the background noise. On running a signal down until its actual level is equivalent to the ambient noise level in the frequency band of the call (assuming a flat ambient noise spectra) then the measured signal of the animal call will be approximately 3 dB greater than the ambient noise level since the noise has added energy to the call. That is, if the call threshold for the detection algorithm is 3 dB then the actual call level without the additive effect of the noise, is the same as the ambient noise level. This was deliberately done as it roughly equates the ambient noise level with the actual call level and partially accounts for the thresholds used in the search algorithms.

A5.1 Fin whale listening area calculations

Estimation of the listening ranges for fin whales was made from each location. Sound transmission modelling was run along radial headings at 45^{o} increments out to 120 n mile (or 222 km) from each receiver location as shown on Figure 25 with the bathymetry profiles shown on Figure 26. Bathymetry profiles were truncated if they ran into water depths of < 50 m. The sound transmission model RamGEO was used to calculate transmission loss at frequencies from 15-30 Hz in 1 Hz steps at a 1 m vertical resolution and 10 m horizontal resolution with data spanning the full water column saved. A soft seabed overlying bedrock was used for the seabed with geo-acoustic parameters listed in Table 9. A vertical sound speed profile for June was selected from the World Ocean Atlas 2005.

For fin whales the signals were tonal (spanned a narrow frequency range), so calculated transmission loss grids were averaged over frequencies of 20, 21 and 22 Hz and using a source depth of 20-40 m. Note that most of the studies which have defined depths of calling baleen whales have returned depth ranges of 20-40 m (i.e. Thode et al. 2000). A calling baleen whale will be restricted in its workable depth by constraints on the physics of oscillating the lung space (i.e. Jones et al. 2003). If the whale dives deeper the lung space resonant frequency and efficiency will increase, if the animal shallows its resonant frequency and efficiency (and so source level) will decrease. The 20 Hz 1/3 octave spans the frequency band 17.5 - 22.1 Hz so covers the dominant spectral bandwidth of the fin whale call (see Appendix 10). A fin whale call source level of 186 dB re 1 μPa was assumed as the upper level (Watkins et al. 1987) and to account for expected individual variation a 3 dB down (half power) source level of 183 dB re 1 μPa was also used to estimate listening range. Ambient noise will have a great influence on the detection range of signals. The ambient noise levels at North and East Porcupine were averaged for each month and are presented in Table 16 and Table 17 respectively (the same statistics were not calculated at Porcupine due to problems with the variable sensitivity of the LF logger and that the HF loggers could not be correctly calibrated at low frequencies). At North and East Porcupine the 20 Hz 1/3 octave ambient noise increased over the recording period (May to September) from 88-107 dB re 1 μPa and 87-102 dB re 1 μPa respectively with mean values of 100 and 96 dB re 1 μPa respectively. The higher ambient levels in this frequency band later in the season were possibly due to the presence of large numbers of calling fin whales or seismic signals. The distributions of received fin whale call levels shown in Appendix 10 Figure 54, agree with the ambient noise estimates as the cut-off seen in detections (at the 101.25 dB level) was due to signals only accepted by the search algorithm if they were 5 dB > ambient noise, suggesting the ambient noise averaged around 96 dB re 1 μPa.

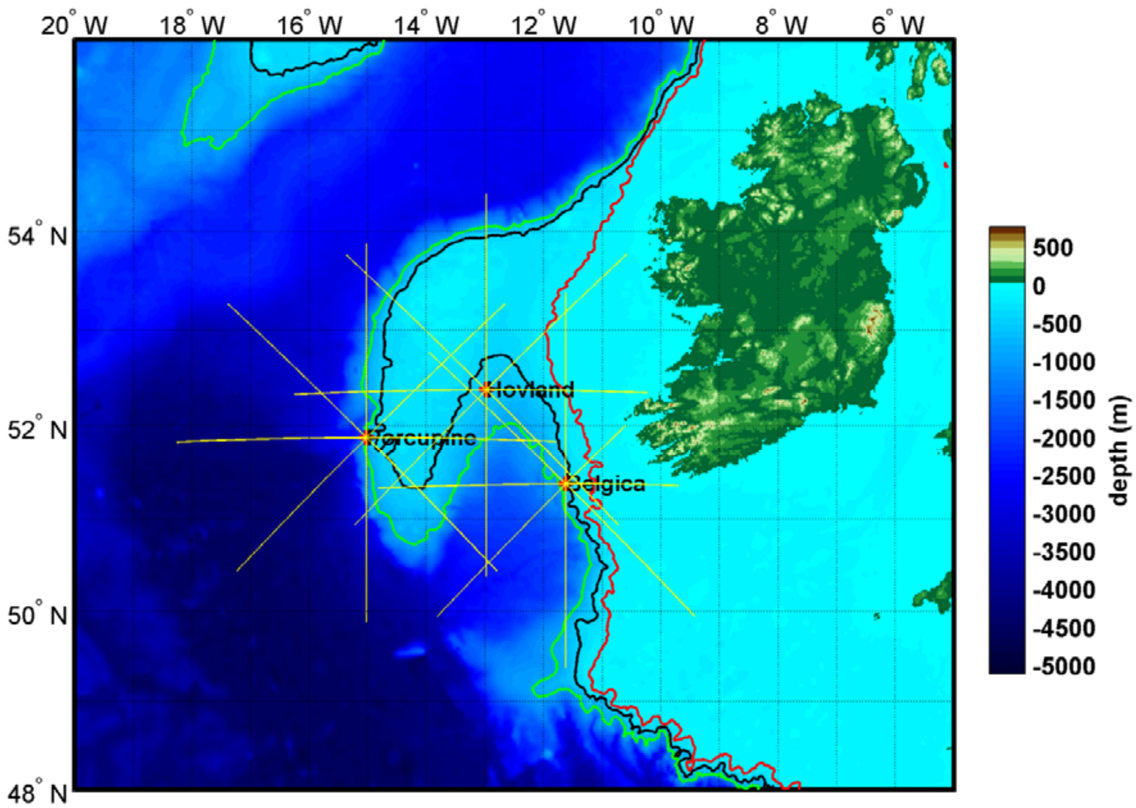

Figure 25: Locations of headings along which sound transmission models were run to estimate fin whale call detection range. The depth contours shown are: 200 m (red); 500 m (black); and 1000 m (green).

Table 9: Seabed acoustic properties used in modelling fin whale call transmission.

Layer thickness	**material**	**Density (kg.m^{-3})**	**Compressional wave speed (ms^{-1})**	**Compressional wave attenuation (dB per wavelength)**
50	Silty sand	1770	1620	0.9
> 50	basement	3500	4500	0.1

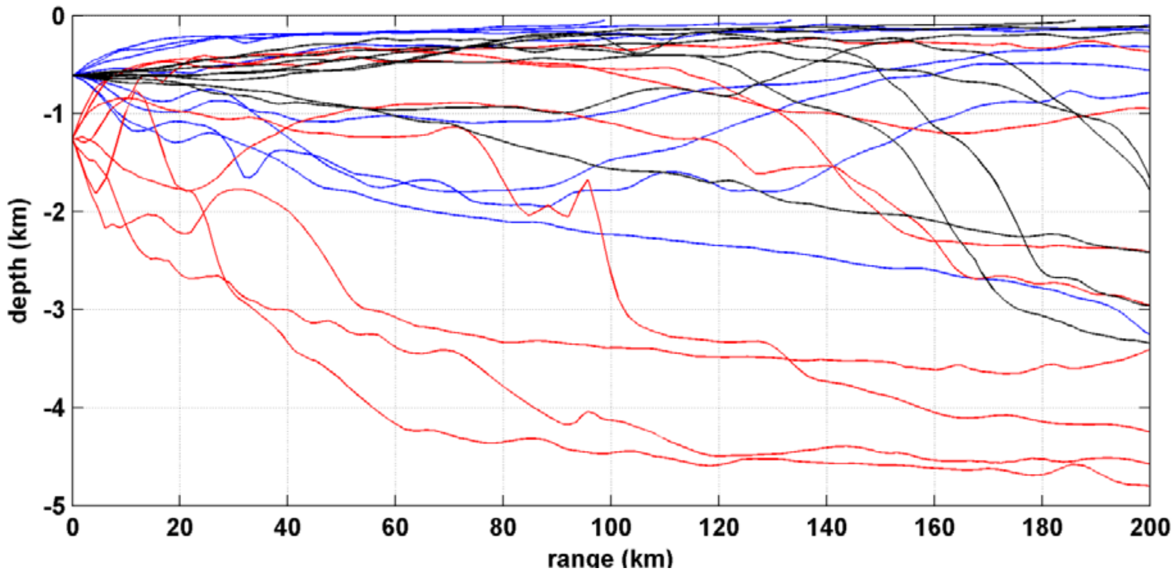

Figure 26: Bathymetry profiles along each heading shown on Figure 25. The curves are coded as: blue - East Porcupine; red - SW Porcupine Bank; black - North Porcupine.

The calculated detection ranges for fin whales at each site along the eight different headings is listed in Table 10 using two source level estimates and background noise levels. In Table 11 the estimated detection areas are listed for the two source levels and a range of ambient noise levels at the three sites. In Table 12 the overlap of detection areas for four regimes of ambient noise and the higher source level are listed. To explore the impact of changing ambient noise levels, the noise loggers listening areas are shown for a range of ambient noise levels on Figure 27. For a background noise level of 96 dB re 1 µPa in the fin whale call bandwidth (around the average) the detection areas at each site are shown on Figure 28. A number of features are evident from Figure 27 and Figure 28, which are:

- the detection range for fin whale calls varied enormously around each site with heading, source level and ambient noise;
- fin whale call transmission was worse when the source was in shallow water (i.e. inshore of East Porcupine);
- fin whale call transmission was worse when the source was over a seabed sloping upwards towards the receiver (i.e. East Porcupine to SW, SW Porcupine Bank to E);
- fin whale call transmission was better when the seabed depth between source and receiver was comparatively uniform (i.e. to the south of East Porcupine);
- fin whale call transmission was better when the seabed sloped downwards from the source towards the receiver (i.e. North Porcupine to SW, or East Porcupine to NE);
- For an ambient noise level of 96 dB re 1µPa the listening areas for fin whales overlapped between the North and East Porcupine sites but not for the SW Porcupine Bank site;
- At high ambient noise levels (110 dB re 1µPa) listening areas dropped to 1-2 x 1,000 km^2 (186 dB re 1µPa source level) at low ambient noise levels (86 dB re 1µPa) listening areas increased to 72, 85 & 46 x 1,000 km^2 (186 dB re 1µPa source level, East, SW Porcupine Bank and North Porcupine respectively) or up to 80 times difference (worst case, comparing 86 and 110 dB re 1µPa ambient noise at SW Porcupine Bank);
- ambient noise levels had relatively constant impacts on listening area at North and East Porcupine (that is the change in listening area was roughly linearly proportional to the increase

in ambient noise in dB) but at porcupine listening area increased dramatically as ambient levels fell below 95 dB re 1µPa, due to the increase in available area in deep water to the west.

Table 10: Estimated detection range for fin whale signals (km) at each site for two source levels and two background noise levels (96 / 100 dB re 1µPa).

Site	0°	45°	90°	135°	180°	225°	270°	315°
B. 183 dB	68.9/ 55.5	44.5/ 38.5	39.5/ 34.5	46.3/ 42.3	36.1/ 32.7	37.1/ 32.1	156.7/ 42.1	150.5/ 33.9
B. 186 dB	81.3/ 63.1	57.1/ 42.7	52.7/ 37.9	58.1/ 44.1	186.3/ 34.7	57.3/ 36.3	166.9/149.3	175.1/112.9
P. 183 dB	77.3/ 60.1	49.3/ 35.7	52.1/ 44.3	53.5/ 33.1	53.5/ 31.5	41.3/ 26.7	54.5/ 37.9	48.3/ 41.1
P. 186 dB	86.7/ 70.7	61.3/ 44.7	58.9/ 50.1	64.1/ 51.9	74.5/ 49.1	67.7/ 41.5	76.3/ 53.1	89.7/ 46.3
H. 183 dB	68.5/ 44.5	69.9/ 55.9	77.3/ 63.3	140.5/ 47.9	53.7/ 43.1	69.5/ 53.1	58.7/ 43.5	52.1/ 40.9
H. 186 dB	74.7/ 61.7	79.5/ 67.3	81.9/ 73.9	148.5/ 99.3	69.7/ 51.9	86.5/ 65.5	66.3/ 52.7	59.9/ 50.3

Table 11: Estimated detection areas (in units of 1000 km^2) for fin whale detections at the three sites with differing ambient noise regimes and call source levels.

Back (dB re 1µPa)	**East Porcupine (1000 km^2)**		**SW Porcupine Bank (1000 km^2)**		**North Porcupine (1000 km^2)**	
	183 dB SL	**186 dB SL**	**183 dB SL**	**186 dB SL**	**183 dB SL**	**186 dB SL**
85	67.2	75.8	77.0	89.2	41.2	49.5
90	51.5	60.0	32.6	64.4	29.0	35.3
95	25.8	43.3	11.3	18.9	20.4	24.6
96	22.2	40.6	9.2	16.8	18.5	23.2
100	4.9	17.2	4.9	8.3	7.7	13.9

Table 12: Estimated overlap (1000 km^2) between sites for fin whales using a source level of 186 dB re 1µPa and various ambient noise levels.

Ambient (dB re 1µPa)	**East Porcupine & SW Porcupine Bank**	**North & East Porcupine**	**SW Porcupine Bank & North Porcupine**
85	11.3	37.3	10.8
90	3.6	26.0	30.9
95	0	15.9	0
96	0	14.6	0
100	0	30.4	0

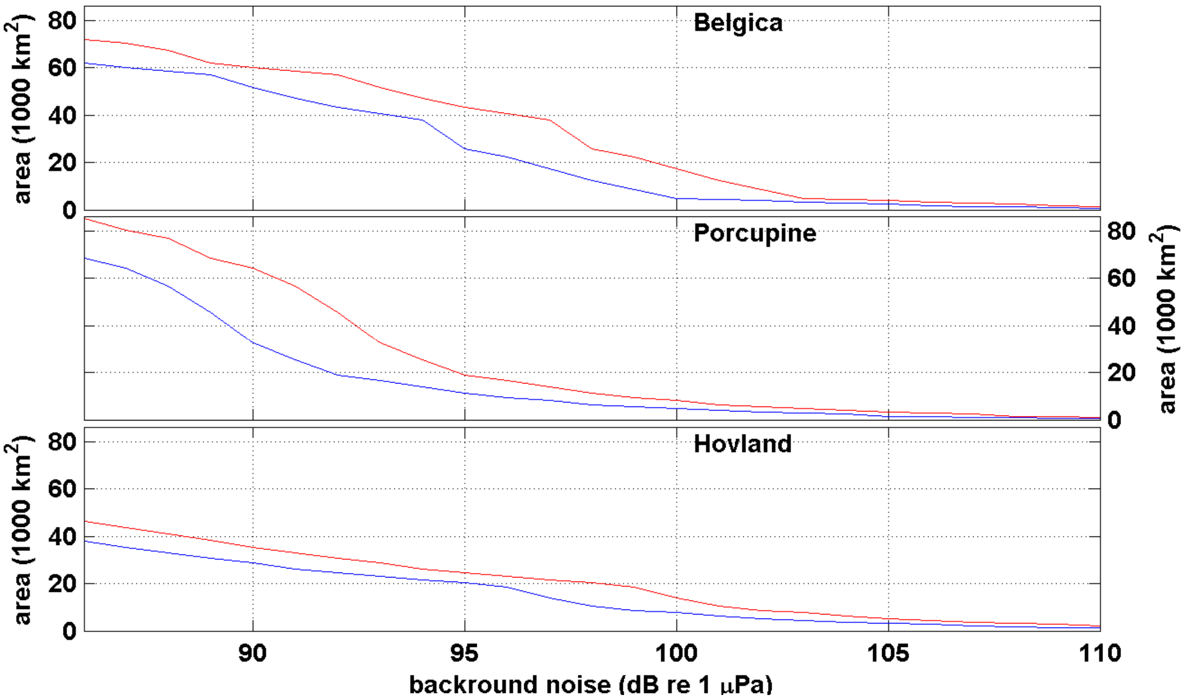

Figure 27: Estimated listening areas at each site for fin whales using two source levels (186 dB re 1µPa red curves and 183 dB re 1µPa blue curves) for a range of expected ambient noise levels in the fin whale bandwidth (starting at 86 dB re 1µPa, which would be near the lowest ambient noise level expected at the sites).

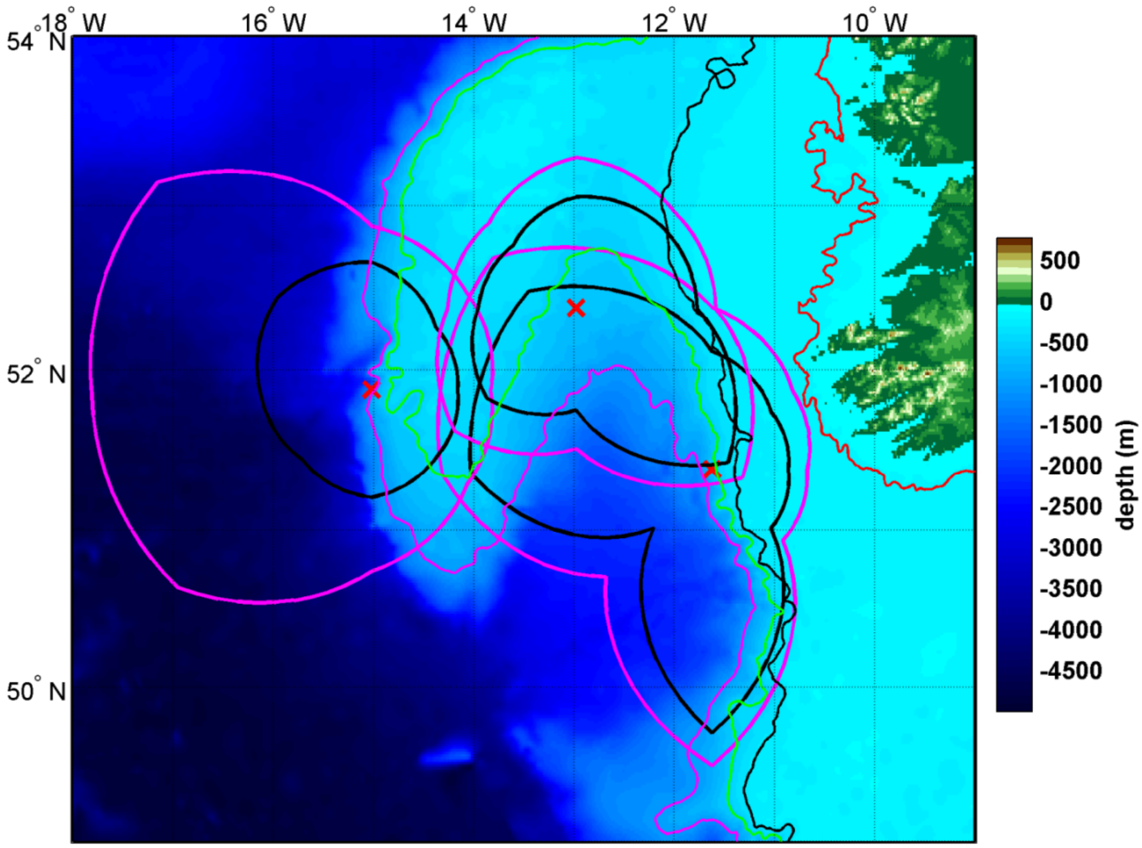

Figure 28: Estimated listening area for fin whales at each site for background noise levels of 90 dB re 1µPa (black curves) and 96 dB re 1µPa (magenta curves) and an assumed fin whale source level of 186 dB re 1µPa.

While the listening area for fin whales could be quite large, and was many tens of thousands of km^2 under low ambient noise regimes it was also highly variable depending on the bathymetry path taken from the receiver location (i.e. heading), the animal source level and the ambient noise regime.

A5.3 Blue whale listening area

The calculations for blue whale estimated listening range were similar to those carried out for fin whales except the frequencies used to estimate transmission loss were 16-17 Hz (the 2014 blue whale calls had a strong tonal peak at close to 16.8 Hz). The ambient noise regime in the 16 Hz 1/3 octave showed similar trends to the 20 Hz 1/3 octave and similar values of ambient noise (Table 16 and Table 17). The listed source level of blue whales is 186 dB re 1µPa (McDonald et al, 2001), the same as that for the high end of fin whale calls. The calling depth of blue whales was considered to be the same as for fin whales, in the depth range of 20-40 m. The table of listening areas at different ambient noise regimes and a plot of calculated detection areas was included for blue whales in section 4.1.

Appendix 6: Air Gun Analysis

Air gun signals were extracted from the sea noise logger data sets by two techniques: 1) a general technique which located samples with air gun like signals then automatically extracted and analysed the signal levels; or 2) by correlating seismic survey lines with sea noise logger samples then using a purpose built GUI to display appropriate samples, set up the analysis parameters, locate and bracket each air gun signal, remove any bad detections and to analyse each signal for various parameters (as defined in McCauley et al 2003). The method for technique 1) involved looking for repetitive impulsive signals of a given length and repeated within a certain time frame. This technique gave a summary of air gun levels across the full data sets. The latter, more accurate technique looked at individual signals and correlated these with the source navigation data to link in parameters of range and angle of receiver from the tow direction. The technique 1) thus gave a broad summary across all of the data sets, while technique 2) gave signal levels with range and aspect. The methodology for technique 2) involved:

1. Locating sea noise logger samples with air gun signals in them by correlating the air gun time/location from the navigation data with the sea noise logger sample times, accounting for estimated travel time.
2. In a graphical user interface (GUI) designed to deal with air gun signal extraction, visualising each high gain sea noise sample (spectrogram and waveform) with potential air gun signals, obtaining a voltage threshold which delineated air gun signals from the noise and setting the pre- and post- time brackets around the detections (the time window to analyse the signal in);
3. Using the signal filtered to keep the waterborne energy (removing ground borne energy), located the leading edge of each air gun signal using the voltage threshold set and a minimum time limit of how far apart consecutive signals must be (5 s used);
4. Checking the input voltage of each air gun signal for overloads and loading the low gain channel if an overload was found (the sea noise loggers are considered as overloaded if the voltage is $\geq \pm$ 2.4 V). No overloaded signals were found in this data set.
5. Displaying the location of the waterborne arrival in the GUI and manually removing any false detections.
6. Obtaining a time period to bracket the waterborne signal with, which was nominally set at ± 3 s but altered if the air gun signal leading or trailing energy around the detection fell outside of this window.
7. Bracketing the identified air gun signal time window using a multiple of two points, extract the signal and calibrate to Pa accounting for any non-linearity's in the system gain with frequency (see below) and using the system hydrophone sensitivity for the appropriate channel. This step gave the calibrated air gun signal waveform in Pa.
8. Calculating a suite of signal descriptors as described in McCauley et al (2003) plus identifying the time of air gun signal waterborne arrival.
9. Calculating the power spectra of each sample (as close as possible to a 1 Hz bandwidth used).
10. Looping through all identified air gun signals and saving the signal descriptors, received times, power spectra and the calibrated air gun waveform.

Each air gun signal was calibrated from volts to Pa by extracting the noise logger signal bracketing the identified air gun signal in a multiple of two points which was greater than the identified signal length and passing this to a program which:

- Calculated the system gain in linear units at a frequency spacing close to 0.5 Hz from 0 Hz to the Nyquist frequency, this gain including the hydrophone sensitivity.
- Returning the FFT of the input waveform section (multiple of two points) at a frequency resolution of close to 0.5 Hz.
- Applying the linear gain correction to the FFT amplitude.
- Assuming a unity phase correction applied to the FFT phase.
- Inverting the FFT back into the time domain.
- Extracting the required air gun signal (since it was of shorter duration than the section calibrated) from this corrected section of the waveform.

The analysis gave the air gun signal descriptors, power spectra, received arrival time of signals (logger clock corrected for drift) and the signal waveform.

The time of each received air gun signal was then used to extract spatial information of the receiver location relative to the source. This involved:

1. Use the received shot time at the sea noise logger (waterborne arrival) to locate the closest shot in the air gun track file, then iterate the time / range of this and the previous few shots allowing for signal travel time, to find the fired shot point which best matched the fired time plus estimated travel time to give the sea noise logger received time;
2. For the identified air gun fired location calculate: the receiver range; the air gun speed and heading (accounting for the flip-flop nature of 3D seismic alternating between two sources if appropriate); the take-off angle of the receiver to the air gun heading (i.e. angle of the receiver from the air gun heading);
3. As an option, calculate the bathymetry profile between source and receiver using 1000 points;
4. Save all data.

All data was saved in a standard format.

Appendix 7: Sonar signals

A number of instances of sonar signals, military and ships sonars occurred in the data sets. These occurrences are not analysed in detail here, although an example of a high signal to noise ratio military sonar signal is shown on Figure 29. These sonar signals occurred over periods of several hours.

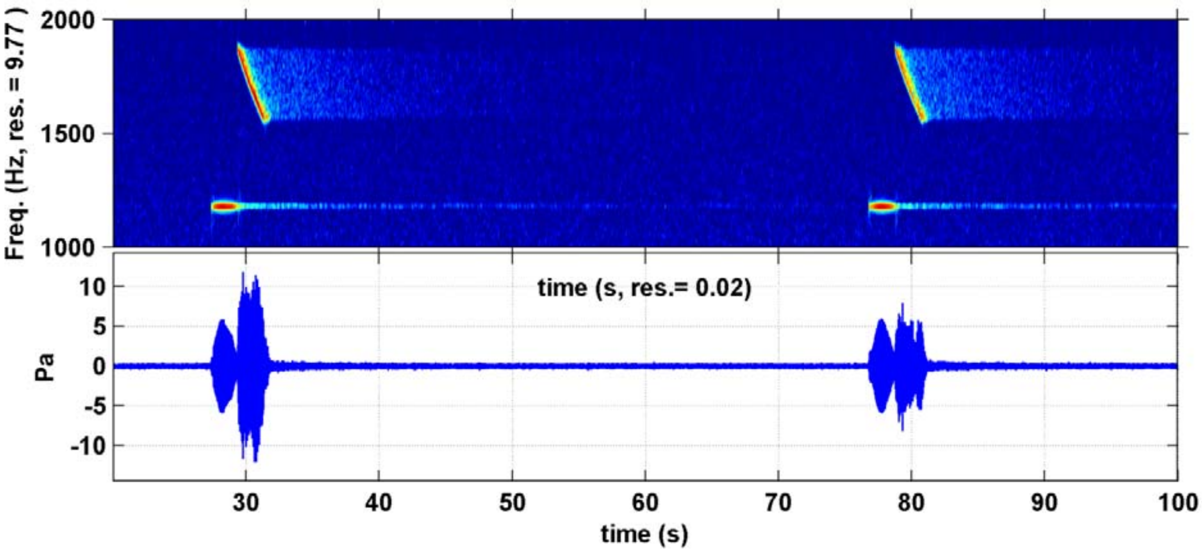

Figure 29: Example of two sets of sonar signals, each composed of a tone burst and a frequency sweep. Reverberation carries on for many s after each signal.

Appendix 8: Ambient noise

A8.1 Low frequency noise logger ambient noise

The low frequency sea noise loggers (LF) were calibrated from 2 Hz to 3 kHz and used to define ambient noise levels at North and East Porcupine. Ambient noise levels could not be defined at SW Porcupine Bank as the LF logger at this site suffered a change in sensitivity and the HF noise logger was not able to be correctly calibrated in the low frequencies.

Ambient noise levels were calculated for periods with and without the seismic survey sources present. The primary analysis of ambient noise was generated using the low frequency (LF) noise loggers (set numbers 3301 and 3307). Two of the high frequency Wildlife Acoustics units (HF) were not capable of being calibrated (sets 3304 and 3305) at the instrument level. These instruments were as purchased from Wildlife Acoustics and came with no capability of calibration so one is reliant on all aspects of the system and the interplay between different system components being as specified. As will be seen, this was found to not be the case at low frequencies. A third HF logger (set 3303) used the SM2 Wildlife Acoustics data logging electronics fitted with a Curtin pre-amplifier and hydrophone in a way where it could be calibrated. The system response of this one agreed with the LF loggers over its useable bandwidth and the overlap bandwidth of the two systems.

To reiterate the calibrations, the LF loggers and the HF logger set 3303 were calibrated by inputting white noise of known level in series with the hydrophone. The white noise generators are purpose built and their outputs are checked against a spectral analyser with a traceable reference standard. White noise is fed into the recording system with settings as for the deployment and recorded for 1-5 minutes. The signal captured is then analysed and the difference between the signal input into the system and the captured signal gives the system gain with frequency. This curve is then used with the hydrophone sensitivity from its calibration sheet, to give system corrections with frequency, to convert from either the time or frequency domain, into calibrated units. For the hydrophones CMST buys we always insist on calibration sheets from the supplier for each hydrophone. By inputting the white noise in series with the hydrophone we account for any impedance mis-match between the hydrophone and pre-amplifier and the pre-amplifier and recording electronics. The calibration curves are never flat, there is always some roll off in the systems.

The ambient noise at north Porcupine and east Porcupine were calculated from the saved 1/3 octave values using the 1/3 octave bands with centre frequency from 8 Hz to 2520 Hz which covered the bandwidth from 6.59 to 2828 Hz. The 1/3 octave values were derived from the time averaged spectra made across each sample. An analysis of ambient noise was undertaken for the entire recording period which included seismic survey signals and for the period without seismic survey signals present. The distribution of ambient noise at the north and east Porcupine for the periods with and without seismic survey signals present are shown on Figure 30. The sites East and North Porcupine were similar during periods of no seismic having broadband ambient noise levels around 105-110 dB re 1μPa and much fewer periods of higher noise levels. During seismic periods the typical broadband level was similar although the spread of higher broadband levels increased considerably, with time averaged levels in excess of 130 dB re 1μPa (ie. the distributions shown on the lower two panels of Figure 30 are skewed to the right).

The ambient noise levels for each 1/3 octave band (5 Hz to 2 kHz) each month from North and East Porcupine are listed in Appendix 8. Details of the broadband levels for periods of no seismic and with seismic from North and East Porcupine are listed in Table 13. The measured broadband levels across the full recording period from North and East Porcupine are shown on Figure 31 with the advent of seismic in early July and it oscillatory nature as the vessel moves around clear on the subsequent recordings. The SW Porcupine Bank seismic survey began in mid-August and its influence on sea noise is clear in the trends shown on Figure 31

The influence of the seismic surveys can be seen by comparing the average monthly sea noise spectra, as shown on Figure 32. Seismic surveys increased the monthly sea noise average below 100 Hz by as much as 20 dB with the biggest impact in the frequency band 6-10 Hz.

Table 13: Statistics of broadband level (dB re 1µPa) across the full recording period and period with no seismic from North and East Porcupine.

Site	Min / max	mean	median	Sd.	95%	N
North Porcupine with seismic	74 / 146	113	111	7.6	0.1	11616
North Porcupine no seismic	74 / 141	107	107	2.8	0.1	5018
East Porcupine with seismic	75 / 135	115	115	6.9	0.1	11884
East Porcupine no seismic	75 / 128	109	109	3.2	0.1	4868

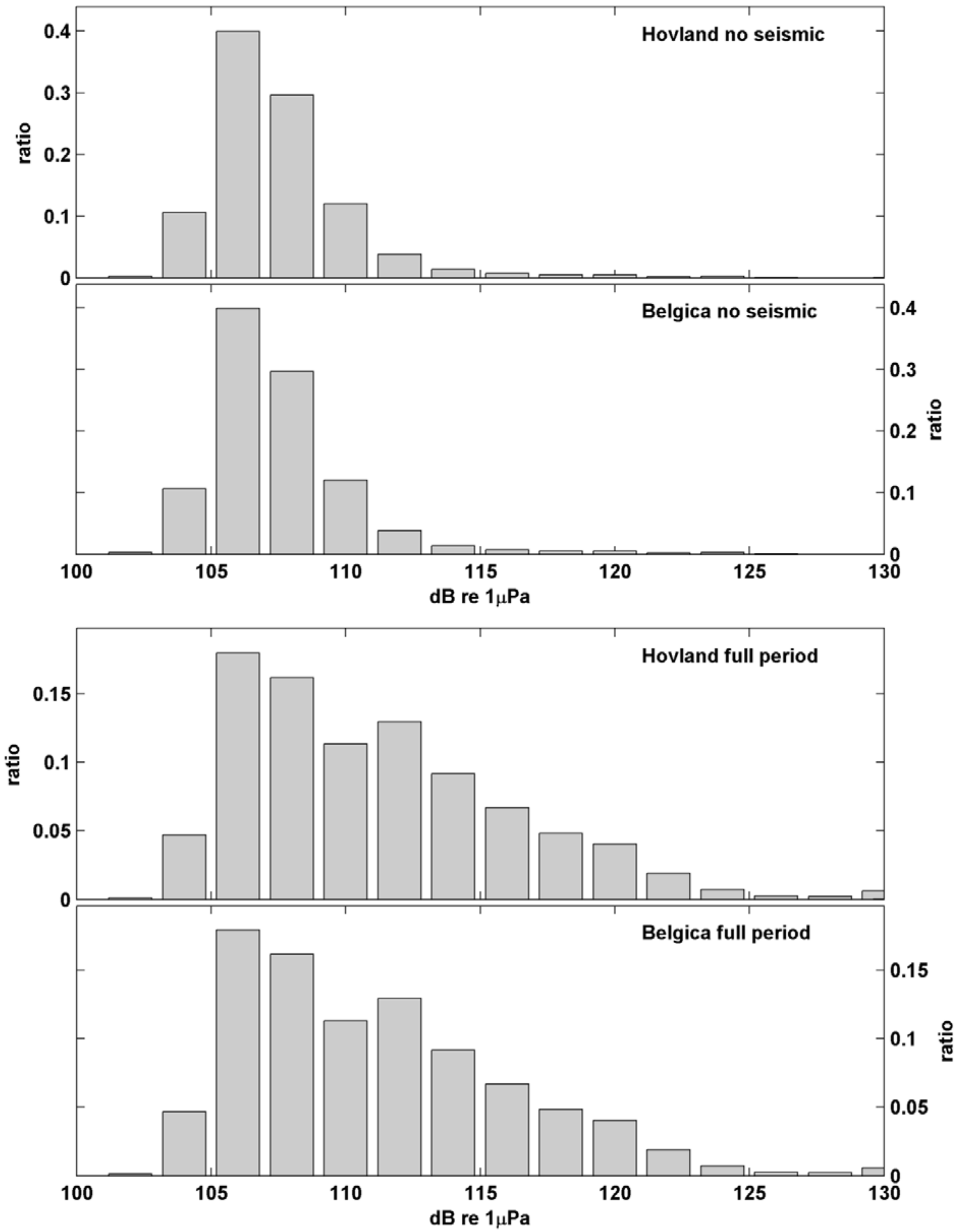

Figure 30: (Broadband ambient sea noise (over frequency band 7-2828 Hz) for: 1) (top) North Porcupine with no seismic signals present; 2) (second down from top) East Porcupine with no seismic signals present;3) (second up from bottom) North Porcupine with seismic signals present; 4) (bottom) East Porcupine with seismic signals present.

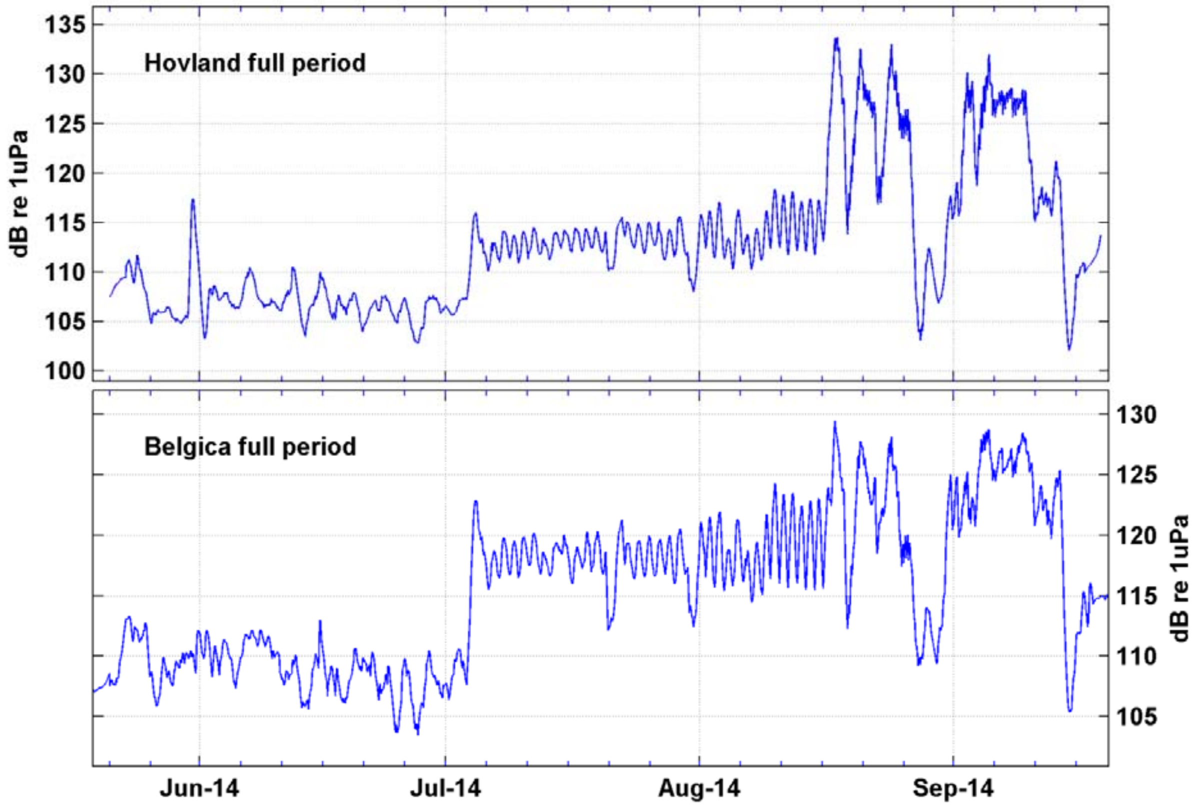

Figure 31: Broadband ambient noise levels for North (top) and East (bottom) Porcupine. Seismic survey signals became apparent at moderate levels in the data sets from 03-Jul onwards.

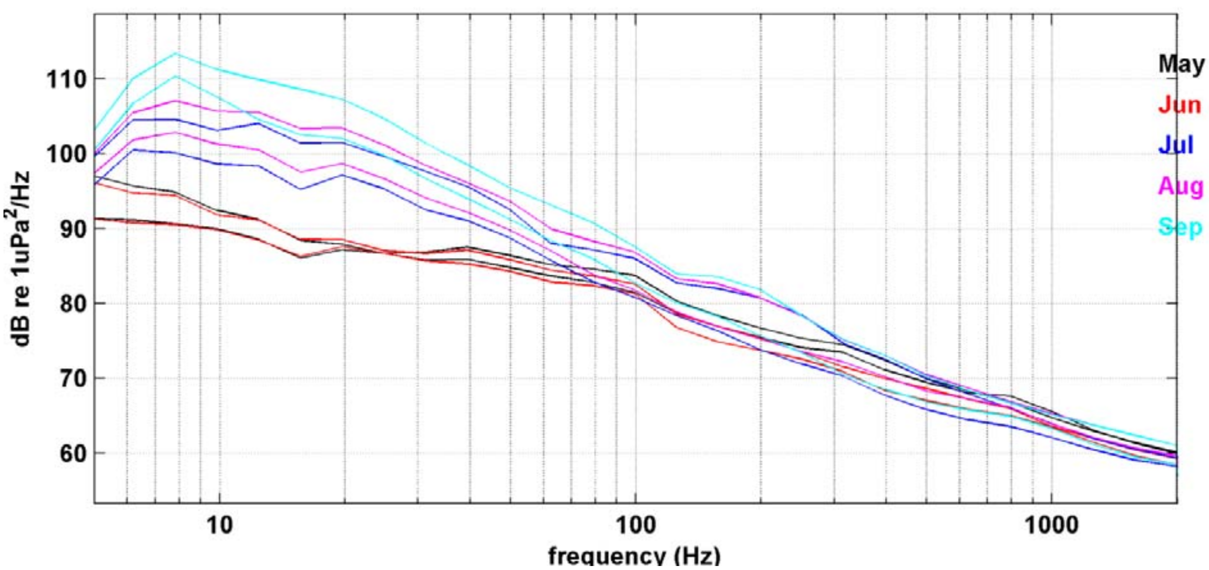

Figure 32: Time averaged monthly sea noise spectra from North and East Porcupine over 5 - 2000 Hz. The months of May and June had little seismic survey activity while all other months had moderate to high seismic survey levels.

A8.2 High frequency logger ambient noise

One of the high frequency (HF) noise loggers (set 3303 at North Porcupine) used a Wildlife Acoustics SM2 card for the digitising electronics, a Reson TC 40333-1 hydrophone and a CMST pre-amplifier. This instrument was set up so that white noise of known level could be injected into the system with the hydrophone in series, enabling the full system frequency response to be calibrated. The other two HF instruments were as purchased from Wildlife Acoustics, using HTI-99-HF hydrophones with built in pre-amplifiers (in the hydrophone). These instruments could not be calibrated with white noise and so the calibration was reliant on the specifications supplied and the gain settings used.

The ambient noise levels given by the HF noise loggers was compared with the low frequency (LF) noise loggers at each site, since a HF and LF instrument were on each mooring. To do this:

- Overlapping samples (in time) of the LF and HF loggers were found for the period up until the end of Jun-2014 when no or only distant seismic signals were present and the length of overlap calculated;
- The time averaged spectra of each sample which overlapped for > 160 s (set 3303) and > 20 s (sets 3304 and 3305) were obtained at three frequency resolutions for the LF and HF instruments respectively (0.076, 1.221, 9.766 Hz for LF, 0.732, 11.719, 46.875 for HF);
- The spectra were calibrated according to the calibration constants (sets 3304 and 3305) or curves (all other sets) available;
- The spectra were over-plotted for comparison;
- Measured curves of ambient sea noise spectra were interpolated over 10 Hz to 2.5 kHz and the value of the interpolated LF minus HF spectra at the same frequency derived;
- All data was plotted and various parameters measured.

The absolute time of the LF loggers, which all used the CMST-DSTO electronics, was known to a high precision (< 250 ms). A time was available for the Wildlife Acoustics sample start-time but this was not corrected for instrument clock drift and we are unclear if this is the time of file opening or sampling starting. Hence the time overlaps can be considered to be approximate and since we did not know the exact time of sample start for the Wildlife Acoustics instruments did not attempt to overlap exact times within a sample for the different instruments, but instead used the power spectra for the entire sample where the nominal time overlap lengths were greater than a certain value.

The ambient spectra for five time-matched samples using the LF and modified HF logger with SM2 card and CMST pre-amplifier from the North Porcupine mooring is shown on Figure 33 along with the mean difference curve of LF minus HF spectra at frequencies interpolated over 10 Hz to 2.5 kHz (with 95% standard errors shown, 67 time matched samples where the time overlap was > 160 s). The match of ambient noise level curves was good for 100 Hz to 2 kHz with as expected, the HF logger not accurate at frequencies <~ 60 Hz with the error increasing as the frequency dropped. The HF logger reached the system electronic noise threshold, 45 dB re 1µPa^2/Hz, at ~ 20 kHz hence shows the flattening out evident on Figure 33.

Matched samples from the Wildlife Acoustics loggers (WLA, as purchased) with the LF loggers from the East Porcupine and SW Porcupine Bank sites are shown on Figure 34 and Figure 35 respectively. The WLA instruments had a consistent jump in sensitivity at 1066 Hz (evident over the range 1-1.2 kHz), which was not real. The matched curves were not consistent between the two sets of instruments. The East Porcupine HF logger was on average 2.6 dB below the LF logger over 10-2500 Hz and in most instances reached the electronic noise floor at 37 kHz at 43 dB re

1μPa^2/Hz, although on one occasion it reached the noise floor at 3 kHz. The sensitivity of the Porcupine HF logger decreased significantly as the frequency decreased below 300 Hz, with the instrument response essentially only flat over 300 Hz to 2 kHz, with the exception of the jump over 1-1.2 kHz. Given the variability in response of the WLA instruments then only the LF loggers or the modified logger using the SM2 card were used for ambient noise measurements.

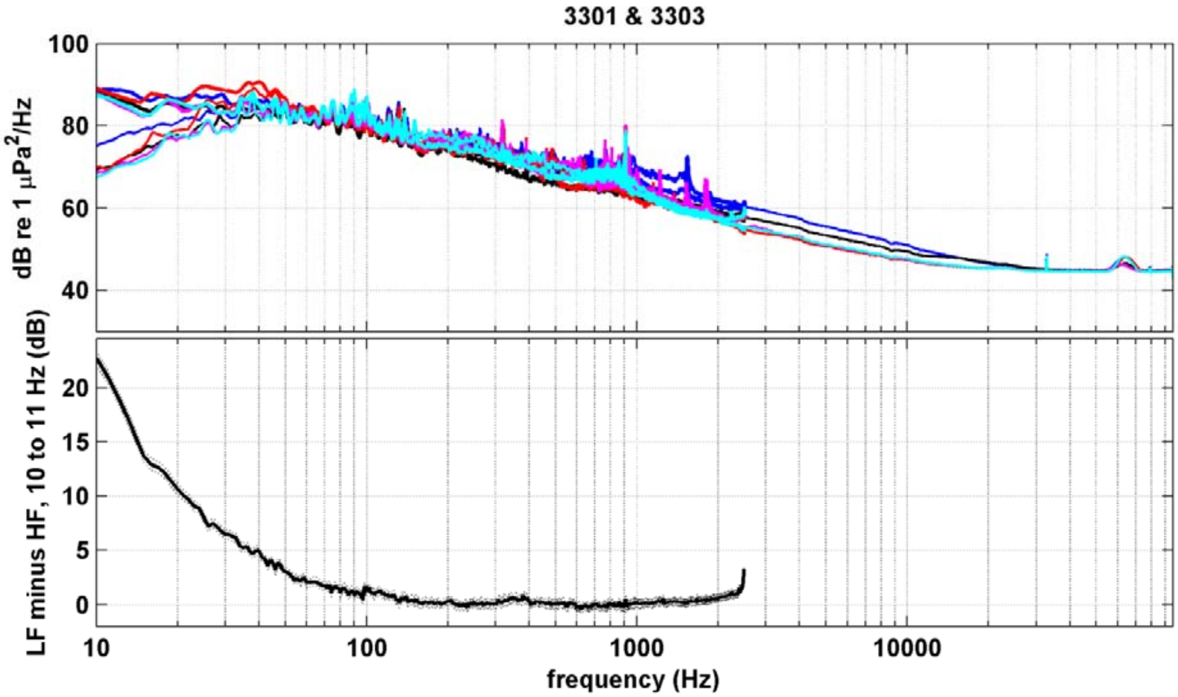

Figure 33: Comparison of LF and HF (CMST pre-amp, WLA SM2 card) loggers from the North Porcupine site where the top plot shows five comparative ambient noise spectra from the LF (heavy lines) and HF loggers (lighter lines) where each matched set are the same colour. The lower plot shows the mean curve derived when subtracting the interpolated HF logger spectra from the matching LF spectra, with the 95% confidence limits shown by the dotted line (67 time matched samples).

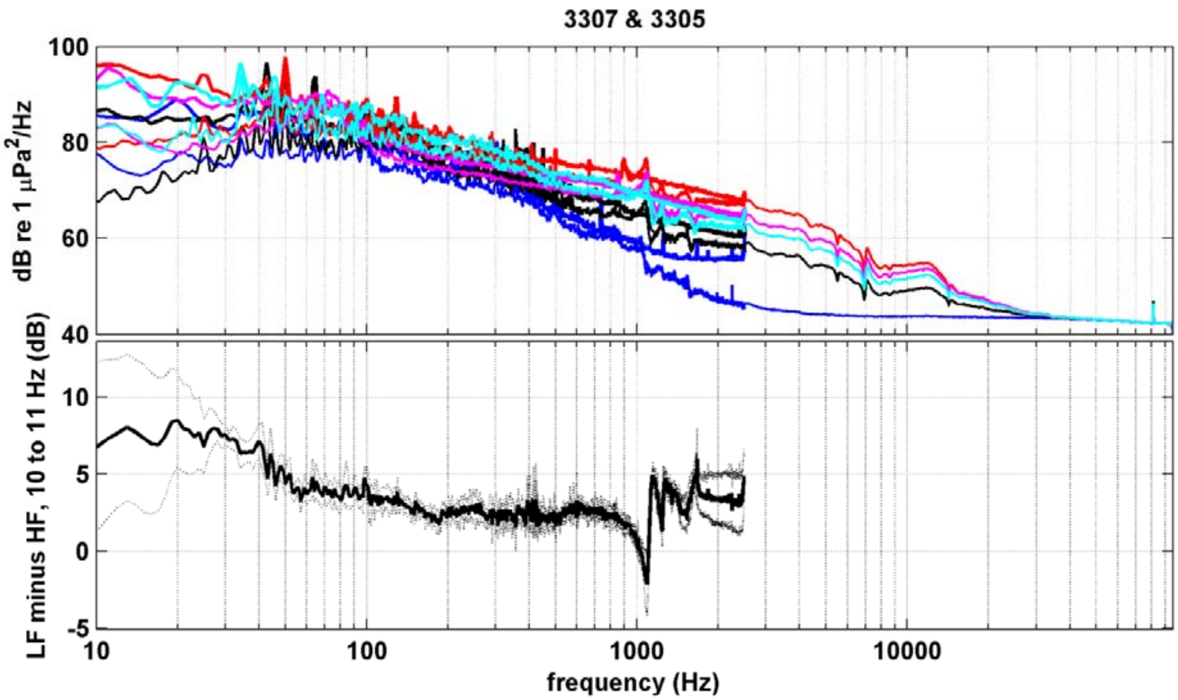

Figure 34: Comparison of LF and HF (WLA) loggers from the East Porcupine site where the top plot shows five comparative ambient noise spectra from the LF (heavy lines) and HF loggers (lighter lines) where each matched set are the same colour. The lower plot shows the mean curve derived when subtracting the interpolated HF logger spectra from the matching LF spectra, with the 95% confidence limits shown by the dotted line (10 time matched samples).

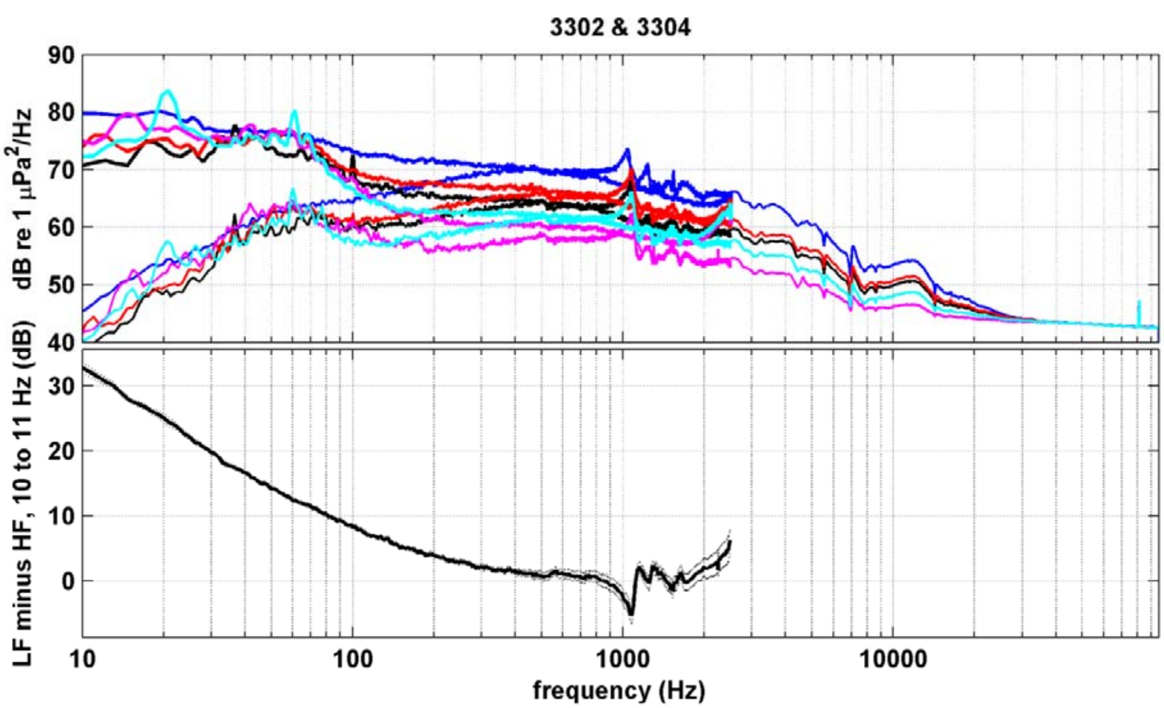

Figure 35: Comparison of LF and HF (WLA) loggers from the SW Porcupine Bank site where the top plot shows five comparative ambient noise spectra from the LF (heavy lines) and HF loggers (lighter lines) where each matched set are the same colour. The lower plot shows the mean curve derived when subtracting the interpolated HF logger spectra from the matching LF spectra, with the 95% confidence limits shown by the dotted line (25 time matched samples).

A8.3 Vessel noise

Vessel noise was relatively common at the three sites. Vessel noise has been discriminated here into two forms: 1) traffic noise, where energy from vessel noise transmits but is not easily attributable to a distinct vessel, this is the noise energy typically ducted at ocean scale distances within the deep sound channel; and 2) passing ship noise, or the noise from a passing ship where noise levels rise up to a peak when a vessel passes, then drop away again, with a distinct vessel passage with time. For sites not coupled to the deep sound channel (or inside the 200 m continental shelf edge), only the noise from passing ships is evident and the traffic noise is lost.

The traffic noise at all sites which could be identified as belonging to ships, was dominated by tonal signals ducted in the deep sound channel. These appeared as tones in the frequency range 5-100 Hz and had little other vessel signature associated with them. There were vessel tones at higher frequencies but these were generally associated with a recognisable vessel. Examples of vessel tones are shown on Figure 70 in the long time averaged spectrograms (Appendix 14) with a series of time averaged power spectra made across a small section of this shown on Figure 36. The contribution of the tones is clear on Figure 36 and while these tones were always present to some degree in the 5-100 Hz frequency band, they were also prevalent at times up to 1 kHz.

The passage of several nearby ships is also obvious on Figure 36. The amount of time passing ship noise was detected was extracted from the three LF data sets for 12-46 days during periods without high level seismic energy present (i.e. ships could still be recognised). This was done by constructing a GUI which displayed two day spectrograms in the band 5-300 Hz with the broadband level below it, then clicking on the beginning, maximum and end of a passing ship passage to obtain the times of passage. The technique was relatively easy but to some degree the length of time a ship was evident was determined not only by its source level, local sound transmission and proximity, but also by the prevailing ambient noise at the time, with ships evident for longer periods when background noise levels were lower.

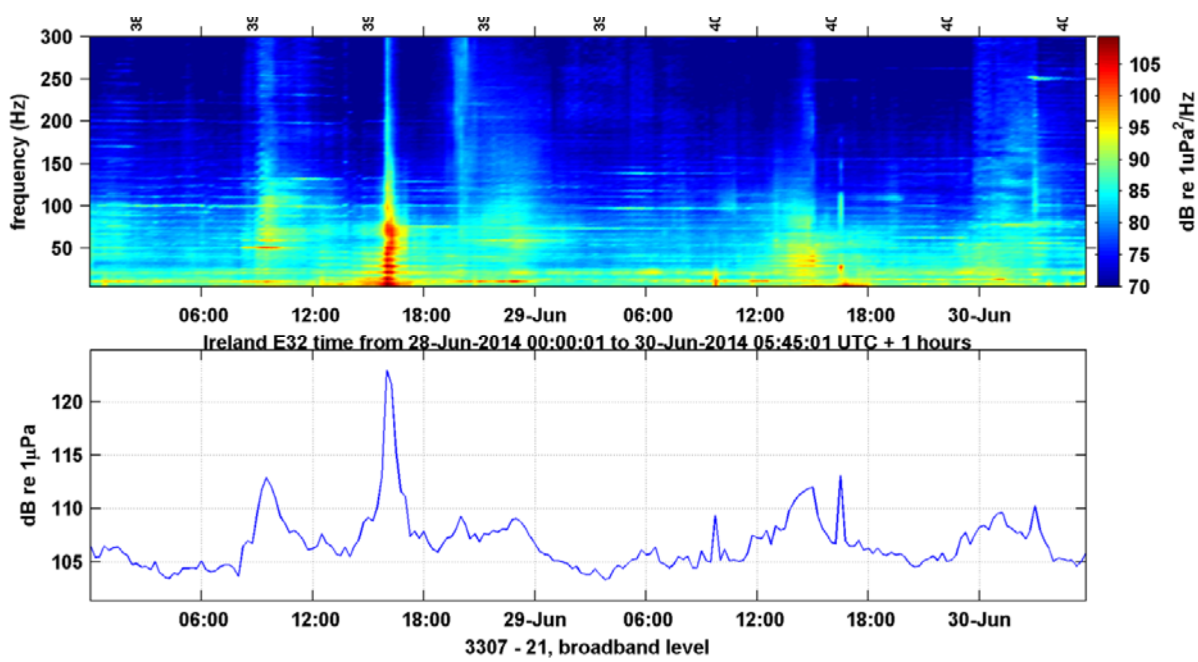

Figure 36: (top) Two day spectrogram (5-300 Hz) showing vessel tones in the background (horizontal lines across the full period, mostly in the 10-100 Hz band) and the passage of nearby vessels (i.e. 15:00 to 17:00 on 28-Jun-2014), (bottom). The same time period with broadband noise levels, highlighting the vessel passage.

All sites had similar magnitude of nearby ship passage numbers, with East Porcupine the highest at 1.8 ships/day, SW Porcupine Bank the least at 1.1 ships/day and North Porcupine at 1.6 ships/day. Using the recognisable passage time for individual ships from each site, the normalised distribution of the recognisable passage time for ships passing is shown on Figure 38 (left plot) with the similar distribution of maximum broadband received levels (11-350 Hz band) during a ship passage shown on the right hand plot. Statistics of passage times are listed in Table 14. The time for a ship to pass at East Porcupine was slightly higher than at North Porcupine or SW Porcupine Bank, at 4.2 hours (median). This suggested East Porcupine was closer to a shipping lane. Assuming an average ship steaming speed of 15 knots this implies ships were evident over approximately 60-74 n mile or 111-138 km of their track (using the mean values' 95% confidence limits and all data lumped). None of the sites were directly on major shipping routes as the average broadband received levels were relatively low. East Porcupine had highest average maximum received levels during a ship passage, reinforcing that it was closer to a regular shipping route than the other sites. Using the ship passage time compared with the total time sampled gave the proportion of time sampled which had identifiable ship passage as 27 %, 31 % and 36 % at North Porcupine, SW Porcupine Bank and East Porcupine respectively.

Table 14: Statistics of vessel passage times and maximum broadband level reached during the passage.

	Total passage time (hours)			**Maximum level during passage (dB re 1µPa)**		
	Mean ± 95% conf.	**Median**	**N (days used)**	**Mean ± 95% conf.**	**Median**	**N**
North Porcupine	4.17 ± 0.84	3.1	67 (43.2)	108 ± 0.6	108	67
SW Porcupine Bank	4.0 ± 1.00	3.0	32 (25.5)	107 ± 1.3	107	32
East Porcupine	4.9 ± 0.68	4.2	82 (46)	112 ± 0.8	112	83
All data	4.5 ± 0.47	3.6	181	110 ± 0.6	110	182

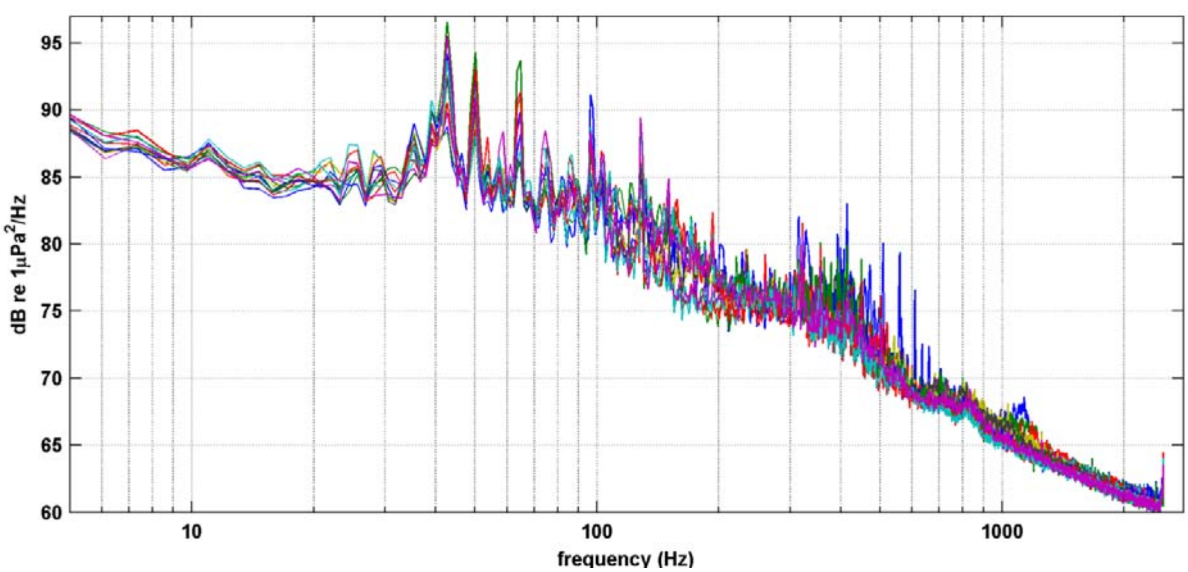

Figure 37: Averaged power spectra made across samples of set 3307 from East Porcupine over 29-Jun-2014, 03:00 to 29-Jun 06:00 (1.22 Hz resolution, 5 kHz sample rate, 4096 point, Hanning window). The vertical spikes are vessel tones.

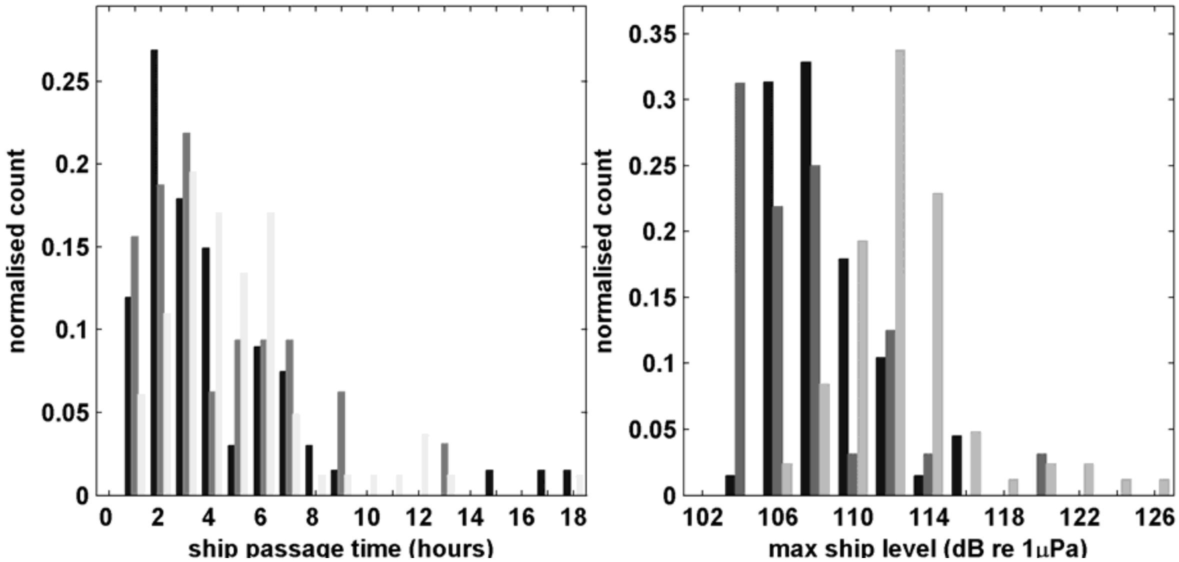

Figure 38: (left) Normalised distribution of the length of time taken for ships to pass at the three sites (darkest is North Porcupine, intermediate is SW Porcupine Bank and lightest is East Porcupine). (right) Normalised distribution of the maximum levels reached during ship passage at the three sites (darkest is North Porcupine, intermediate is SW Porcupine Bank and lightest is East Porcupine).

A8.4 Seismic survey signals

Three seismic surveys were run in western Irish waters over the time frame of recording. Significant effort was made by Woodside Energy staff to obtain the source navigation data for all surveys (the date, time and location of each air gun array signal for which data was collected) but this data was only made available from one of the survey companies.

Details of the seismic source and navigation data were supplied by SeaBird Exploration through Woodside Energy (Ireland) Pty. Ltd. The 2D Porcupine seismic survey was conducted using a 4100 cui array on an 81.3 m length, vessel of 4009 gross tonnes. Details of the seismic survey are listed in Table 15 and the location of the survey lines shown on Figure 39.

Table 15: Details of seismic surveys for which navigation data was available. Given are the; seismic array total volume; date / time of first shot (UTC); date / time of last shot (UTC); number of shots; mean shot spacing (median); number of survey lines; survey line mean length (median); mean time between survey lines (median).

source cui	**start**	**end (days)**	**# shots**	**spacing (s)**	**# lines**	**Line length (hours)**	**Between lines (hours)**
4100 2D	17-Aug-2014 00:30:26	14-Oct-2014 10:33:59 (58.4)	195702	11.8 (12)	51	12.5 (11.1)	15.2 (4.2)

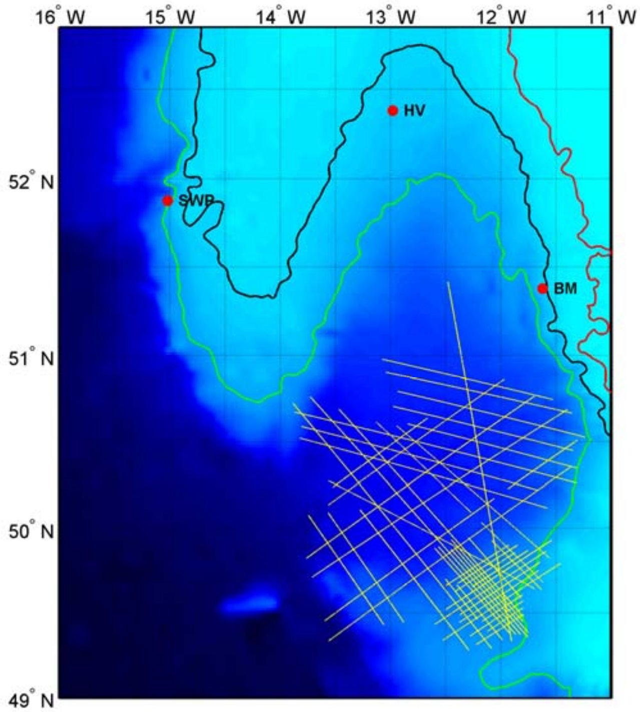

Figure 39: Location of Porcupine seismic survey lines (yellow lines) and the receiver locations. Sites are: BM = East Porcupine (recording sets 3307, 3305, LF & HF respectively); HV = North Porcupine (sets 3301, 3303); SWP = SW Porcupine Bank (sets 3304, 3302). Depth contours are shown as: 200 m - red; 500 m - black; and 1000 m - green.

A8.4.1 Seismic survey signals in general

Seismic survey signals dominated the latter part of the sea noise collected at North and East Porcupine. An example of two days of seismic in mid-August from North Porcupine is shown on Figure 40. Two seismic surveys were present in the data shown on Figure 40 and the survey lines can be clearly seen with the source approaching and departing the receiver slightly. The shifts in frequency content are due to the source moving with respect to the receiver and sound transmission selectively filtering the received signal with this varying with range. A single sample with a spectrogram and waveform of two seismic sources apparent is shown on Figure 41. Having two sources at moderate levels will have made interpreting the seismic data for the respective contractors difficult. There were instances of three seismic sources present.

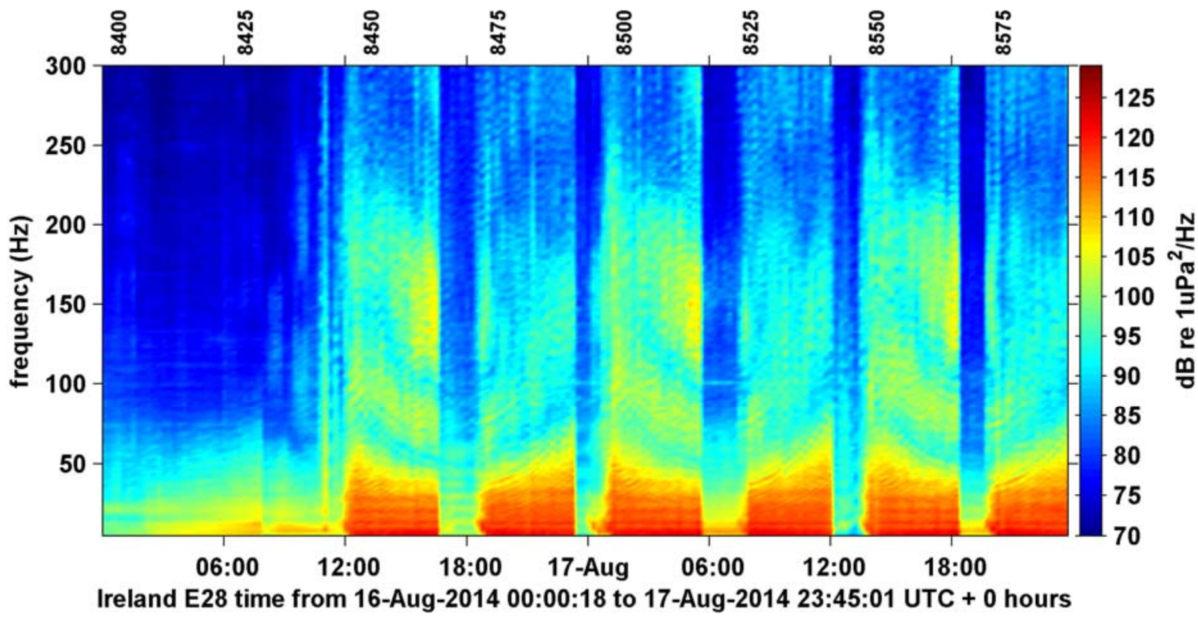

Figure 40: Two days of stacked sea noise spectra from North Porcupine with two seismic surveys present, one at low level and one at moderate level starting around 12:00 on 16-Aug-2014.

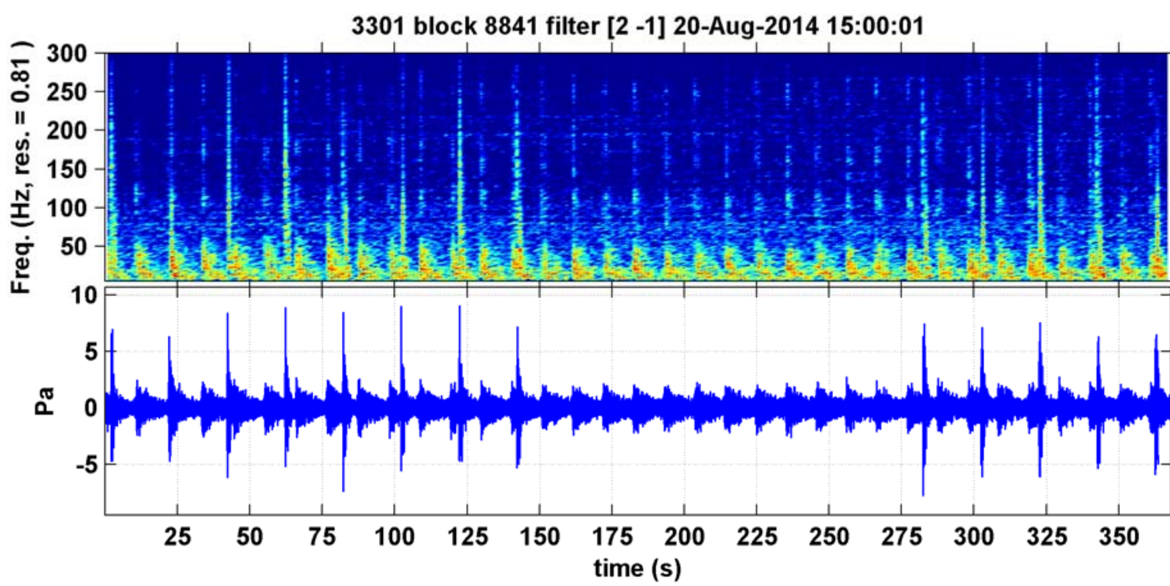

Figure 41: Two sets of seismic survey signals as received at North Porcupine. A lower level signal is continual in the background with a higher level signal superimposed over this.

The seismic signals displayed some good examples of sound transmission phenomena. An example is shown on Figure 42 where five air gun signals are displayed (from North Porcupine) which all show the impacts of modal structure (bands of energy) and dispersion (causing the bands of energy to change in frequency and stretch in time) from long range transmission. The signals have stretched from being milliseconds long at the source to almost 10 s long as received. The location of the air gun array source for these signals was not known. These dispersed air gun signals played havoc with the fin whale detectors.

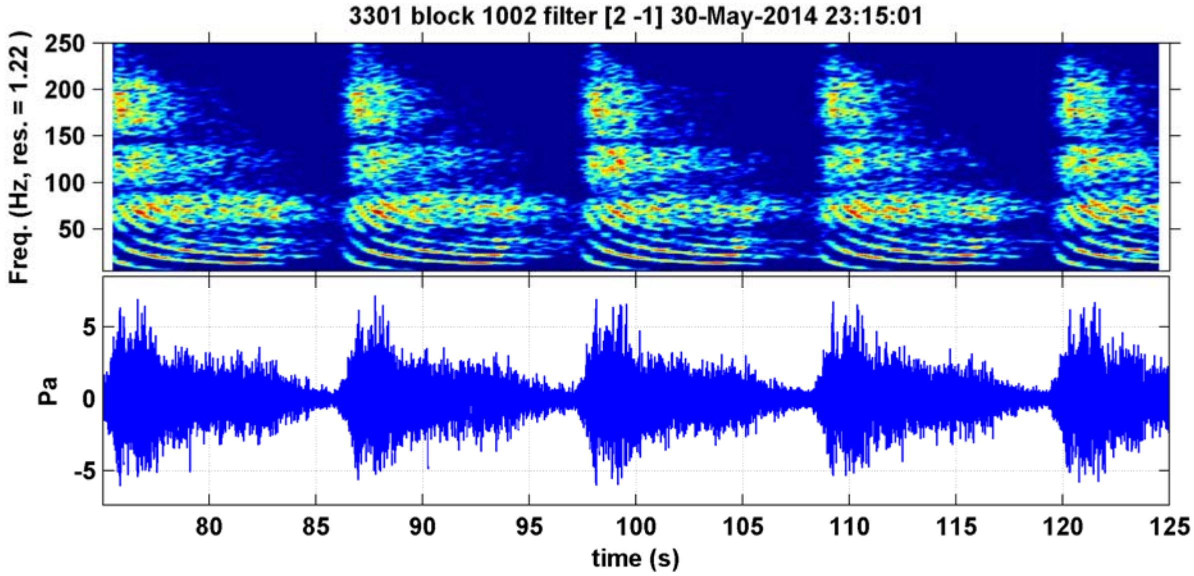

Figure 42: (top) Spectrogram of five air gun signals recorded from North Porcupine showing pronounced dispersion. (bottom) Waveforms of these signals.

An algorithm which locates seismic signals in the LF logger samples was run across the North and East Porcupine data sets. The algorithm was not run across the SW Porcupine Bank LF logger as it was too noisy (mooring artefacts and change is system sensitivity). For each sample, this algorithm located regular increases in the signal level of an appropriate duration (i.e. length of air gun signal) which were repeated at time increments within specified bounds typical of air gun operations (time between air gun signals). When a sample was deemed to contain air gun like signals the level (SEL, mean squared pressure and peak values) plus the signal duration were determined for each air gun signal. The signal duration was based on the time taken for 90% of the signal energy to pass. The time taken for 90% of the energy of each air gun signal to pass for all air gun signals in a sample was then divided by the total sample length to give the proportion of time air gun signals were present in a sample. The detector output is shown on Figure 43 for the mean values per sample measured (SEL and proportion of time air gun signals present). Air gun operations were persistent across the sample period at the North and East Porcupine sites (and presumably at SW Porcupine Bank), with mean levels per sample up to 140-142 dB re 1µPa^2·s (SEL) although commonly at 110-130 dB re 1µPa^2·s.

The proportion of time air gun signals were present (time 90% of their energy was present in a sample divided by sample length) sat around 20-30% for most samples with air gun operations present, but often reached 35-50% of the time. At these high values communication signals of marine mammals would have been masked for up to half of the time.

The level of each air gun array signal identified across the full deployment for the North and East Porcupine sites are shown on Figure 45. The presence of a distant seismic source across the full seismic period is evident as the levels in the range 90-120 dB re 1µPa^2·s, for the closer, *Porcupine* survey levels in the range 110-135 dB re 1µPa^2·s over August to September and for the third survey, from July onwards.

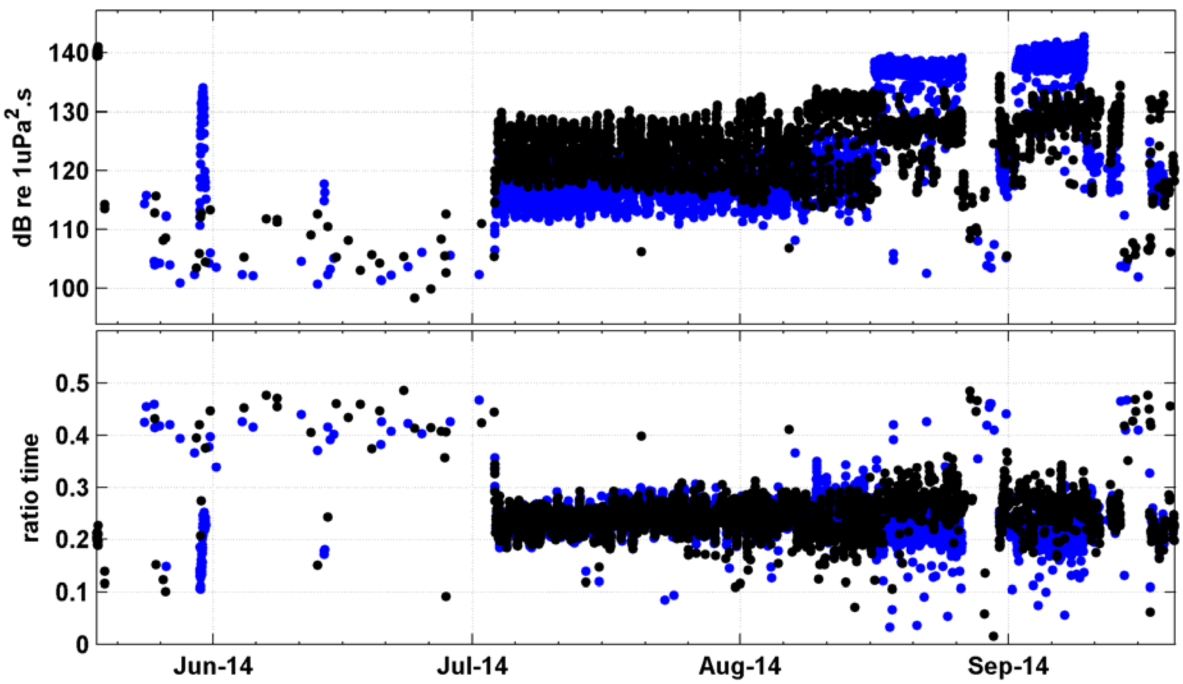

Figure 43: (top) Mean received level (sound exposure level) for all air gun signals in a sample for the full deployment for North Porcupine (blue) and East Porcupine (black). (bottom) Proportion of time air gun signals present per sample over the deployment duration at North Porcupine (blue) and Porcupine (black).

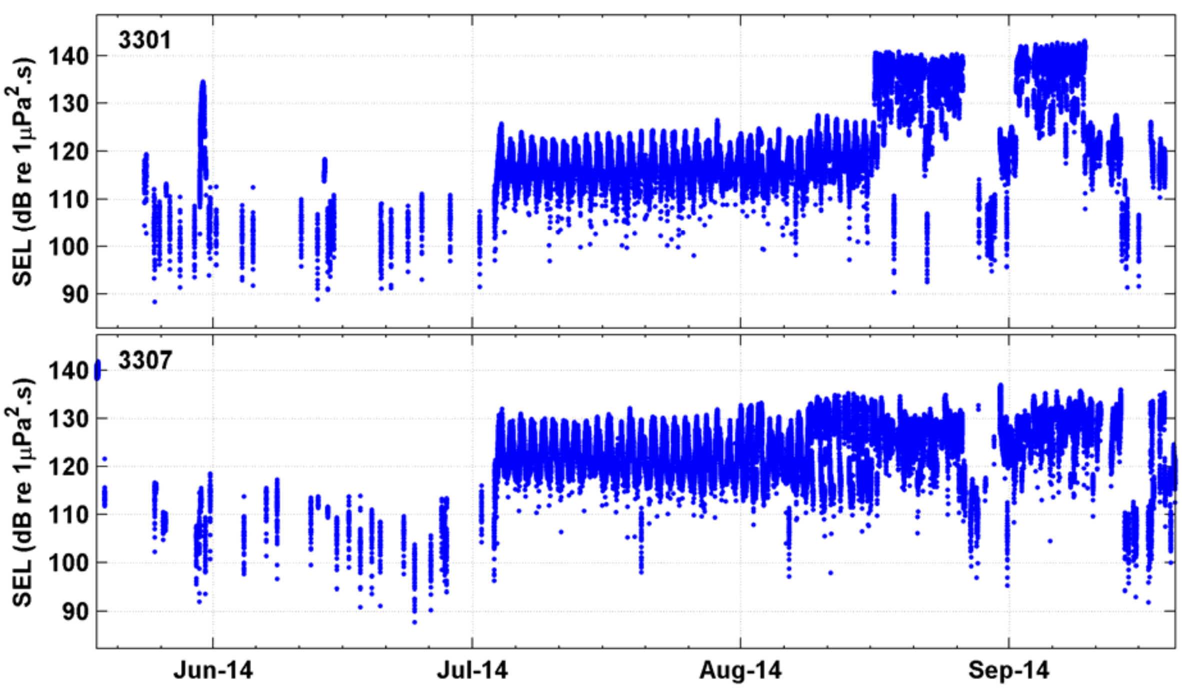

Figure 44: Sound exposure level of each air gun signal measured over the entire deployment from North Porcupine (top) and East Porcupine (bottom).

A section of high levels signals from north Porcupine was analysed for air gun levels as received over a 12 hour period, this is shown on Figure 45. This was derived by the routine automatically locating air gun like signals in the data sets and analysing these for received signal parameters. There were two sets of air gun signals present in this time period, distant signals from the *Porcupine* survey and closer signals from another survey (unknown). The algorithm preferentially locked onto the higher level signals at 140-145 dB re 1μPa^2.s (SEL) and only calculated levels for the lower level seismic signals when the higher level signals were not present.

The waveforms of 30 of the higher level air gun signals as received at North Porcupine are shown on Figure 46. These signals have stretched in time considerably from the expected short (< 0.5 s) signal generated near to the air gun array.

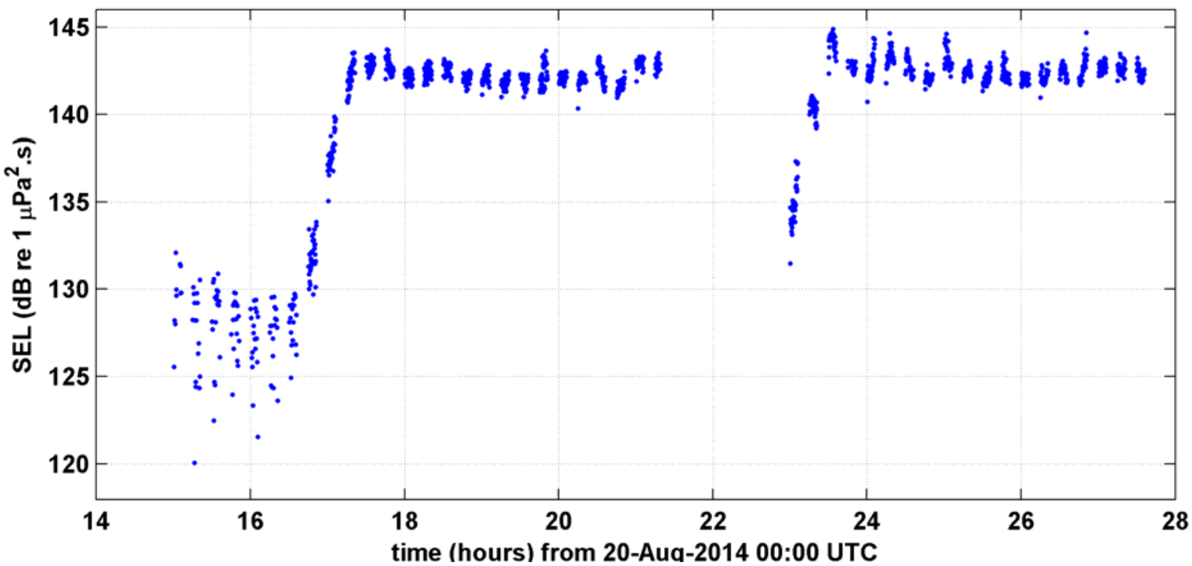

Figure 45: Received air gun signal sound exposure levels at North Porcupine over an approximate 12 hour period. Again, two sets of seismic survey signals are present, the lower level at 120-130 dB re 1μPa^2.s (SEL) and a closer range set of signals at 140-145 dB re 1μPa^2.s (SEL).

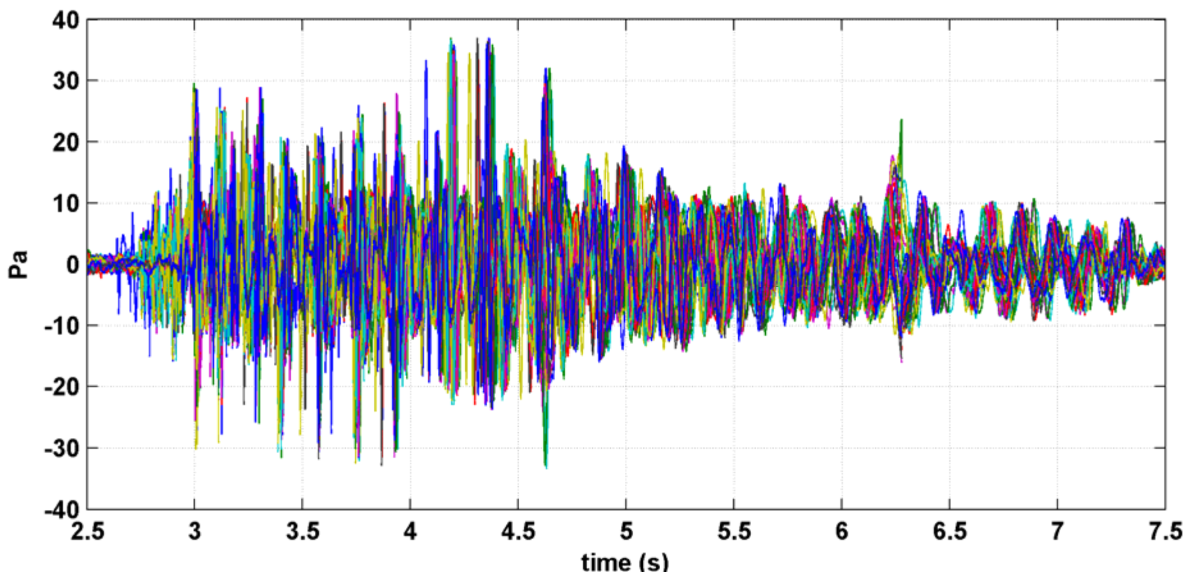

Figure 46: Waveforms of 30 high level air gun signals as received at North Porcupine on 20-Aug-2014. The signals are aligned by the positive leading edge at approximately 20 Pa. Each signal is a different colour. Range to the air gun array source was unknown.

A8.4.2 Porcupine seismic survey signals

By having the navigation data for the *Porcupine* seismic survey program the received signal levels were linked to range and aspect (azimuth of receiver from array tow direction) of the air gun array. Air gun signals along several seismic survey lines were pulled off the data sets. Note that the recording period did not span the full period of seismic so not all signals or survey lines could be extracted. Signals were extracted from the North and East Porcupine locations. It was found that there were periods where multiple seismic survey signals (up to three surveys were operational at any one time) arrived at similar levels so during these periods signals could not be extracted as the source vessel could not be identified. There were some instances of signals from a seismic survey other than *Porcupine*, picked up by the analysis process with most removed from further analysis.

The locations of signals analysed for various levels are shown on Figure 47. The overlapping seismic sets created significant problems in processing as the algorithm which matched received to source locations would pick the wrong sets of signals. A large number of processed air gun signals had to be removed as they clearly were not signals from the Porcupine seismic survey.

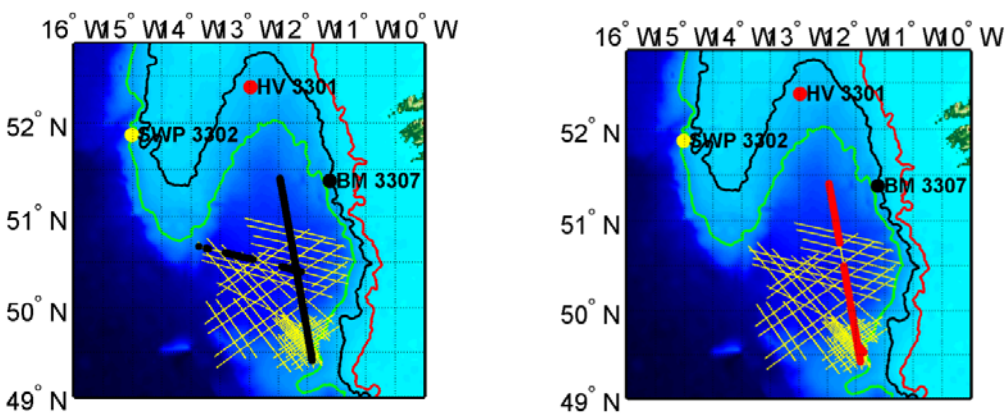

Figure 47: Air gun signal locations extracted from the North Porcupine (left) and East Porcupine data sets (right). The survey tracks are shown by the yellow lines and the air gun shot locations by the highlighted points, colour coded to the site.

The signals processed which were believed to originate from the *Porcupine* seismic survey are shown on Figure 48. Several features relating to sound transmission from air gun arrays are evident in the data sets, these being:

- A rapid increase in the signal level at the East Porcupine site from signals coming from the array beam (evident as the steep rise in received level at short range, black signal points, or the seismic track on a more east-west orientation at East Porcupine, as seen on Figure 48);
- Multipath transmission causing the signal level to oscillate with range;
- The sloping bathymetry towards the receivers at the southern end of the north-south survey line, causing more energy to be trapped in the sound channel duct due to reflections off the seabed closer to the horizontal, compared with when the seismic source was over deeper water with a flat seabed. This caused a significant increase in signal level (peak-peak and SEL) compared with when the source was operating over deeper water areas with relatively flat seabeds, but closer to the receivers. This was evident on the East Porcupine signals from 160 km (101 n mile or 1.7° of latitude) out to the maximum range signals were analysed at and from beyond 255 km at North Porcupine (138 n mile or 2.3° of latitude).

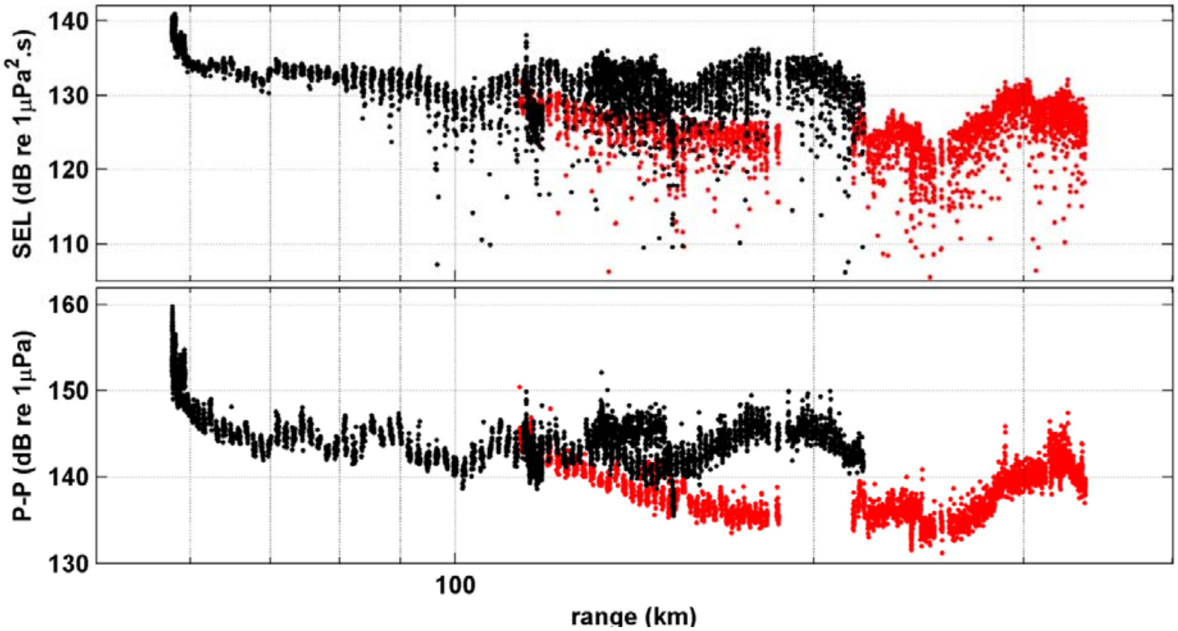

Figure 48: Received signal levels in SEL (top) and peak-peak (bottom) levels with log range (range scale 50-300 km). The red points are from the North Porcupine site and the black points from the East Porcupine site.

The frequency spectra of five signals made at 115, 230 and 330 km from North Porcupine and at 58, 110 and 210 km from East Porcupine, along with May and June ambient noise, are shown on Figure 49. At ranges > 100 km no signals had energy appreciably above ambient levels for frequencies above ~ 100-200 Hz. Only the 58 km signals from East Porcupine had energy over 100 - ~ 400 Hz. All signals had most energy over the 5-10 Hz range, although they were above ambient over the range 5-100 Hz. These frequencies are consistent with sound travelling via the deep sound channel, which also matches the jump in levels seen when the shallow source was over a seabed which sloped down towards the receiver.

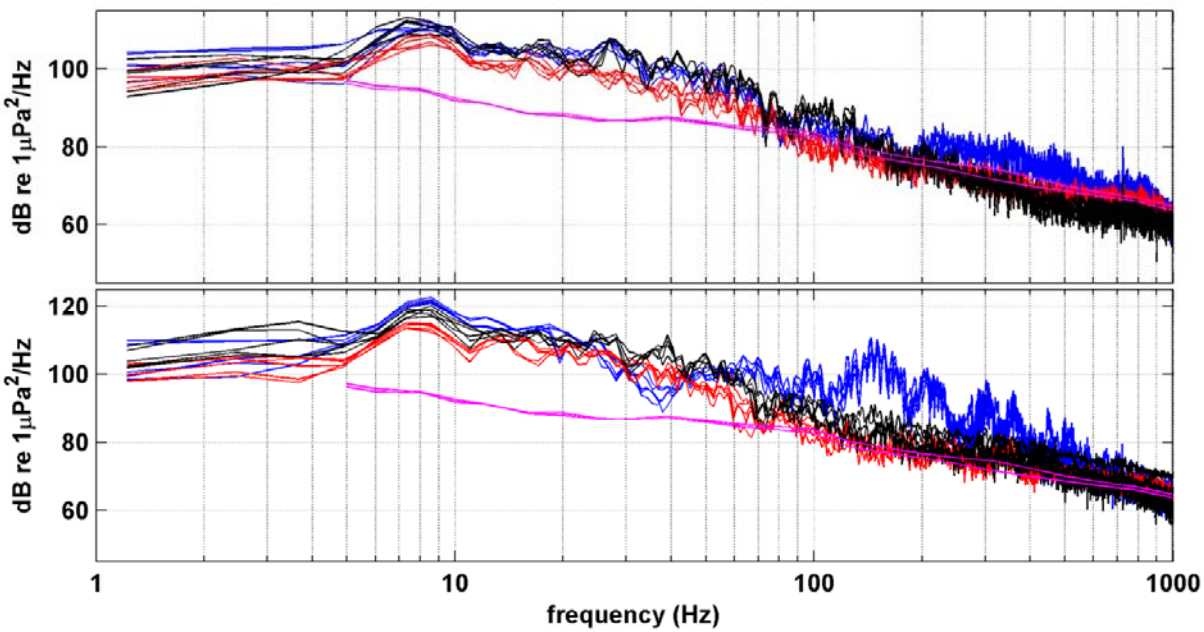

Figure 49: Spectral density of three sets of air gun signals recorded from North Porcupine (top) and East Porcupine (bottom). The North Porcupine signals are colour coded as five signals about 115 (blue), 230 (red) and 330 km (black) and the May and June ambient noise from North Porcupine (magenta). The East Porcupine signals are colour coded as five signals about 58 (blue), 110(red) and 210 km (black) and the May and June ambient noise from East Porcupine (magenta).

A8.5 Tabulated ambient noise

The ambient noise levels for 1/3 octave bands over centre frequencies 5 Hz to 2 kHz are given in Table 16 for North Porcupine and Table 17 for East Porcupine, split by month of recording. May and June were the months of no or low seismic survey activity.

Table 16: Ambient noise statistics for North Porcupine across the full recording period for the 1/3 octaves 5 Hz to 2 kHz. Given are: 1/3 octave centre frequency band; dB re 1µPa level in that frequency band for each month of recording; the mean across the months of recording; and the number of samples per month and in total over which mean values calculated (each sample was a mean across the sample) as the bottom row. May and June were the months of no or low seismic survey activity.

CF	May	Jun	Jul	Aug	Sep	Mean
5	91.4	91.3	95.5	97.1	100.1	93.9
6	91.2	90.8	100.5	101.9	106.7	97.5
8	90.6	90.5	100.2	102.9	110.4	98.5
10	90.0	89.9	98.7	101.3	107.6	96.7
12	88.6	88.5	98.4	100.5	104.5	96.0
16	86.1	86.3	95.2	97.6	102.6	92.9
20	87.2	87.6	97.1	98.7	102.1	95.8
25	86.7	86.7	95.4	96.7	99.8	93.6
31	85.8	85.7	92.5	94.1	96.7	90.4
39	85.9	85.3	91.1	92.2	94.1	89.0
50	84.8	84.4	88.8	89.9	91.3	87.3
63	83.7	82.9	85.7	87.0	88.4	85.0
79	82.8	82.4	82.9	83.9	86.0	83.0
99	81.5	81.3	80.8	81.8	82.8	81.3
125	78.8	76.8	78.4	78.9	80.2	78.2
157	76.9	74.9	76.4	76.9	78.3	76.2
198	75.5	73.8	73.8	75.3	75.7	74.3
250	74.1	72.6	71.9	73.6	73.5	72.8
315	73.5	70.9	70.3	72.2	70.6	71.1
397	71.2	68.4	67.8	70.2	68.6	68.6
500	69.4	67.0	65.8	68.3	66.8	67.0
630	68.1	65.8	64.4	67.3	65.8	65.8
794	67.6	65.1	63.6	66.2	64.9	65.0
1000	65.5	63.5	62.1	63.9	63.3	63.3
1260	63.1	61.4	60.4	62.1	61.1	61.3
1587	61.3	59.7	59.1	60.7	59.5	59.8
2000	59.9	58.5	58.2	59.6	58.5	58.8
N	960	2784	2880	2880	1728	11616

Table 17: Ambient noise statistics for East Porcupine across the full recording period for the 1/3 octaves 5 Hz to 2 kHz. Given are: 1/3 octave centre frequency band; dB re 1µPa level in that frequency band for each month of recording; the mean across the months of recording; and the number of samples per month and in total over which mean values calculated (each sample was a mean across the sample) as the bottom row. May and June were the months of no or low seismic survey activity.

CF	May	Jun	Jul	Aug	Sep	Mean
5	97.1	96.2	99.3	99.6	102.7	99.1
6	95.7	94.8	104.5	105.5	110.1	102.2
8	94.9	94.5	104.6	107.1	113.4	102.0
10	92.5	91.8	103.1	105.7	111.3	100.3
12	91.3	91.2	104.0	105.5	109.9	99.8
16	88.4	88.6	101.5	103.4	108.6	97.3
20	87.9	88.6	101.5	103.5	107.3	99.8
25	86.7	87.1	99.6	101.2	104.8	96.6
31	86.9	86.7	97.7	98.5	101.4	93.5
39	87.6	87.1	95.7	96.2	98.6	92.2
50	86.4	85.9	92.6	93.7	95.5	90.3
63	85.2	84.5	88.0	90.0	93.2	87.3
79	84.6	83.7	87.2	88.4	90.8	86.2
99	83.8	82.6	86.0	86.9	87.6	84.7
125	80.3	78.6	82.8	83.3	84.0	81.4
157	78.4	76.9	82.0	82.6	83.6	79.9
198	76.7	75.4	80.8	80.8	81.9	78.4
250	75.4	73.6	78.5	78.4	78.4	76.6
315	74.5	71.6	74.7	75.1	75.2	74.2
397	72.4	70.0	72.6	73.0	73.0	72.2
500	70.0	68.6	69.9	70.5	70.3	69.9
630	68.3	67.2	67.9	68.7	68.4	68.1
794	66.8	65.9	66.0	66.9	66.7	66.5
1000	64.7	63.6	63.9	65.3	65.1	64.5
1260	62.9	61.9	62.0	63.8	63.7	62.8
1587	61.4	60.4	60.5	62.4	62.4	61.3
2000	60.1	59.3	59.4	61.1	61.0	60.0
N	1152	2783	2861	2880	1824	11884

Appendix 9: Biological signal searching

Searching for biological signals was carried out by a variety of techniques tailored for the signal type in question and the noise regime. The presence of multiple air gun signals complicated the detection of species with signals in the frequency band 10-100 Hz due to large numbers of false detections (algorithms triggering on the variety of air gun signal permutations). This was a significant problem for fin whale signals, where the detector developed worked extremely well in periods of low noise or low level air gun signals, but generated many false detection scenarios for moderate or high level air gun signals due to the huge variety of multipath and transmission permutations for the signals generated by the three seismic vessels operating. To counter for this the detector outputs from the three sites were fully cross checked for fin whale signals. A streamlined cross checking process was used, which retrieved samples as output by the detector, removed any samples which had been previously checked, displayed the spectrogram with detections labelled, then allowed editing of detection times (removal or addition of time stamps). This process could be used as required on any of the species encountered, although was typically run for one species at a time with the display limited to the bandwidth of the signal of interest. A summary of which data sets were searched for what, is listed in Table 18.

Details of each detection algorithm are listed below, but can be summarised as:

- **Fin whales** - A time series cross correlation on the filtered, normalised sample waveform combined with checking of the noise regime before the call and above and below the defined call frequency band. Various techniques of looking at the drop in frequency with time and tone burst structure were trialled but not used due to multipath permutations. Spectrogram cross correlations gave poor detection power due to multipath permutations. All techniques had high false detection rates on air gun signals.
- **Blue whales** - A relatively simple detector was used which looked for consecutive peaks in spectrograms > 5 dB above surrounding noise over the frequency range 5-20 Hz, with sets of consecutive suitable spectral peaks spanning > 3.5 s and < 25 s in length. The detector missed only low SNR calls but gave a few false detections, thus all algorithm outputs were manually corrected.
- **Dolphin whistle detector** - A technique which looked for whistles of any shape in a defined frequency band (4-18 kHz) which exceeded a set time limit (length of whistle) worked extremely well. The algorithm had no false detections and detected all samples with whistles in 300 manually checked samples. This algorithm was tailored for whistles and set a limit set on the time/frequency rate of change allowed, so did not capture short duration pulses or echolocation clicks.
- **Toothed whale echolocation clicks** - Samples were split into 10 s blocks of waveforms, calibrated, filtered into two groups, 2-30 kHz and 30-96 kHz, a threshold value for that block defined (80 x $median(Pa^2)$) for each filtered section, signals (Pa^2) > threshold found which were > 4 ms after any previous 'hit', hits with a signal envelope of length 0.1 (ms) < L < 1.5 (ms) located, and the signals waveform, location, spectral content and levels, saved. A total of 1,407,525 clicks were located.
- **Sperm whale click discriminator** - Clicks found above were deemed to be from sperm whales if they had: a spectral peak in the range 2-15 kHz; and an internally reflected signal present (within the spermaceti organ).
- **Beaked whale click discriminator** - Clicks were deemed to be from beaked whales if they had: a spectral peak > 35 kHz; and had a definitive increase in frequency throughout the waveform (FM upsweep).

Table 18: Status of searching data sets for different species types. Alg = detection algorithm run; Man= manually cross checked; M. = metric used. Abbreviations are: NPrc = North Porcupine; SWPrcB= SW Porcupine Bank; Eprc = East Porcupine; Y=Yes; Y(P)= Yes but only part of data set processed; P = partly; C/200 = calls/200 s; NI = number individuals; % / day = proportion of samples within a 24 hour period with signal type present

Data set	**Fin whales**			**Blue whales**			**Dolphin whistles**		**Echolocation clicks**		**Beaked whale click discrimination**	**Sperm whale click discrimination**
	Alg	**Man**	**M.**	**Alg**	**Man**	**M.**	**Alg**	**M.**	**Alg.**	**M.**	**Alg.**	
3301 LF (NPrc)	Y	Y	C/200 NI	Y		NI						
3303 HF (NPrc)							Y	% / day	Y	% / day	Y	Y
3302 LF (SWprc B)	Y	Y(P)	C/200 NI	Y(P)	Y	NI						
3304 HF (SWPrc B)	Y	Y	C/200 NI	Y	Y	NI	Y	% / day	Y	% / day	Y	Y
3307 LF (EPrc)	Y	Y	C/200 NI	Y		NI						
3305 HF (EPrc)							Y	% / day	Y	% / day	Y	Y

The relative abundance metric used to display signal presence varied. Typically other workers have used some measure of detected call presence /counts per time period as the metric. For example a measure of presence such as the number of samples per defined time period which have calls from that species present is commonly used. While this is a good metric for comparing seasonal abundance or longer time frame trends it has less power at displaying smaller time frame trends especially if many calling animals are commonly present, as the metric will flatline at 100% easily. Measures of call counts per unit time give a better definition of smaller scale trends in animal abundance but do not correctly account for idiosyncrasies in calling structure or amongst animals. For example many varieties of a 'song' may be present within a species involving different call structures or repetition intervals for the specific signal type searched for, thus number of calls counted may not directly equate to number of whales calling. For example while a specific signal type may occur only once per song unit the repetition interval of this signal type may vary considerably, naturally. Thus, while often robust, counting the number of times a call type occurs per unit time can on occasions lead to large errors in estimating relative abundance. This author prefers to use a measure of the maximum number of individual whales calling within a sample as the metric for comparing abundance, which removes many of the problems of variable call repetition rates and the calling idiosyncrasies of individual whales. This was achieved for fin, blue whales and dolphin whistling with the techniques used described in the results below. Generally information on song or call structure and repetition intervals is inherent in the acoustic data sets, at least for the locations and times sampled, but requires effort to confirm.

Appendix 10: Fin whales

Signals from fin whales were common. The signals comprised sets of pulses mostly over 18-30 Hz as can be seen on Figure 50, although with on occasion higher frequency pulses over 30-80 Hz present following the lower frequency pulses. High signal to noise ratio (SNR) 'pulses' comprised a single tone burst of around 1.5-2.5 s in length which dropped in frequency with time. Lower SNR signals had multipath distortion and often appeared as a series of pulses, or multipath arrivals. The waveform of a high SNR pulse evident on Figure 50 over 82.5 - 84.5 s is shown on Figure 51. All of the other pulses seen on Figure 50 had multiple tone bursts. The higher SNR fin whale signals always swept downwards in frequency with increasing time, although for low signal to noise ratio calls where the signal degenerated into a series of multipath tone bursts, this shift in frequency became vague and could even appear to sweep upwards with time, as the different frequency components dropped out or dispersion altered the signal time structure. The higher frequency pulses (30-80 Hz) always swept downwards in frequency with increasing time.

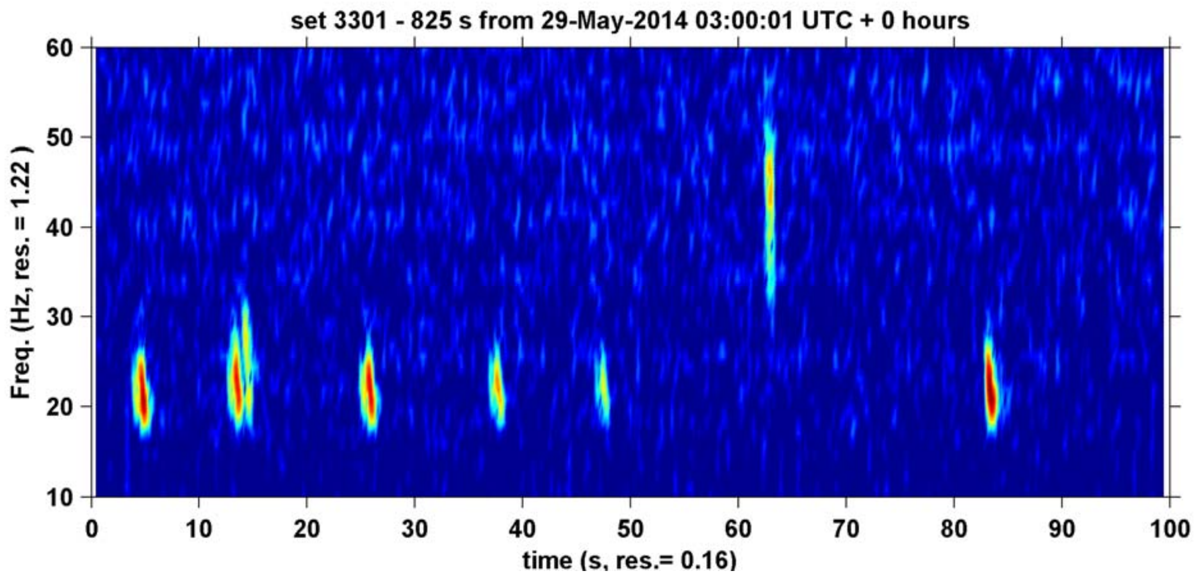

Figure 50: Spectrogram of fin whale calls from North Porcupine.

An algorithm was built to locate fin whale signals. The algorithm was run across LF data sets 3301, 3307 and HF data set 3304. The search algorithm struggled with the presence of air gun signals so several noise rejection techniques were developed to reduce the incidence of false detections on air gun signals. The wide variety of air gun signal arrival structures due to multipath and dispersion made this a challenging task. Air gun signals produced pulses with tone bursts over the correct frequency band for fin whales, plus dispersion effects due to sound transmission often resulted in the air gun signal sweeping downwards (or upwards) across this frequency band, as did the fin whale signals. Various techniques were trialled in the fin whale search algorithm to remove air gun signals and while they worked for many scenarios, they did not work for all the permutation of all air gun signal arrivals. Thus the fin whale search algorithm output was culled for air gun signals by manually checking all search algorithm outputs ('hits') and removing or adding time stamps for fin whale calls as required.

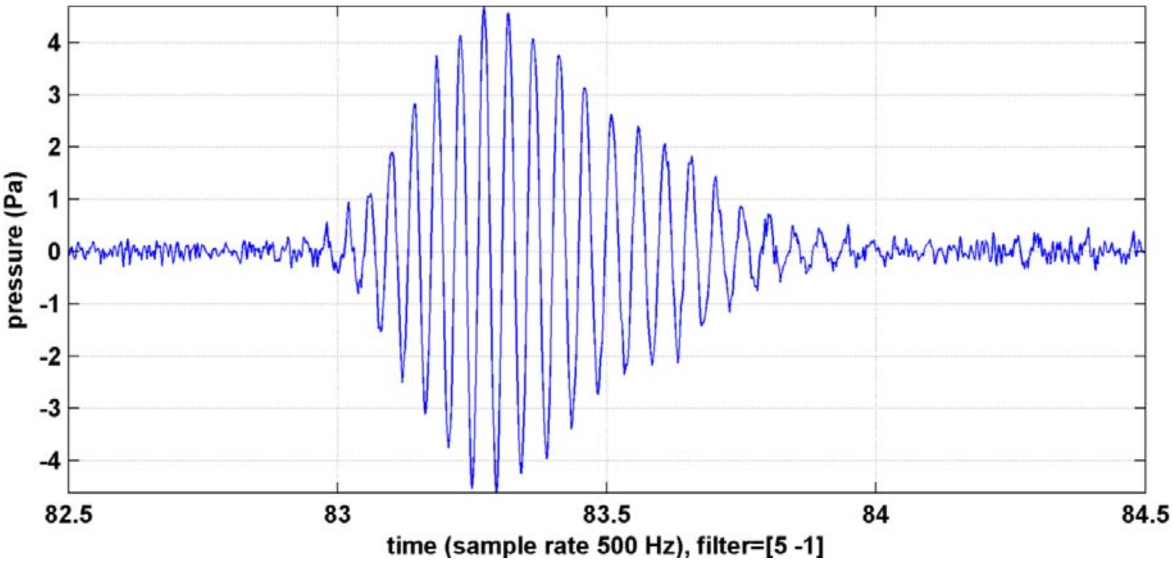

Figure 51: Waveform of fin whale pulse seen on Figure 50 over 82.5 - 84.5 s.

The search algorithm output and the manual checking process gave time stamps for each fin whale signal > 5 dB above the ambient noise level. Each of these identified 'hits' was then extracted and for each signal:

- The noise in the bandwidth 8 - 15 Hz (below the fin whale energy) and 50 - 65 Hz (above the fin whale energy) calculated,
- The signal level (+ve, -ve and peak-peak, msp, SEL) and the time taken for 90% of the signal energy to pass, was calculated (see McCauley et al 2003 for the same parameters as extracted for air gun signals);
- using the time points which encompassed 90% of the signal energy, the time of arrival of the signals was calculated (in absolute time units using the drift corrected time) from the 5% energy point.

Using data set 3301 (North Porcupine) the time between all fin whale pulses within a sample was used to give an idea of inter-pulse interval and to look for common time intervals between packets of pulses. Calls appeared to be a group of between 1-9 pulses, when scrolling through spectrograms, although there were many instances where a single individual whale continued to produce pulses across the 300 s samples. To quantify inter-pulse interval and possibly identify 'packet size' of pulses, the following assumptions and technique was applied:

- It was assumed that an individual whale repeats a call (group of pulses here) at a near constant repetition rate, realising that this rate may vary amongst individuals;
- It was assumed that a whale will produce consecutive calls at similar source levels, within a few dB. Since the time frame between repeated calls is usually small, perhaps tens to hundreds of s, then we would expect received levels at the hydrophone to be similar for calls produced in a short time frame from the same animal.
- The received level of each pulse was calculated in mean squared pressure and SEL units as above;
- The time stamp of when a pulse occurred was retrieved using the time when the pulse energy reached 5% of its total;

- For each sample with more than one fin whale pulse the time and level difference between all combinations of pulses in that sample was calculated to give a series of values of time and level differences between pulses;
- A density distribution was calculated where all time-level difference data was binned into counts of values for set time and level difference increments to return a 2D matrix of call time-level difference pairs;
- The call time-level matrix was plotted at a fine resolution. Since it will be expected that consecutive calls from the same animal will arrive at almost the same received level then we expect to see higher densities of counts at the time spacing between consecutive pulses at near zero level differences. For signals from different animals the time level differences will be random so these will form background noise and would not be expected to form clumped distributions. If common time increments occur between packets or groups of pulses from many animals, then a spike at this time would be expected to occur.

The resulting matrix of time and level differences for all combinations of fin whale pulse arrivals and the sum of counts of values with level differences < 2.5 dB for data set 3301 is shown on Figure 52. Figure 53 shows the similar calculations for data sets 3301 (North Porcupine), 3304 (SW Porcupine Bank) and 3307 (East Porcupine) but only displaying the curve of the sum of counts of level differences < 2.5 dB. Using this analysis we can see that the average spacing between pulse sets as the spikes in the 2D matrix with level differences approaching zero (top plot) and the curves derived from this (bottom plot). Using the smoothed data of set 3301 (5 point linear fit), peaks in the time between pulses (start of one pulse as given by 5% energy peak in pulse, to start of next pulse) occurred at:

pulse increments (s) - 14.4 (pulse 1-2), 14.8 (2-3), 14.8 (3-4), 15 (4-5), 14.7 (5-6), 14.3 (6-7), 15 (7-8), 15 (8-9), 14.8 (9-10)

with a mean pulse to pulse interval of 14.74 ± 0.206 s (± 95% confidence limits).

There was no easily identifiable time which could be attributed to a constant sized 'packet' of pulses, implying there was no defined packet size for the pulses.

The proportion of the average number of pulses within a fin whale call can be estimated using this data set of pulse-pulse increments and level-difference's. On perusing spectrograms it appeared that a fin whale 'song' had commonly between 1 and 6-7 pulses repeated regularly. The spikes seen on the lower panel of Figure 52 were present up to at least ten pulses (the first peak on the lower plot of Figure 52 represents the second pulse in a group of pulses). Using the data derived here from data set 3301 and:

- if we assume that all calls had a minimum of two pulses (since to get the first peak on the lower plot of Figure 52 requires two pulses) ;
- we subtract the median count value of the curve for raw data shown on the lower plot of Figure 52 from the peak count values;
- then divide the value of each peak by the value of the first peak;

we get an estimate of the proportion of how many pulses in a call relative to the number of two pulse 'packets'. These values calculated at:

- 100% for two pulses (assumed);
- 51% for three pulses (ie. for every two-pulse group there was approximately one 3 pulse group);

- 40% for four pulses;
- 26% for five pulses;
- 21% for six pulses;
- 16% for seven pulses.
- 12% for eight pulses
- 8% for nine pulses
- 8% for ten pulses

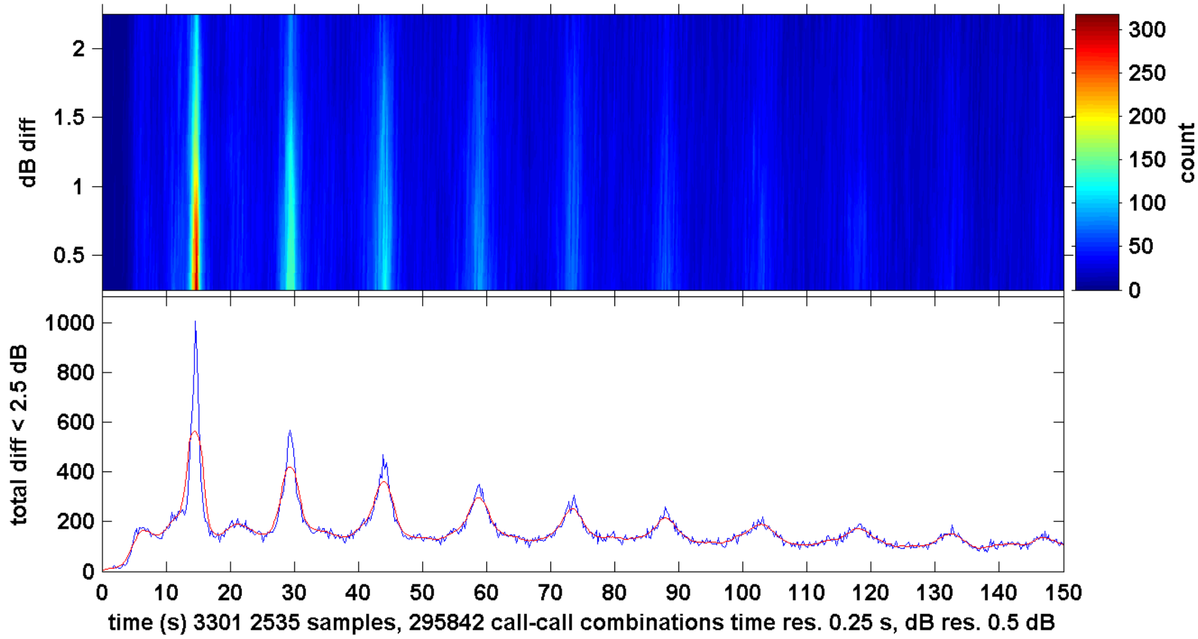

Figure 52: Analysis of time spacing and level difference between all combinations of pulses from within samples of data set 3301. The counts are the number of values within each defined bin, with bin sizes listed on the figure. The top figure shows the counts of values as a time-level 2D plot while the lower figure sums the counts for level differences < 2.5 dB, showing the inter-pulse time spacings. The red curve is smoothed (linear fit, 5 points about), the blue curve is raw data.

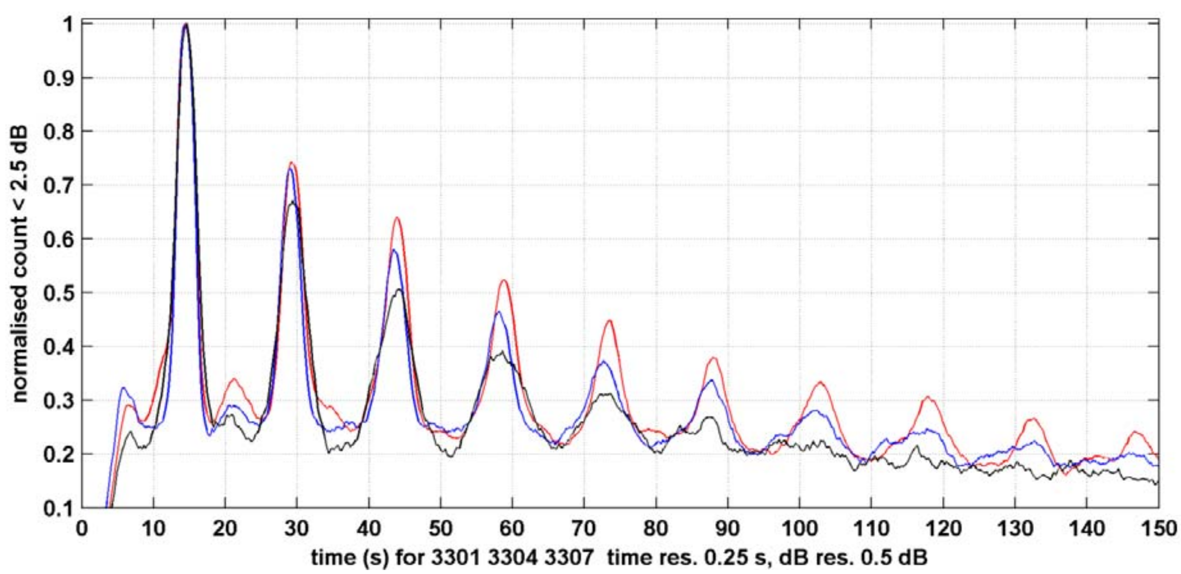

Figure 53: Calculated time differences between fin whale pulses (1-2, 1-3, 1-4 etc) from data sets 3301 (red), 3304 (blue) and 3307 (black).

The normalised distribution of received levels (mean squared pressure) of calls from data sets 3301 (North Porcupine) and 3307 (East Porcupine) are shown on Figure 54. The LF data set from SW Porcupine Bank was only partly suitable for this analysis due to its change in sensitivity across the recording period and the HF logger from this site had a huge roll off in the fin whale bandwidth (i.e. see Figure 35) which could not be reliably corrected for, thus only the North and East Porcupine sites were included in this analysis. At each site most of the fin whale calls were received at relatively low levels with only a few calls received at moderate to high levels. This indicated that animals were mostly at moderate ranges from the receivers (probably many tens of km). The data sets have a sharp drop off at low levels which is indicative of the signals falling into the ambient noise (noting signals were only detected if they were > 4-5 dB above the ambient noise in the fin whale frequency band).

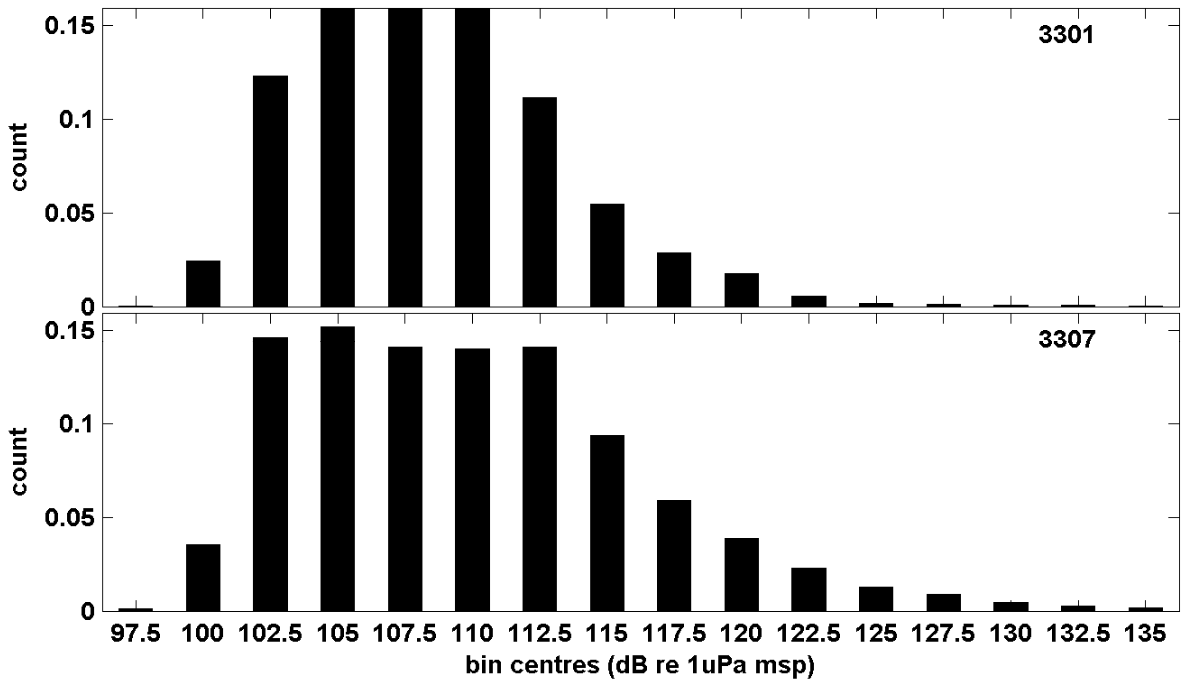

Figure 54: Normalised distribution of received levels of fin whale calls at North Porcupine (top) and East Porcupine (bottom).

Using the time taken for 90% of the signal energy to pass and data set 3301 and 3307, statistics on pulse length (defined as time taken for 90% of signal energy to pass) were: mean length 2.25 ± 0.007 s (95% confidence limits), median =2.18, sd. 0.723, N=36,028

The calculated call lengths were normally distributed, as shown on Figure 55.

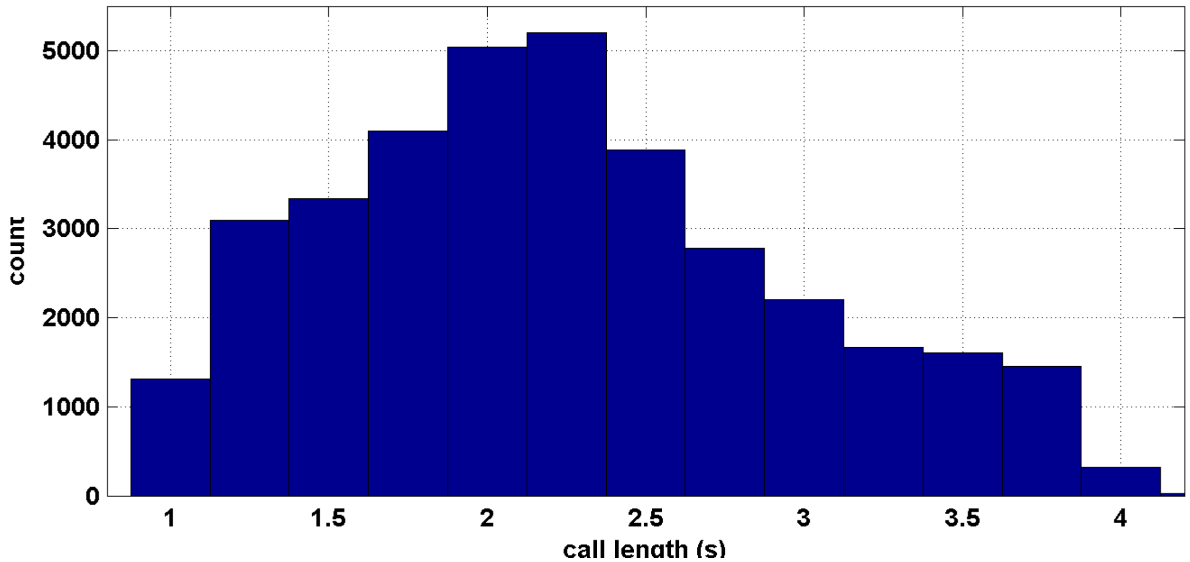

Figure 55: Distribution of fin whale call lengths. The bin widths are 0.25 s.

The fin whale pulses were consistent in their frequency content, with spectra of the 20 highest level calls from North Porcupine (set 3301) shown on Figure 55. The maximum spectral frequency of fin whale calls was calculated for the 201 highest level signals from North Porcupine and gave the statistics:

Range	19.5 - 39.6 Hz
Mean	21.5 ± 0.30 (± 95% confidence limits)
Median	21.0 Hz
std.	2.13 Hz
N	201

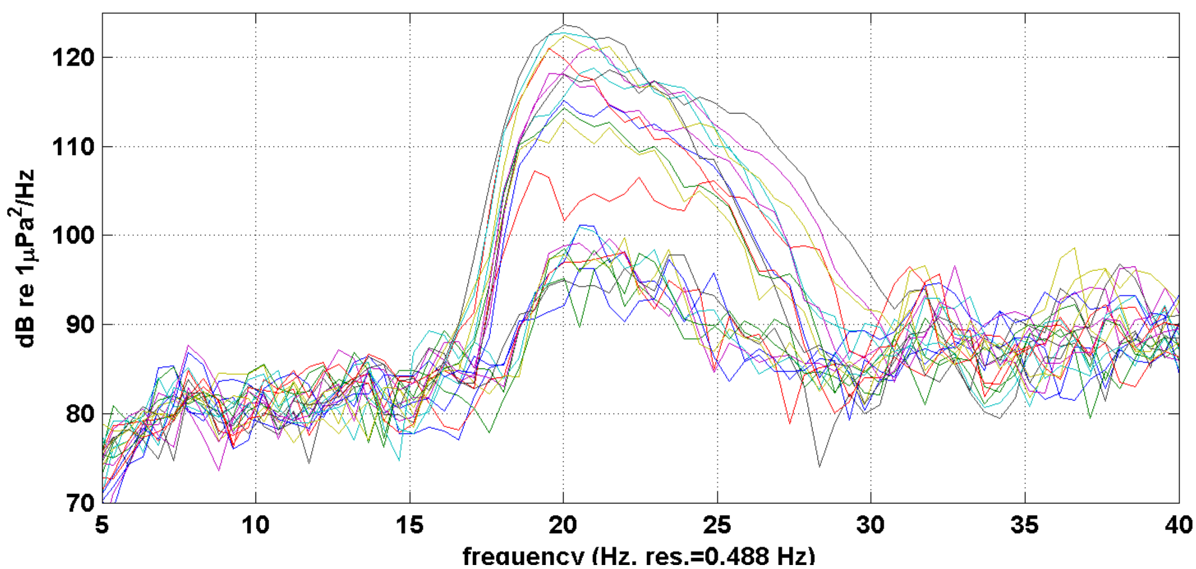

Figure 56: Spectra of the 20 highest level fin whale calls from North Porcupine (3301).

The detections of fin whale calls were used to illustrate the trends in calling at the three sites. Ideally we would prefer the number of individual whales calling at any point in time as the unit for displaying time trends. Determining the number of individual whales calling at a point in time is normally carried out by counting the number of specific song components within the repeat time interval between consecutive song's (a song being a group of components in an ordered and repeated pattern). As the fin whales here produced many consecutive and similar pulses with seemingly no normal grouping of pulses defining a song, this was not possible. Instead two metrics have been used to define the relative abundance of fin whale calling.

The first metric used a simple count of calls detected per unit time (200 s). Each sample was divided into 200 s blocks and the number of calls within each block's time span counted. If the block was < 200 s long (block at end of sample) the count was normalised to 200 s. The maximum count of calls / 200 s was used for that sample. The second metric attempted to estimate the number of calling individual whales per sample. In this method:

1. a pulse-pulse interval of 14.74 s was used (derived above);
2. a sample was divided into blocks of (3*14.74)-3 s length, with the first block time increment taken from the time of the first call detected within the sample and the last block time increment taken to the end of the sample;
3. within each block the number of calls was counted (*N*)
4. the integer value (high side or ceiling in Matlab) of $I = ceil\left(\frac{N}{3}\right)$ was calculated for each time block
5. the maximum value of *I* was then use as the estimate of the number of calling whales in this sample.

The logic here was to divide the sample into short periods, each of just less than three times the inter-pulse interval. Assuming all pulses of a calling whale were detected and they all produced pulses at near the mean inter-pulse interval, then each calling whale would produce three pulses within this time frame (with four pulses produced in exactly three times the pulse interval, and three for just short of three times the pulse interval). As it transpired the two metrics used were highly correlated, so the calls / 200 s has been used to display trends and estimate of the numbers of calling fin whales to quantify relative abundance.

Since many great whales have daily cycles in call patterns the prevalence of day-night patterns in calling was investigated. This was done by two techniques:

1. calculating sunrise, midday and sunset for each day at the respective location (using a Matlab astrophysical package of Ofek, http://webhome.weizmann.ac.il/home/eofek/matlab/) and calculating calling rates in periods around these;
2. or comparing calling rates in uniform time bins across a 24 hour period (which was not corrected for drift of sunrise and sunset across the recording period).

The resulting analysis of changes in call trends across a 24 hour period, and as tied to sunset and sunrise is shown on Figure 57. There was a slight indication of greater calling over night time periods and after sunrise and sunset but with the current analysis these trends were not significant.

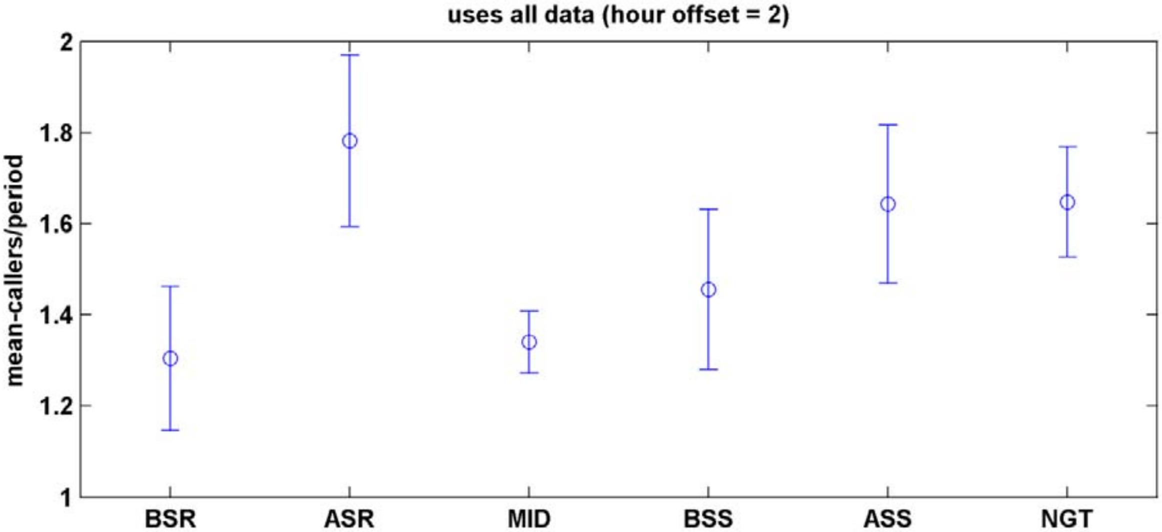

Figure 57: Using all normalised data, mean (± 95% confidence limits) number of calls/200s in uniform periods: BSR - before sunrise; ASR - after sunrise; MID - about midday; BSS - before sunset; ASS - after sunset; and NGT - across the night-time period. The before and after periods were 2 hours, midday and night were sampled for 1 hour either side of the time. The time of sunrise and sunset were as calculated for each site, midday and midnight were half way between sunrise and sunset, or sunset and sunrise, respectively.

While there was no clear evidence for diurnal trends in the fin whale calling, for displaying seasonal scale trends in calling behaviour the counts of fin whales calls per unit time were averaged in 24 hour periods (12:00 UTC one day to 12:00 UTC the next). The trend of the number of fin-whale calls/200 s across the recording period at all sites using mean values per 24 hour period and the two metrics discussed above (calls/200 s and estimated number of individual fin whales calling), are shown on Figure 58. The smoothed trends of 24 hour means of calls/200 s are shown overlain for each site on Figure 59.

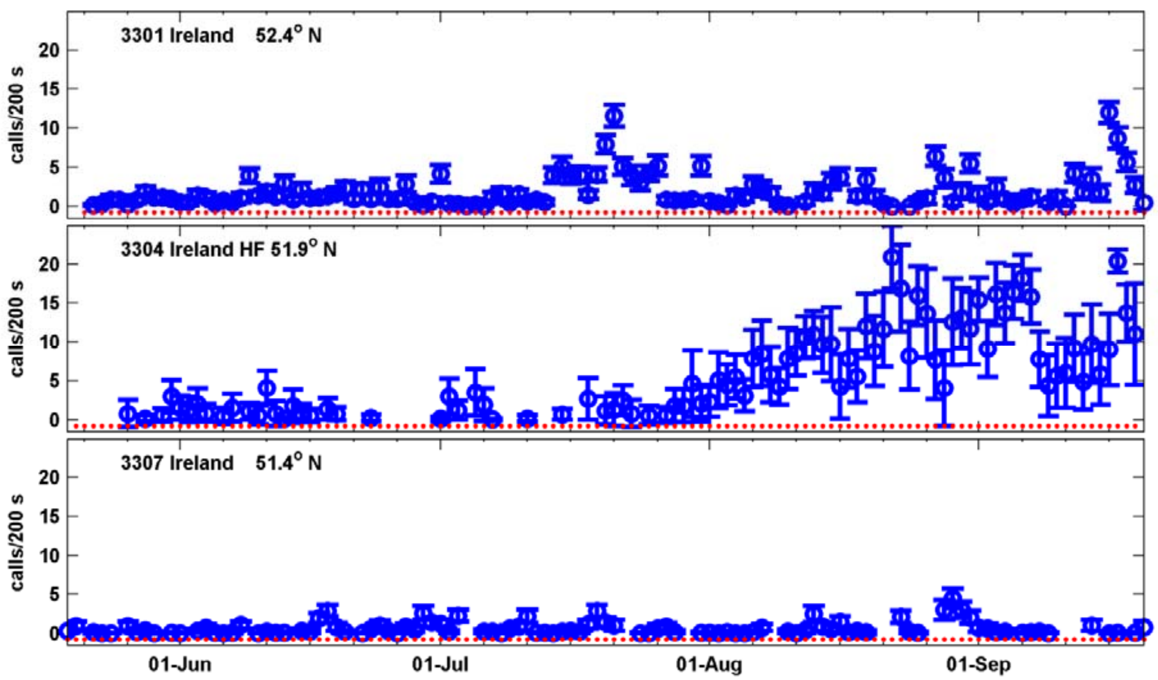

Figure 58: Trends in fin whale calling at North Porcupine (top), SW Porcupine Bank (middle) and East Porcupine (bottom) across the full recording period with the metrics of: 1) calls/200 s used in the top three panels; and 2) number of calling individuals used in the lower three panels. All data is presented as the mean value across a 24 hour period (12:00 to 12:00 UTC) with 95% confidence error bars shown.

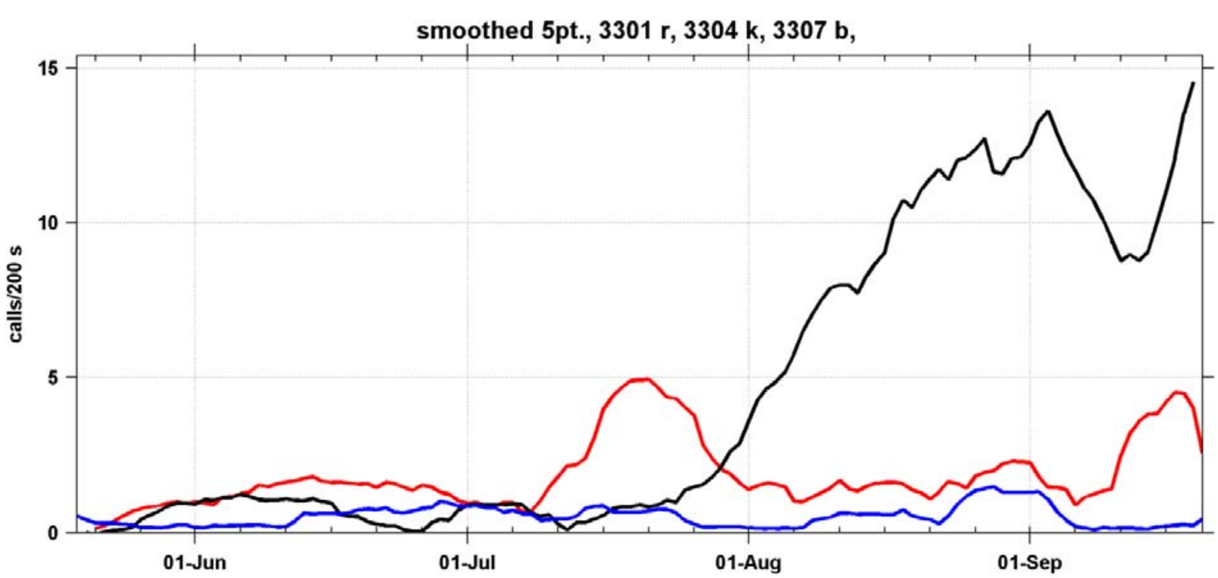

Figure 59: Smoothed trends of fin whale calls/200s from: SW Porcupine Bank (3304, black curve); North Porcupine (3301, red curve); and East Porcupine (3307, blue curve).

The fin whale counts shown on Figure 58 and Figure 59 show:

- Fin whales were present across the full recording period (including times of seismic surveys) at all sites;
- At North Porcupine two small peaks in calling in mid-July and mid-September;

- A consistent trend for constant, low numbers of calls at East Porcupine;
- A major increase in calls detected through late July and August at SW Porcupine Bank;
- Around five times as much calling at SW Porcupine Bank as at North or East Porcupine in September.

To quantify the total numbers of calling fin whales detected at the three sites the curves of calling individuals through time were integrated across each site (giving $CI \bullet days$ with CI the number of calling individuals), then normalised to the full sampling period (divided by) to give the mean number of calling individual fin whales in each data set. This gave:

- North Porcupine 0.333
- SW Porcupine Bank 0.602
- East Porcupine 0.103

Thus the call rates output when averaged across May-Sep 2014 showed almost three times as many calling fin whales at North Porcupine than at East Porcupine and roughly twice as many calling individuals at SW Porcupine Bank than at North Porcupine. This suggests that fin whales were found preferentially at the offshore site and increased in numbers post August offshore.

The calculated number of calling individuals gave the maximum number of calling fin whales as three at each site and the median number 1-2. Note that the maximum number of calling fin whales calculated was partly a function of ambient noise, the higher the ambient noise the more difficult it was to discern faint, singing fin whales. The prevalence of air gun signals at North and East Porcupine made discerning long range singers difficult.

As a further view of the trends in fin whale calling across the season the time averaged sea noise spectra was followed across time. The prevalence of fin whale calls and their ducting in the deep sound channel raised ambient noise across the call bandwidth (shown on Figure 56). Examples of the increase in sea noise in the time averaged sea noise was clear on Figure 70 to Figure 72 (long time frame sea noise, Appendix 14 below). An example of three days of sea noise in mid-September at North Porcupine indicating the increase in energy received by fin whales is shown on Figure 60. By using the 25 Hz 1/3 octave band (intensity in the bandwidth 22.10 - 27.84 Hz) as a proxy for fin whale calling and removing periods of air gun noise, as they dominated this band during periods of moderate air gun levels, then the trend across the season using the LF data from each site is shown on Figure 61. There was a clear increase in level in this frequency band across the recording period at all sites which was attributable to an increased prevalence of fin whale calling. This suggested fin whale calling increased across the sampling period and was highest in late September at the recording end, as given by the rates of calling.

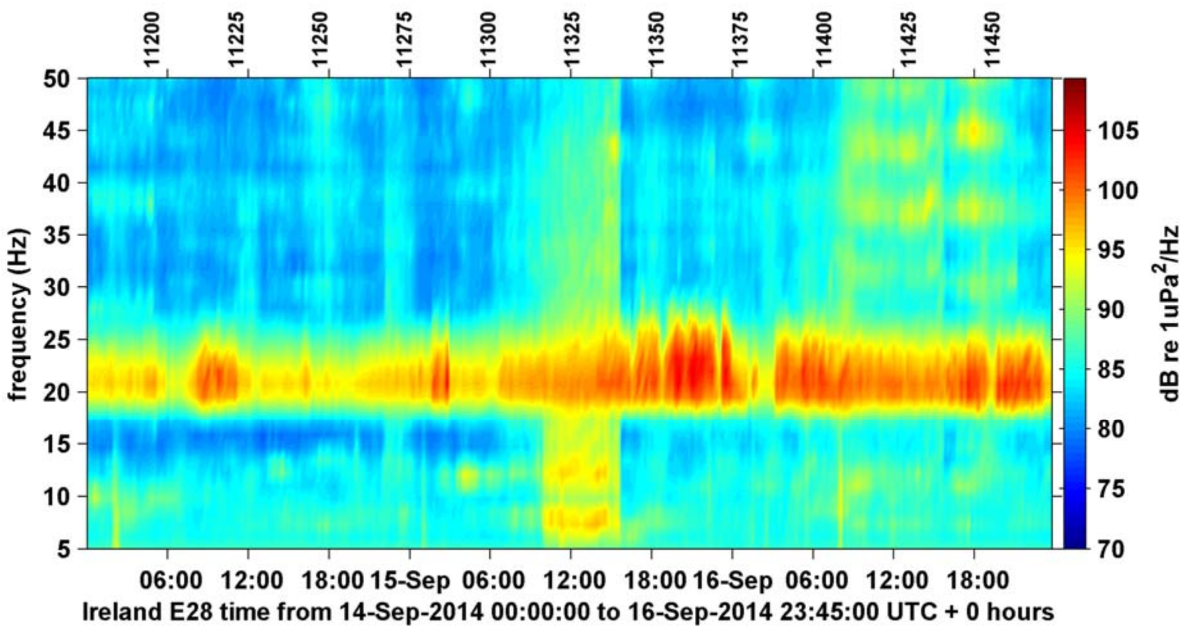

Figure 60: Three day spectrogram highlighting the presence of fin whale calling (energy over band 18-26 Hz) from North Porcupine.

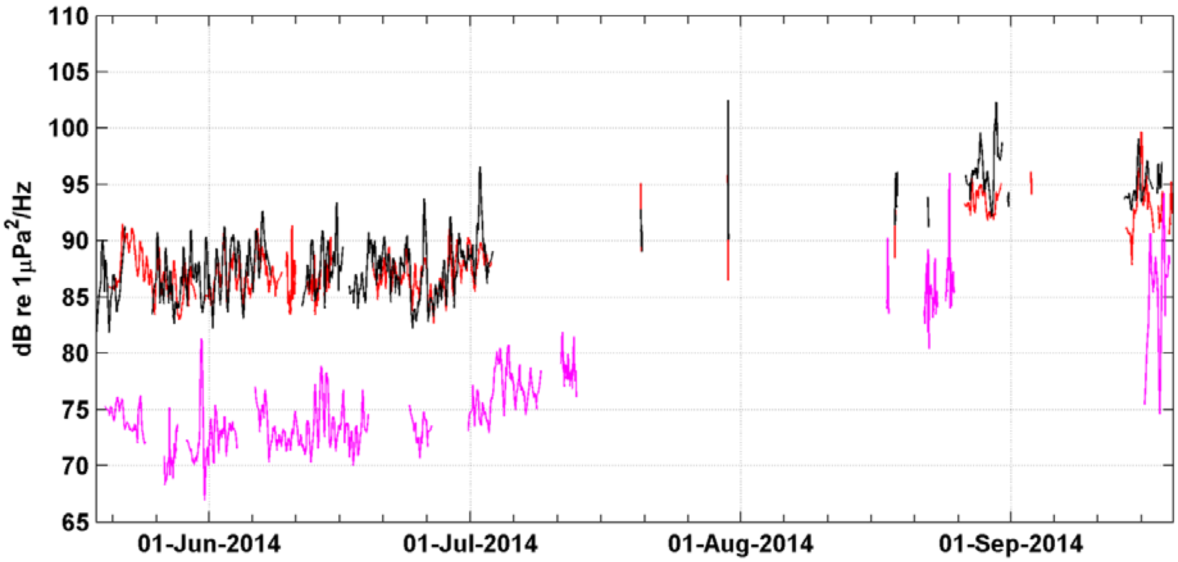

Figure 61: The 25 Hz 1/3 octave level followed through time at: North Porcupine (red curves); SW Porcupine Bank (magenta curves) and East Porcupine (black curves).

Appendix 11 Blue whales

A signal type described from north Atlantic blue whales (i.e. Mellinger and Clark, 2003) was detected from the SW Porcupine Bank site. This signal was similar to the part A-B call shown by Mellinger and Clark (2013). Blue whale calls with the part A component were most common, although on many signals part B was present. An example of this call type is shown expanded on Figure 62 and on Figure 63 where fin whale pulses and air gun signals were also evident.

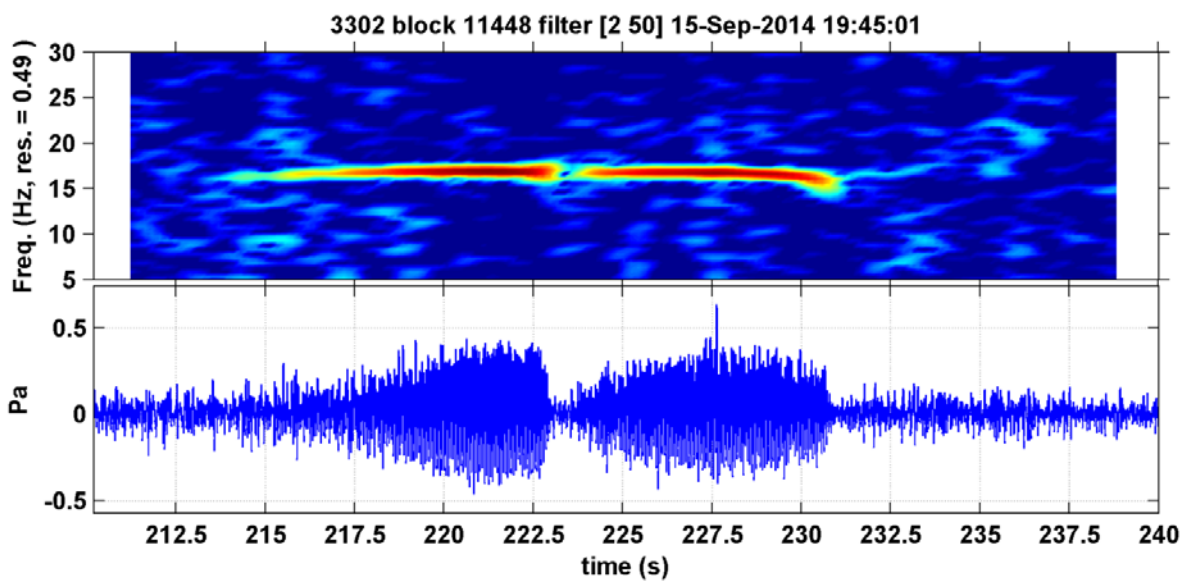

Figure 62: Example of part-A and B of a blue whale call detected from Porcupine. This call had most energy at 16.8 Hz.

There were compartively few blue whale calls detected, all of these at the SW Porcupine Bank site and almost all detected in the presence of fin whale calls and / or air gun signals. As fin whale and air gun signal energy overlapped with the blue whale call frequency content this made establishing call parameters for the blue whales difficult. The call frequency content of 27 calls from SW Porcupine Bank (LF logger, calibrated for low frequency roll off in time domain) are shown on

Figure 64. These spectra included some calls with parts A and B (noting part B shifted downward in frequency compared with part-A). The median frequency was 16.9 Hz.

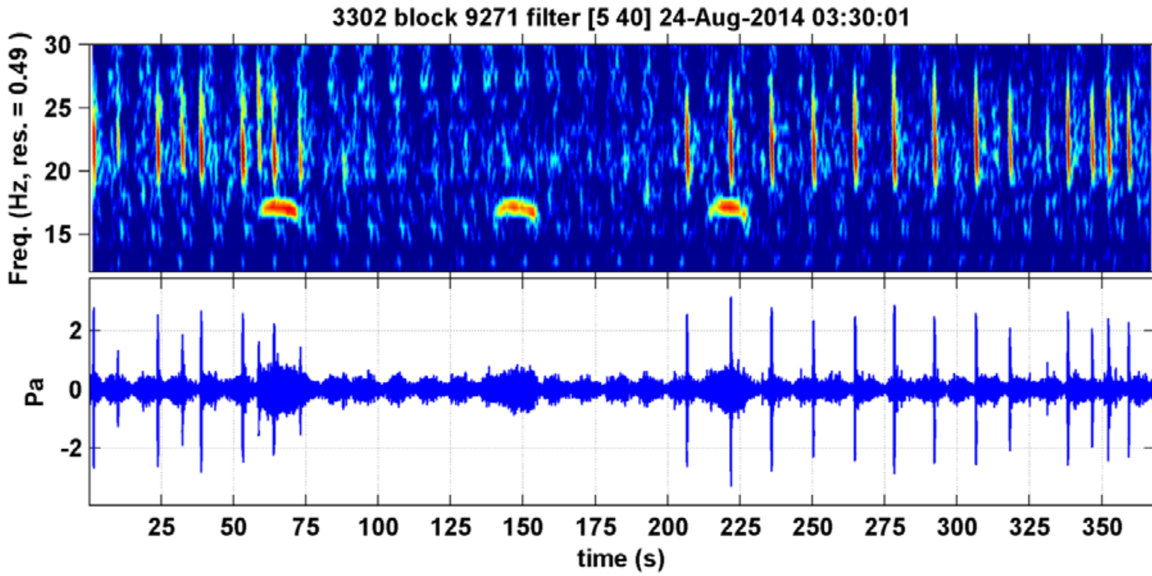

Figure 63: Spectrogram (top) and waveform (bottom) of three blue whale signals (energy at 16-17 Hz), fin whale signals (pulses over 19-30 Hz) with air gun signals in the background (regularly spaced pulses).

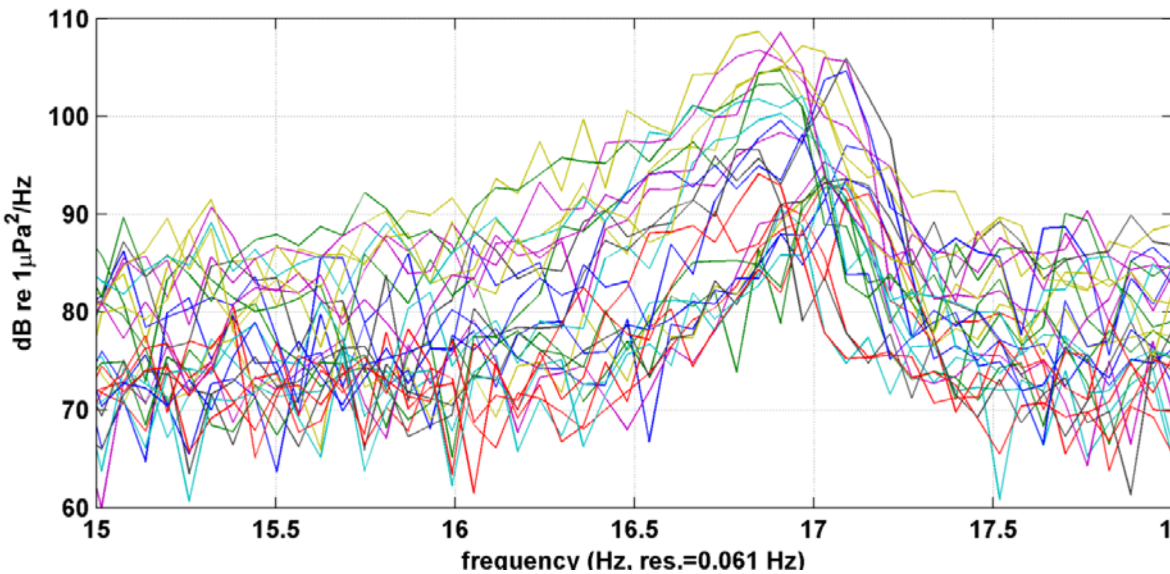

Figure 64: Spectra of 27 blue whale calls showing the frequency peak at 16.7-17.1 Hz made at a fine frequency resolution (0.061 Hz or 4096 points when downsampled to 250 Hz). These calls included animals with part A and part part B calls.

The blue whale call detector was run across the HF and LF loggers at SW Porcupine Bank and the LF loggers at North and East Porcupine. After manual checking no blue whales were found in the North and East Porcupine data sets. There were sufficient calls from the HF logger at SW Porcupine Bank (data set 3304) to establish call-call increments. As for the analysis of fin whale calls above, a plot of the time separation between blue whale calls and the one after that, are shown on Figure 65. This analysis gave the call separation as:

- 72.3 s for first following call

- 141.6 s for second following call

- or approximately 71 s between consecutive calls.

Using a call separation time of 68 s to count for the number of callers (all detections within a 68 s window must have been different individuals) then the trend in number of calling individuals observed across the sampling period from Porcupine is shown on Figure 66. Detections of blue whales increased across the sampling period, from the first single detection in June to the greatest number of animals detected in August and September 2014. The maximum number of animals calling detected was two and the median one.

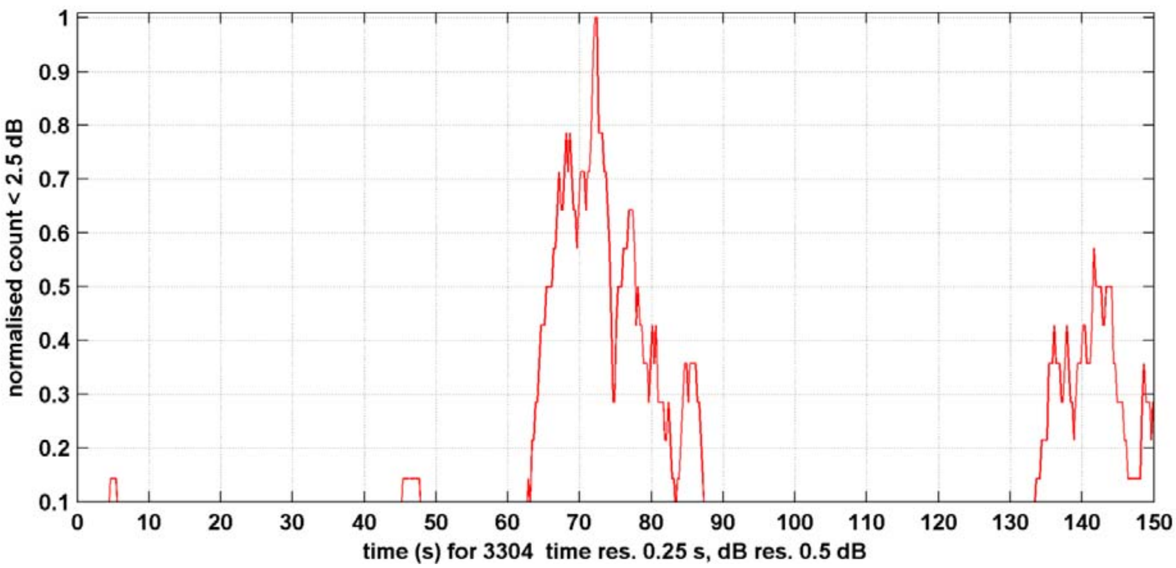

Figure 65: Blue whale call-call separation between time of call 1 to following call 2 and 3 using data from the HF logger at Porcupine.

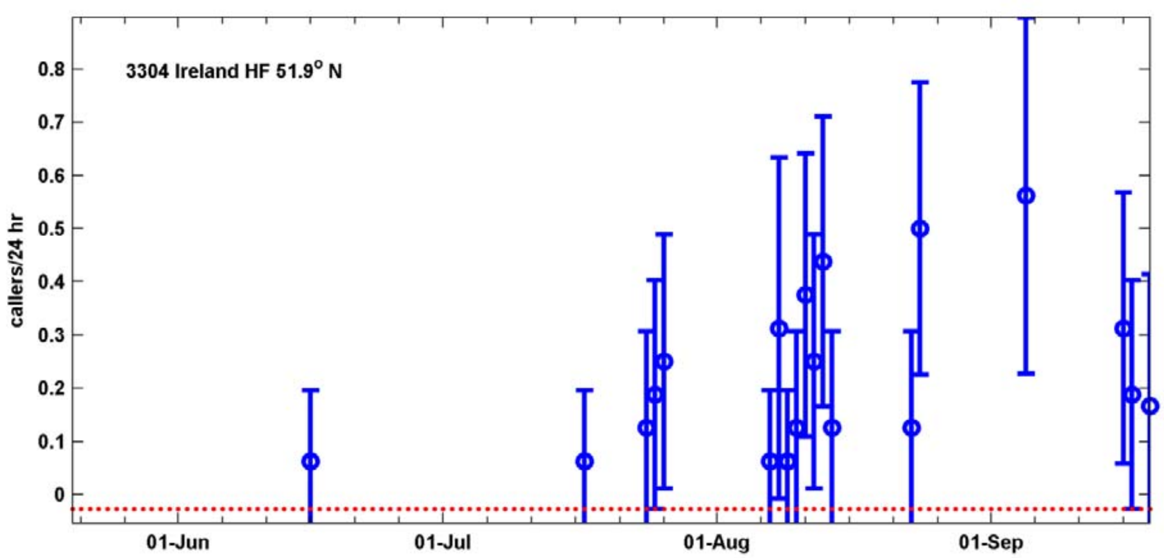

Figure 66: Number of calling blue whales averaged over 24 hour periods (12:00 to 12:00 UTC) shown with 95% confidence limits s error bars from data set 3304. Minor ticks are at 5 day increments.

Appendix 12: Dolphin whistles

The dolphin whistle presence showed:

- a general increase in dolphin activity at all sites later in the season
- greater dolphin whistling present at SW Porcupine Bank and East Porcupine than at North Porcupine
- no clear trend for more diurnal trends in whistle presence.

Samples with whistles detected were re-processed and all dolphin whistles within the sample identified. This allowed a minimum estimate of the number of dolphins to be made, by:

- stepping through each time point within each identified whistle within a sample
- locating all other whistles which had this time point but a different frequency value at this time point and saving the number of other whistles overlapping this time
- obtaining the minimum and maximum count of different whistles across a sample to give a measure of the number of different dolphins whistling simultaneously in this sample.

The distribution of dolphin whistle bout lengths are shown below (Figure 67).

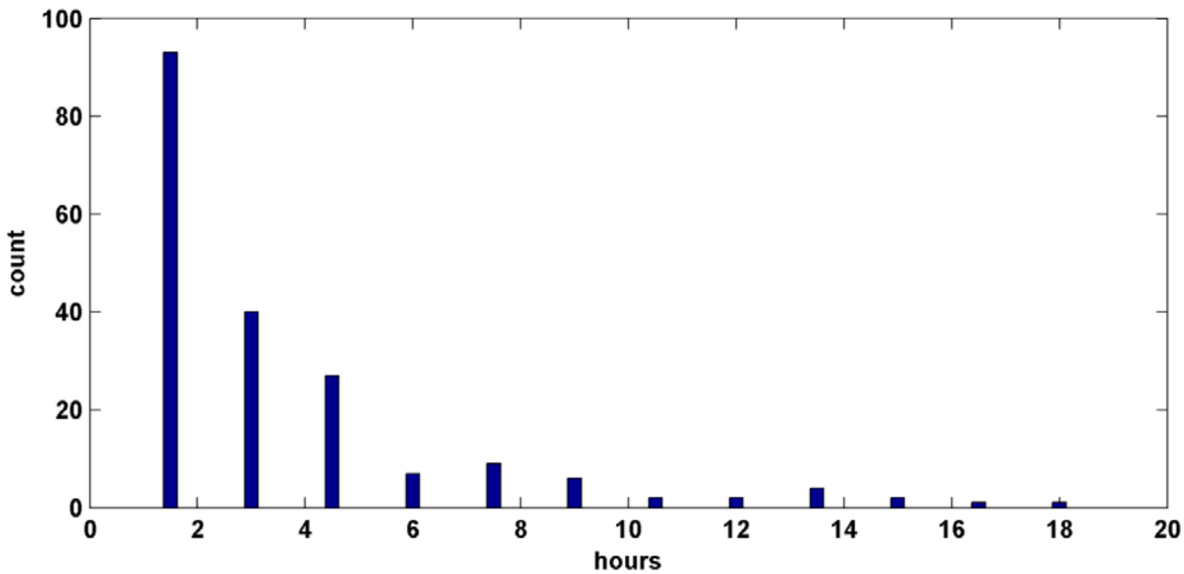

Figure 67: Distribution of dolphin whistle bout lengths using data from all sites.

Appendix 13: All toothed whale data

The presence of toothed whales was calculated as:

1. whistles - produced by dolphins, most likely common dolphins.
2. sperm whale clicks
3. beaked whale echolocation clicks
4. echolocation clicks in the band 2-30 kHz
5. whistles & echolocation clicks in the band 2-30 kHz (small toothed whales)
6. echolocation clicks in the band 30-96 kHz.

which was then reduced to four toothed whale categories of:

1. *sperm whales*
2. *smaller toothed whales* - presence of whistles or non-sperm whale echolocation clicks with dominant energy < 30 kHz
3. *beaked whales*
4. *high frequency echo location clicks (HF clicks).*

The smoothed trend of the presence of *sperm whales, smaller toothed whales, beaked whales and high frequency echo location clicks* was shown in the discussion. The presence of *smaller toothed whales* was substantial at all sites with comparatively, least detections at North Porcupine (up to 60% of samples/day) and most detections at SW Porcupine Bank and East Porcupine (up to 100% samples/day). Beaked whale presence was comparatively low at all sites (usually << 20% of samples / day). There was a general trend for an increase of sperm whale, beaked whale, smaller toothed whale and HF clicks post late July at SW Porcupine Bank and North Porcupine. All toothed whale categories had oscillating trends in presence, with periodicity in the 3-15 day period.

The distribution of echolocation click peak frequencies for all clicks with discernible frequency peaks (1.4 million) is shown on Figure 68. A lower frequency peak dominated by sperm whale clicks was present plus a peak at 32.5 kHz from probably various toothed whales, including beaked whales (which may have spectral peaks up to 50 kHz according to literature).Note that the filtering applied in analysis will have under-sampled for spectral peaks in the 28-30 kHz brackets due to the filtering and the way spectral peaks were determined.

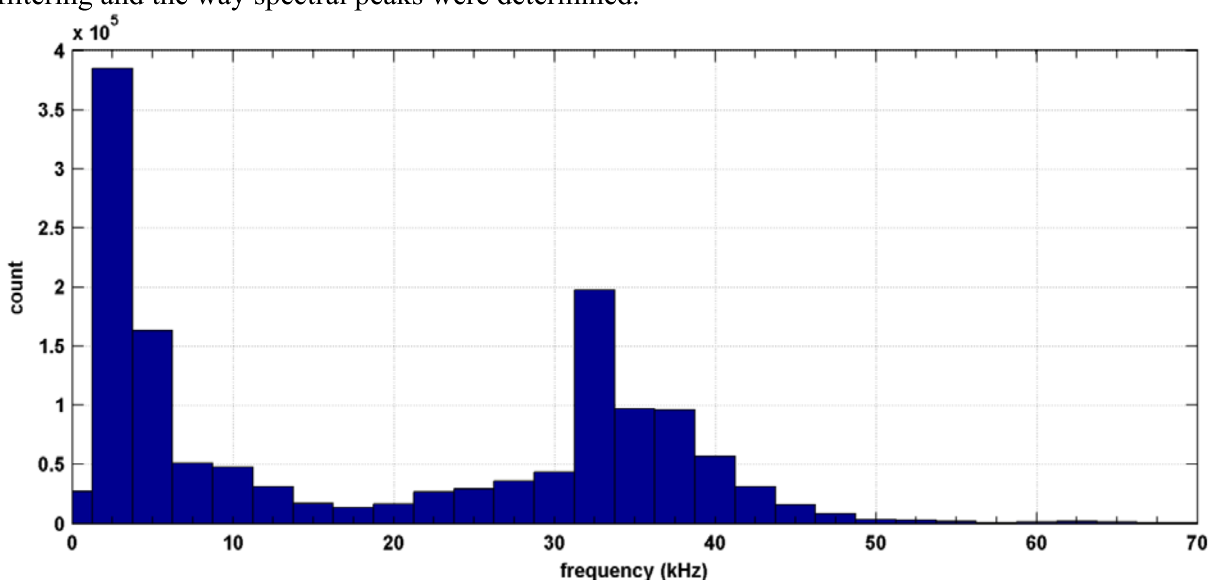

Figure 68: Spectral peak frequency for all echolocation clicks found using data from HF loggers at all sites (uses a 2.5 kHz bin width).

Many samples had whistling and echolocation clicks present. An example spectrogram and waveform of a section with high click rates plus dolphin whistling is shown on Figure 69.

Statistics on the total clicks and whistles detected are listed in Table 19. A high proportion of samples at SW Porcupine Bank and East Porcupine had toothed whale clicks or whistles present. North Porcupine had the least toothed whale clicking detected while SW Porcupine Bank had the most, with East Porcupine also having comparatively large numbers of samples with clicking present. Click rates were on occasion high, with the maximum clicks per sample detected running at ~ 32 clicks / s, and noting that the click detector was not designed to capture every click in a sample so this rate was probably slightly higher. Mostly clicks were detected in low numbers per sample (one to a few).

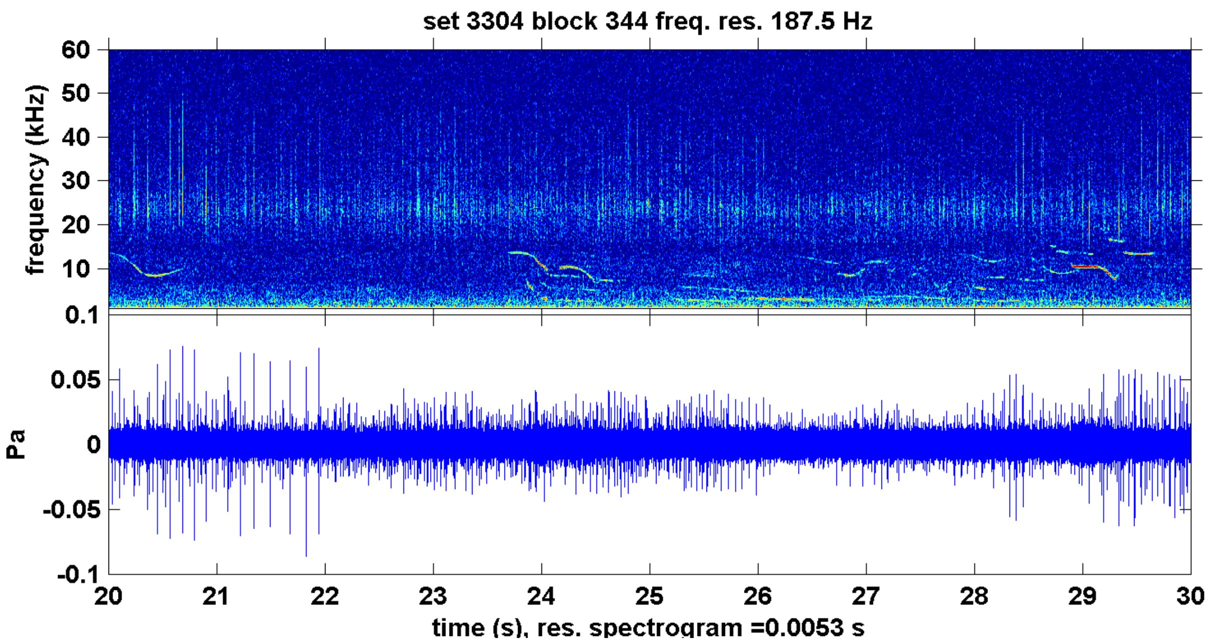

Figure 69: (top) Spectrogram of 10 s of HF data from Porcupine (10-Jun-2014 00:36) which had 10,327 clicks in the 501 s sample, none identified as sperm whale clicks, plus whistles present. (bottom) Waveform of sample shown above (high pass filter at 1 kHz).

Table 19: Statistics of whistles, sperm whale signals, beaked whale echo location, clicks in the frequency bands 1-30 kHz and 30-96 kHz. Values in brackets are ratios of total sample effort. In total 1,407,525 echolocation clicks were detected.

		1-30 kHz clicks					**30-96 kHz clicks**					**Samples with whistles & 1-30 kHz clicks**	**Samples with whistles**
site	**# samp**	**# clicks**	**max clicks / sample**	**samples with clicks**	**sperm whales**	**Other samples**	**# clicks**	**max clicks / sample**	**samples with clicks**	**Samples with Beaked whales**	**Other samples**		
3303 North Porcupine	1949	55639	8344	389 (0.20)	126 (0.06)	263 (0.13)	7181	2975	48 (0.02)	19 (0.01)	29 (0.01)	409 (0.21)	146 (0.07)
3304 SW Porcupine Bank	1963	463838	10327	1385 (0.70)	533 (0.27)	852 (0.43)	230159	9037	739 (0.38)	251 (0.13)	488 (0.25)	1244 (0.63)	392 (0.20)
3305 East Porcupine	1996	356633	22478	1085 (0.54)	379 (0.19)	706 (0.35)	294075	17943	526 (0.26)	238 (0.12)	288 (0.14)	1173 (0.59)	467 (0.23)
Total		876,110					531,415						

Appendix 14: Data summary

To visually display data, summary stacked sea noise spectra have been calculated in 40 day periods from each site. A technique was applied to remove noise spikes produced by hydrophone movement. For the low frequency noise loggers the resulting figures are displayed with a logarithmic frequency scale from 10 Hz to 2500 Hz with colour bounds from 55 to 110 dB re 1 μPa^2/Hz on Figure 70 to Figure 72, with the three sites displayed for the same 40 day period on each figure. The colour scale bounds were fixed to standardise the plots and optimise the colour dynamic range. Extreme values were set to the colour bounds. Figures displayed are listed in Table 20.

Table 20: List of 40 day stacked sea noise spectra (10 Hz to 2500 Hz).

Figure	dates shown
Figure 70	12:00 20-May-2014 until 12:00 29-Jun-2014 from SW Porcupine Bank (top) East Porcupine (middle) and North Porcupine (lower)
Figure 71	12:00 29-Jun-2014 until 12:00 08-Aug-2014 from SW Porcupine Bank (top) East Porcupine (middle) and North Porcupine (lower)
Figure 72	12:00 08-Aug-2014 until 12:00 17-Sep-2014 from SW Porcupine Bank (top) East Porcupine (middle) and North Porcupine (lower)

These figures show broad scale temporal patterns and because of the averaging involved (within a sample and across the eight consecutive averaged samples used to create the plot) can miss or not display well signals which are short in relation to the sample length. The plots tend to highlight signal types which are either intense or which persist across the sample length either through a long signal duration or multiple signals within a sample. Vessel noise, seismic survey signals and fin whale calling shows up well in the plots.

The high frequency data was plotted similarly (100 Hz to 96 kHz, in 40 day blocks) but the averaging involved in displaying a 40 day period on a single plot and the normally low received levels of biological signals in the higher frequencies meant the figures do not show trends of source presence well. For exploring the high frequency data five days batches were plotted up and used to identify periods of high frequency source presence. These figures are not shown here.

The 40 day panels from the low frequency noise loggers highlight dominant sources which are listed below. Great whale signal types not detected include those from humpback and minke whales. Major sources were:

Vessel noise - The passage of ships was evident at all sites and particularly at East Porcupine. Background tones of passing ships can be seen from all sites on Figure 70 to Figure 72, particularly on Figure 70 over May to June when seismic survey signals were lowest. The tones can be seen as horizontal lines over approximately 20-100 Hz although they on occasion occurred up to 1 kHz. The passage of individual ships can be seen as a broader band rise in noise level, typically over 10 Hz to 50-100 Hz, occurring over 4-6 hour periods as highlighted for East Porcupine on the centre panel of Figure 70.

Seismic survey signals - At least three sets of simultaneous seismic survey signals were present in the data sets. Seismic signals were present at SW Porcupine Bank early in the sampling period as can be seen over 25-27 May and > 20-Jun on Figure 70 (top panel) while absent at North and East Porcupine over this time frame. From ~ 03-Jul to 15-Sep seismic signals dominated the low frequency sea noise (< 1 kHz) at North and East Porcupine but were largely absent at SW Porcupine Bank. From 16-Aug to 14-Sep seismic was close to the receivers of North and East Porcupine with another distant survey also present, as can be seen on the lower panel of Figure 72.

Wind noise - wind generated noise was clearly evident in the data with a section of increased wind noise highlighted on for SW Porcupine Bank. The noise produced by wind is generated by the wind and sea producing bubbles with surface waves pushing these bubbles below the surface. The bubbles then oscillate or implode in the water column generating noise. A range of bubble sizes, bubbles being driven deep into the water column and large aggregations of bubbles oscillating as for a larger bubble of equivalent volume, give wind generated noise a wide frequency spectrum. On the panel highlighted at SW Porcupine Bank (Figure 70) the wind noise increases ambient level substantially up to 1 kHz.

Sonar signals- Several periods of sonar signal near to the receiver were evident across the survey period. The presence of a low frequency sonar is highlighted from East Porcupine on the centre panel of Figure 70. Ships echosounder sonar signals near 50 kHz were also evident at times on the high frequency noise loggers.

Fin whales - Fin whale calling became dominant later in the recording period notably at the receivers to the west. The energy of many distant fin whales arriving via deep sound channel ducting increased toward the latter part of the recording period such that the frequency band over the range 18-26 Hz was dominated by fin whale energy.

Dolphin signals - Periods of dolphin whistling were detected primarily at East Porcupine and primarily in the 8-20 kHz range. The dolphin whistling was not commonly detected and occurred in 1.5 - 6 hour bouts.

Sperm whales - Sperm whale clicks were detected, particularly at North Porcupine.

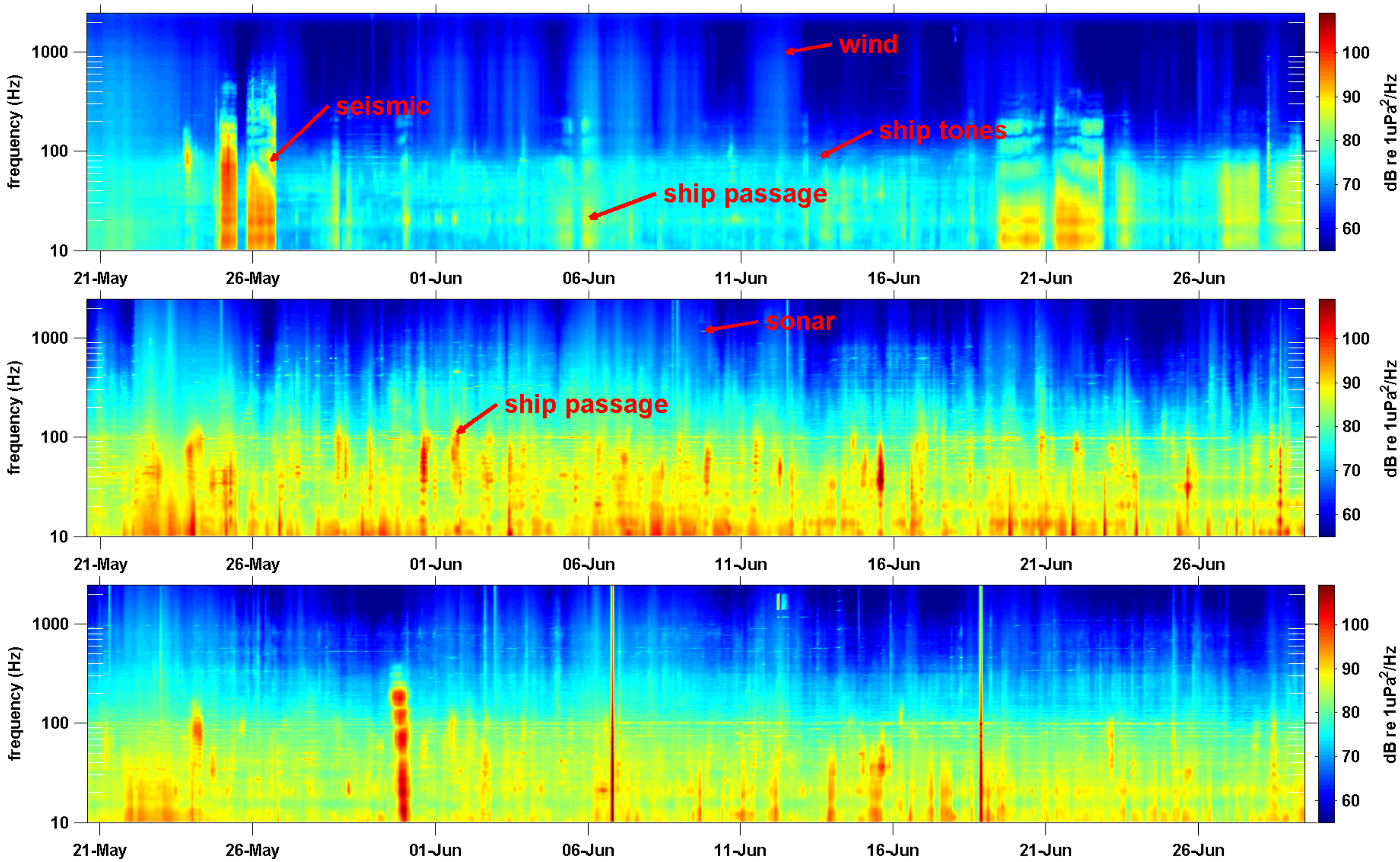

Figure 70: Stacked sea noise spectra over 10 Hz to 2500 Hz from the low frequency noise loggers in 40 day batches over 12:00 20-May-2014 until 12:00 29-Jun-2014 from SW Porcupine Bank (top), East Porcupine (centre) and North Porcupine (lower).

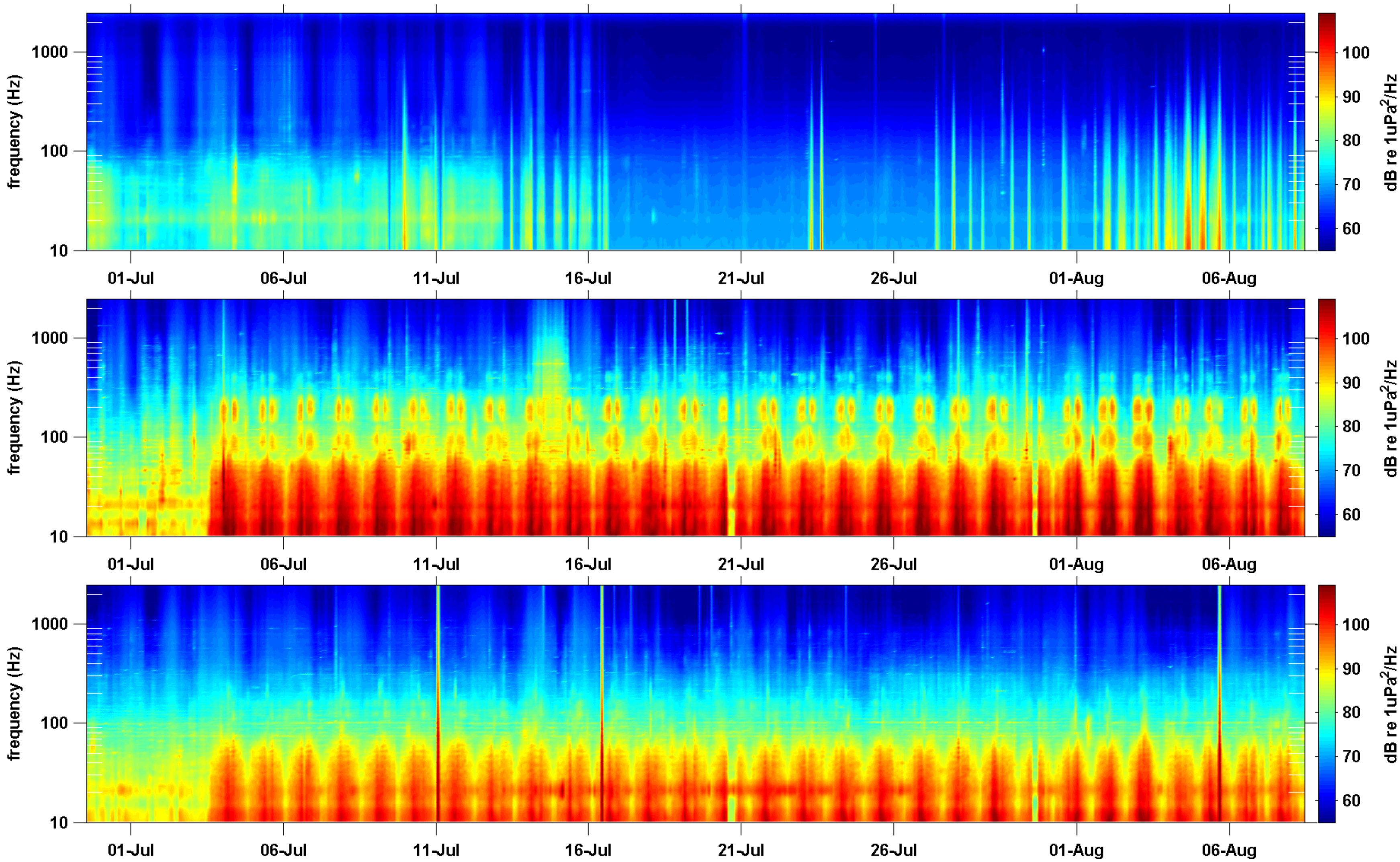

Figure 71: Stacked sea noise spectra over 10 Hz to 2500 Hz from the low frequency noise loggers in 40 day batches over 12:00 29-Jun-2014 until 12:00 08-Aug-2014 from SW Porcupine Bank (top), East Porcupine (centre) and North Porcupine (lower).

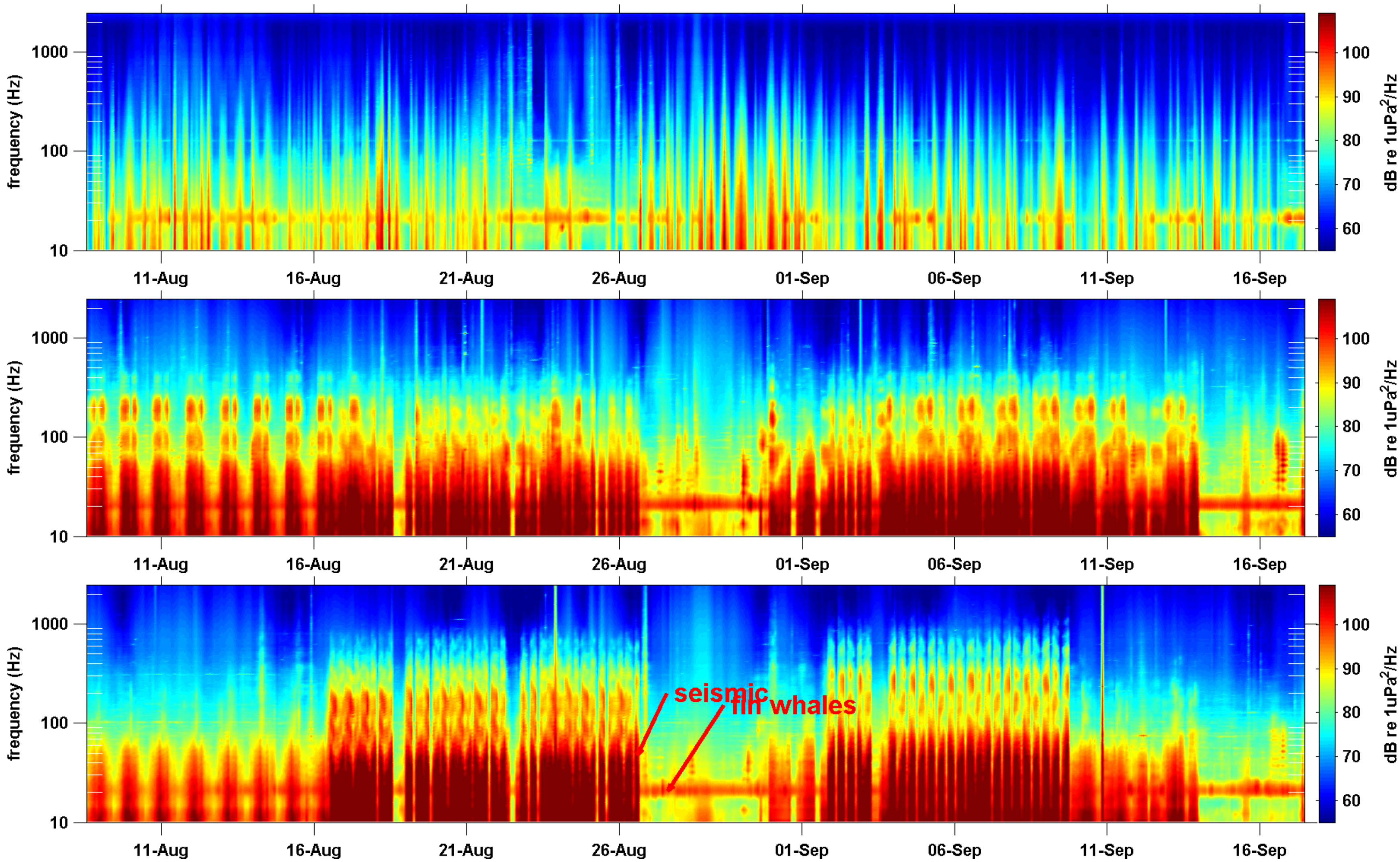

Figure 72: Stacked sea noise spectra over 10 Hz to 2500 Hz from the low frequency noise loggers in 40 day batches over 12:00 08-Aug-2014 until 12:00 17-Sep-2014 from SW Porcupine Bank (top), East Porcupine (centre) and North Porcupine (lower).