GREAT AUSTRALIAN BIGHT RESEARCH PROGRAM

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Great Australian Bight sea noise 2015: Whale, fish, seismic survey, and ambient noise

Report to the Great Australian Bight Research Program

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GREAT AUSTRALIAN BIGHT RESEARCH PROGRAM

The Great Australian Bight Research Program is a collaboration between BP, CSIRO, the South Australian Research and Development Institute (SARDI), the University of Adelaide, and Flinders University. The Program aims to provide a whole-of-system understanding of the environmental, economic and social values of the region; providing an information source for all to use.

Acknowledgments

This work would not have eventuated without support and resources from the South Australian Research and Development Institute (SARDI), whose staff deployed and recovered the Kangaroo Island mooring using their vessel *RV Ngerin*. Passive acoustic data from the Kangaroo Island and Portland sites was made available through the Integrated Marine Observing System (IMOS). IMOS is supported by the Australian Government through the National Collaborative Research Infrastructure Strategy and the Super Science Initiative. The Bremer Bay sea noise data was sourced from the Centre for Marine Science and Technology archives and was deployed with the assistance of Naturaliste Charters and Curt and Micheline Jenner of the Centre for Whale Research (WA Inc.).

Contents

1. Introduction

This document describes various phenomena measured using sea noise collected by autonomous sea noise receivers set across southern Australia and emphasising a site located on the eastern side of the Great Australian Bight, west of Kangaroo Island. The document is produced under contract to CSIRO under the auspices of the Great Australian Bight Research Program (GABRP, http://www.misa.net.au/GAB). At this point in time the discussion is brief given a focus on extracting data.

2. Methods

Sea noise data from the Australian Integrated Marine Observing System (IMOS) Kangaroo Island and Portland sites plus a site run by the Centre for Marine Science and Technology (CMST) off Bremer Bay have been used in analysis, with locations and sample times listed in Table 1. The initial analysis has focussed on the Kangaroo Island site (abbreviated KI hereafter) which was sampled through most of 2015, compared with trends of several great whales and fish from the IMOS Portland and Bremer sites. The locations of sites sampled are shown on Figure 1 and in more detail for the Kangaroo Island site on Figure 2.

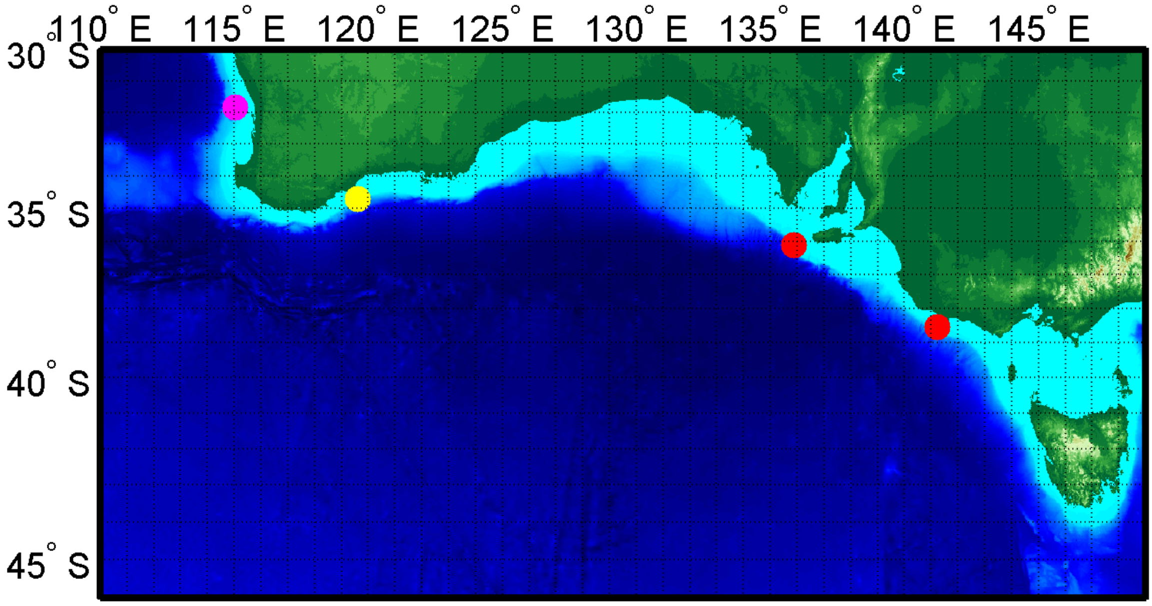

Figure 1: Location of Portland and Kangaroo Island IMOS Passive Acoustic moorings (red filled circles), Bremer Canyon receiver (yellow) and IMOS Perth Canyon (magenta) sites.

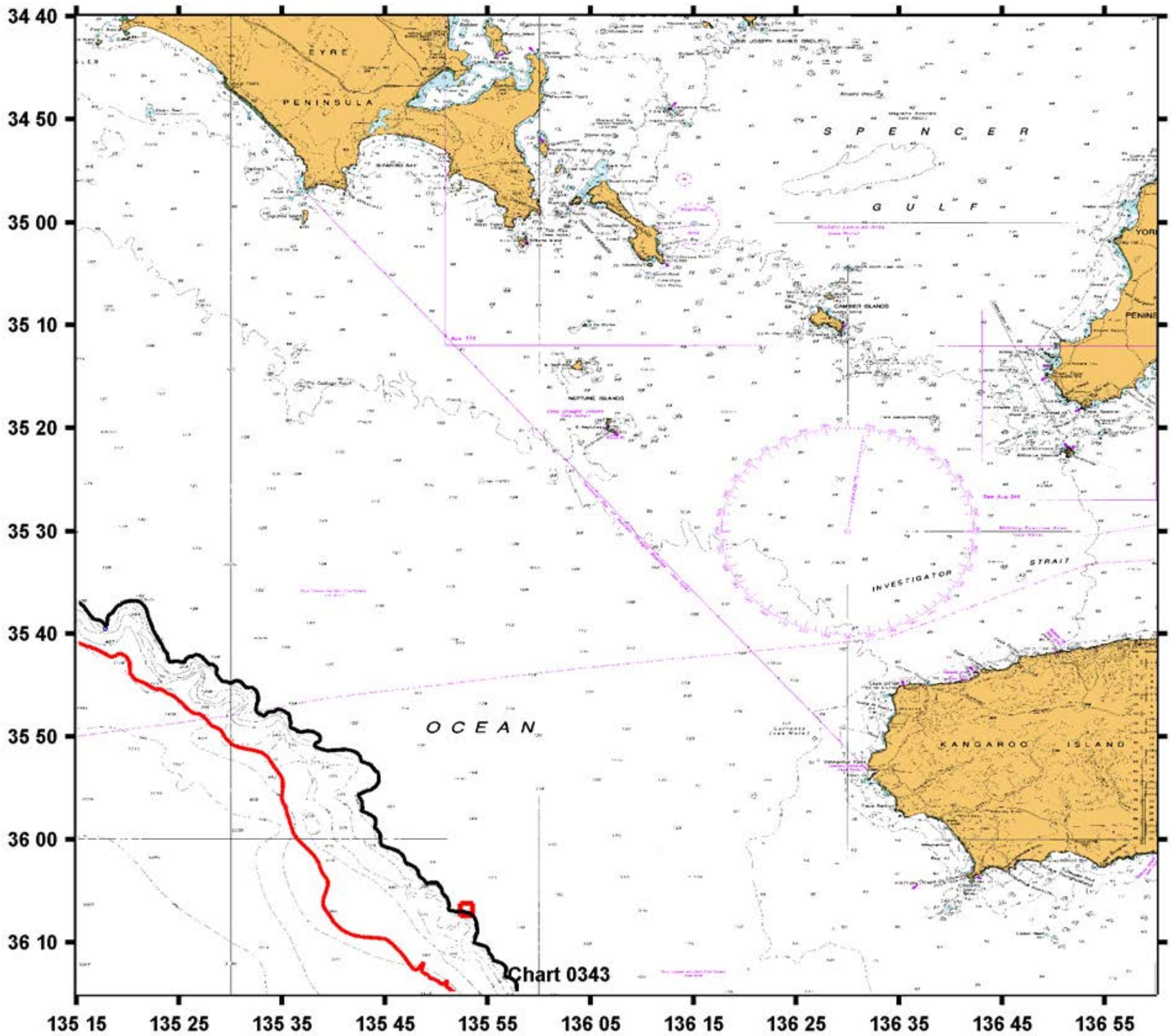

Figure 2: Chart showing Kangaroo Island sea noise logger mooring location (red square). The 200 m and 1000 m depth contours are shown by the black and red lines respectively.

Table 1: Details of gear deployed with: set number; location; latitude; longitude; water depth; start sampling in-water (UTC+10 hours Portland, UTC+9.5 hours Kangaroo island; UTC+8 hours Bremer Bay); end sampling in-water (time bases as start of a sample); days sampled; and sample numbers in-water. The bold data sets are 2015 deployments. For comparison all of the Portland IMOS data sets are included.

set	location	latitude (S)	longitude (E)	depth (m)	start	end	days	samples
2846	Portland (IMOS)	38º 32.981'	141º 15.235'	165	06-May-2009 20:15	22-Dec-2009 16:30	230	1 - 21982
2926	Portland (IMOS)	38º 33.031'	141º 15.232'	165	07-Feb-2010 20:15	25-Sep-2010 17:15	230	1 - 21904
3073	Portland (IMOS)	38º 32.559'	141º 13.047'	165	15-Feb-2012 14:15	06-Nov-2012 08:05	265	1 - 25202
3102	Portland (IMOS)	38º 33.604'	141º 15.125'	165	30-Dec-2010 12:15	03-Dec-2011 11:30	338	1918 - 34144
3184	Portland (IMOS)	38º 32.034'	141º 14.589'	165	07-Nov-2012 12:00	17-May-2013 09:45	191	1 - 18327
3274	Portland (IMOS)	38º 32.218'	141º 14.854'	165	30-Dec-2013 09:30	27-Nov-2014 02:15	332	2775 - 34618
3381	**Portland (IMOS)**	**38º 32.521**	**141º 13.263**	**160**	**03-Feb-2015 10:15**	**26-Jan-2016 09:00**	**357**	**355 - 34620**
3382	**Kangaroo Island (IMOS)**	**36º 6.819'**	**135º 52.952'**	**173**	**09-Dec-2014 01:00**	**17-Nov-2015 05:45**	**343**	**1-32948**
3385	**Bremer Bay (CMST)**	**34º42.422'**	**119º 35.928'**	**250**	**10-Feb-2015 10:00**	**06-Feb-2016 15:00**	**361**	**1-34677**

2.2 Hardware

A single mooring was deployed at KI, with the mooring layout shown on Figure 3. The mooring was set to reduce mooring induced movement at the hydrophone, since any movement of the hydrophone and to a lesser extent housing and hydrophone cable, will generate noise artefacts. Twin ORE CART acoustic release units were used on the mooring. All moorings presented in Table 1 were of a similar design.

The sea noise logger (CMST-DSTO type) sampled 300 s every 15 minutes at 6 kHz with a 2.8 kHz anti-aliasing filter and a gentle low frequency filter applied to reduce noise levels in the low frequencies where sea noise is naturally high. The system gain was checked prior and after deployment by inputting white noise of known level with the hydrophone in-series and analysing the logged gain as a function of frequency, which is shown on Figure 4. The gain response with frequency was combined with the hydrophone sensitivity (for KI site, Massa TR1025-C serial number 500, sensitivity -196 dB re $V^2/\mu Pa^2$) to calibrate the signal in the time or frequency domain, as required.

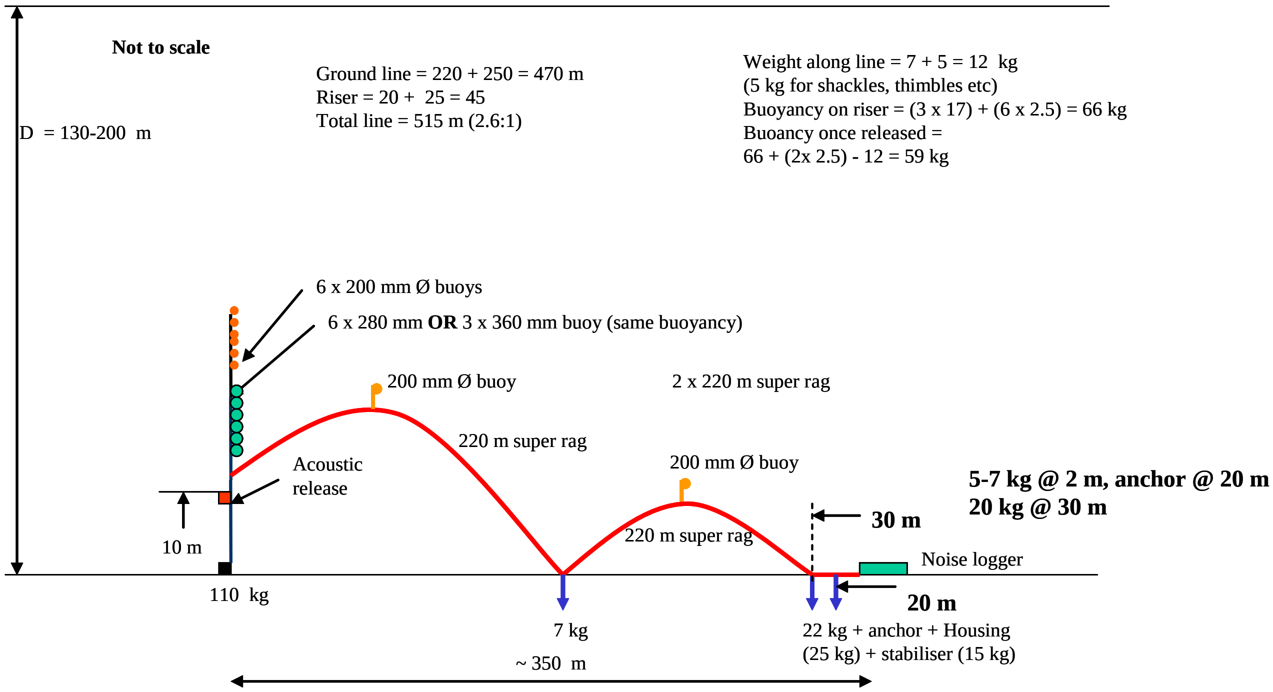

Figure 3: Schematic of mooring (not to scale).

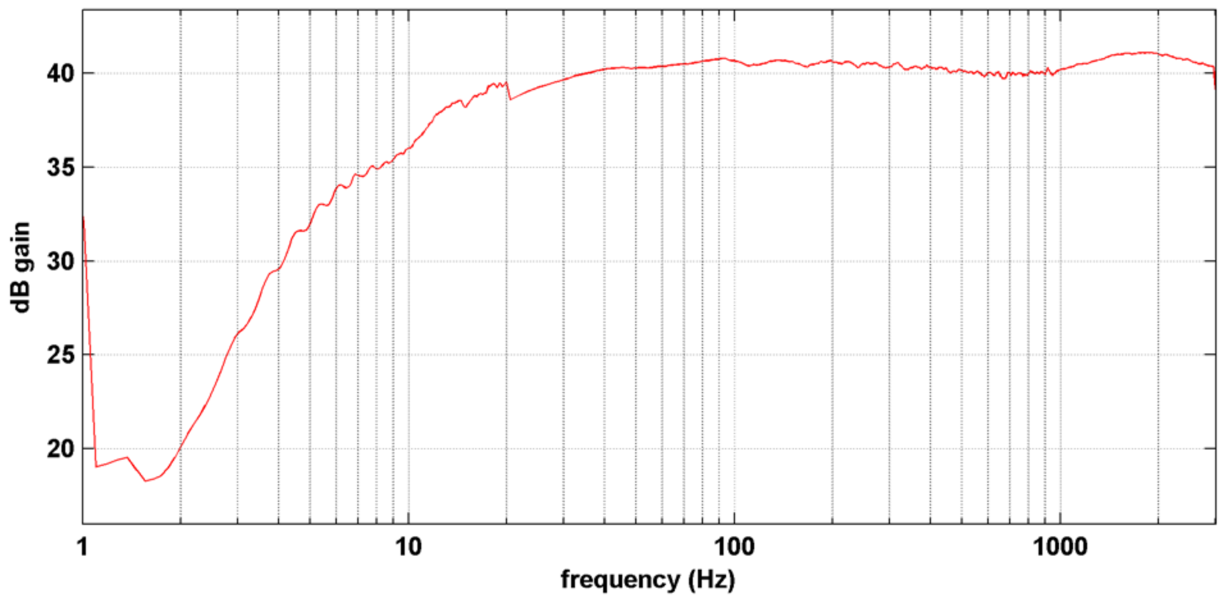

Figure 4: System gain with frequency for set 3382.

2.3 Whale searching and abundance measures

Searching for biological signals was carried out by a variety of detection algorithms tailored for the signal type in question and the noise regime. Some of the detector outputs were fully cross checked, by manually viewing spectrograms. A 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 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. Following manual checking of the algorithm output the samples with 'hits' were bracketed by three samples and the spectrogram of those not previously checked displayed sequentially. Time stamps were added if new detections were found. This process was iterated until no more new detections were found (ie. all samples which had detections had been searched for three samples prior and after). A summary of which data sets were searched for what, is listed in Table 2.

To track trends in whale numbers through time based on received calling there are several relative abundance measures which can be used. It needs to be recognised that following trends in received calling by a species is not necessarily an exact correlation with the numbers of animals in the area unless various features of the calling behaviour are understood. A lack of received calling by a particular species is also not an indication there are no animals in the area, they may be non-calling whales. A summary of the techniques used to create relative abundance indexes from received calling is listed in Table 3. 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. To do this requires knowledge of whale calling habits, notably the repetition interval of songs. 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. Not all whale signal types can be analysed to give the number of calling animals at any time point, thus various techniques have been used for different species.

For pygmy blue whales the second song component (type II) was localised in time at a standard point along the call, the five minutes of a sample was split into 90 s windows, the number of type II calls counted in each window, and the maximum number within any window was deemed as the number of individual whales calling within that sample. A 90 s window was used as this is known to be the repeat time spacing for one of the pygmy blue whale two most common song structures. The most common song structure has a repeat interval of 180 s.

Table 2: Status of searching for various signal types showing: the set number and location (PO = Portland, KI = Kangaroo island, BR = Bremer Bay); and whether the data set was searched for the whale type listed (Y = yes or N = no) and manually checked (with P = partly checked).

set	**Pygmy blue**		**Antarctic minke**		**'Spot' call**		**Sperm whales**
	algorithm	manual	algorithm	manual	algorithm	manual	Manual
3381 PO	Y	P			Y	N	Y
3382 KI	Y	Y	Y	Y	Y	N	Y
3385 BR	Y	Y			Y	N	Y

Table 3: Techniques and measures used to give relative abundance measures of whales based on received calling parameters.

#	Summary	Measure type	Advantages Disadvantages	Units
1	Calls / time	Call rates per unit time	A. - Simple and gross measure of animals in area D. - Not an immediate reflection of number of animals in area, does not account for propensity of animals to call, call rates, etc.	Calls / hour Calls / day etc
2	Ratio samples with calls	The ratio (or %) of samples with call type present	A. -Simple and gross measure of animals in area, suited for call types where difficult to make accurate counts calling such as toothed whale echolocation clicking or more than 3-4 humpbacks singing D. - Not an immediate reflection of number of animals in area, measure "flatlines" (ie reaches 100% easily)	Ratio or % / time periods
3	Number animals calling	Animals calling / unit time	A. - Is a direct measure of number animals calling in an area. Can be averaged across time, typically 24 hour periods to remove diurnal trends. Requires counting number individual whales calling at an instant in time (generally a sea noise sample)	Instantaneous callers Callers / 24 hours
4	Track Intensity	Level Signal to noise ratio (SNR)	A. - Relatively simple to extract, shows long term trends, integrates wide area for open ocean great whales, useful for fish choruses D. - Impacted by "noise" natural or non-natural, is a gross reflection of whale abundance only, can suffer from species produce most intensity at similar frequencies (usually not an issue for great whales, can be for fish)	Spectral level at nominal Hz or frequency band dB SNR

2.4 Tracking deep sound channel, whale energy

A sound speed duct occurs in deep ocean waters which traps the energy of many great whale calls and allows fragments of the call energy to travel long distances (many hundreds if not thousands of km). The sound speed structure in the ocean is set by a number of factors, but chiefly by water temperature and pressure (Urick, 1983). Given typical sound speed profiles in the deep oceans towards the equator from the polar convergence zones, then the vertical sound speed structure has a minimum value at around 1000 m depth. Refraction effects create a sound duct centred on this sound speed minimum - sound "rays" which travel upwards through the sound speed minimum are bent towards the lowest sound speed, or downwards, while sound "rays" passing downwards through the sound speed minimum are bent upwards. This results in horizontally travelling sound signals becoming trapped in the duct. As these trapped signals do not interact with the sea surface or seabed they suffer no losses at boundaries or interfaces, which typically create high loss rates in continental shelf waters particularly at the seabed interface. As absorption losses are almost negligible over the frequency band 10-100 Hz then these frequencies lose little energy when trapped in the duct. Very long wavelength, or low frequency signals, trapped in the duct may still interact with the seabed so lose energy. The results is that in the deep ocean, energy over the band ~ 10-100 Hz from acoustic sources which become trapped in this duct or "deep sound channel" can travel ocean scale distances. The energy drops as it leaves the source by spreading loss alone, or the energy moving into an expanding circumference. For shallow sources such as whales, not all of their energy produced during calling is trapped in this duct, some is directed downwards at steep angles so does not couple into the duct before interacting with the seabed. The presence of this duct has been known since the late 1940's and has various names, "deep sound channel", "SOFAR" etc. This phenomena does not occur on the continental shelf.

Many baleen whales have taken advantage of this open ocean deep sound channel, optimising their call frequency to fall within the range of energy which transmits in the duct and producing fine tones, which translate into narrow frequency bands of energy which appear in the duct, with tonal frequencies generally different for different species. For the sea noise receivers along Southern Australia all were coupled to energy transmitting in the deep sound channel, although being on the shelf edge all sites suffered some losses in transmitting energy from the open ocean up the shelf slopes. Thus in all sites narrow bands of energy belonging to different whale species appear at the times when they are calling and located south of Australia and north of the Antarctic convergence. The Antarctic convergence acts as a boundary to these signals, calls produced by animals south of the convergence tend not to make it north and vice-versa. Thus the presence and level of the energy in these distinct frequency bands can be used to give an indication of whale presence and relative abundance in southern Australia. Gavrilov and McCauley (2013) used these energy spikes to study blue whale call frequency changes with time while Širovic´ et al. (2015) suggested using energy indexes as relative whale abundance measures. It should be noted that this long range tonal energy which arrives at a receiver is not in the form of a recognisable whale call for that species, but arrives as small 'packets' of energy only. This is distinct from recognisable whale calls, where the full structure of the call is evident. Recognisable calls tend to be limited to around 100 km in the deep ocean (ie. Gavrilov et al. 2012, Gavrilov and McCauley 2013).

Measures of call energy trapped in the deep sound channel and produced by great whales have been used here to compare trends in the presence of Antarctic blue, pygmy blue and an unknown whale call termed the 'spot' call, which at this stage is believed to be produced by southern right whales (McCauley et al. 2013). To measure these 'energy indexes' the average power spectra of each sample was calculated at a 0.0916 Hz resolution (65,536 points at 6 kHz sample rate, hanning window, no overlap, averaged across full sample). Frequency bands were chosen to encapsulate each signal type and surrounding noise. These frequency bands are give in Table 4, with a low and high frequency band adjacent the tone used to get surrounding noise levels and a band encapsulating the tone used to get peak levels. Note that all of these whales lower their call frequency across a season and the following season jump back to the mean of the last month of the previous season (Gavrilov and McCauley 2013). This means a frequency band encapsulating the change of frequency over the period sampled needs to be set to cover the seasonal downward frequency drift. Also note that different species have different rates of change in call frequency per season, so again the frequency band differs in bandwidth between species for the same time period. The tones of the 'spot' and Antarctic blue whale were close together so only small upper and lower noise frequency bands could be selected (respectively).

Table 4: Frequency bands used for calculating noise levels or maximum levels (in-band) for different call types, using 2014-2015 southern Australian data. The lower band is used to get noise levels on the low frequency side of the tine, and the upper band the same but on the higher frequency side. N refers to the number of values in that frequency range.

Call type	**Lower band (Hz)**	**N**	**in-band**	**N**	**Upper band (Hz)**	**N**
pygmy blue	65.73 - 66.56	10	66.65 - 68.39	20	68.48 - 69.31	10
Antarctic blue	25.09 - 25.27	3	25.36 - 26.37	12	26.46 - 27.37	11
spot	22.80 - 23.71	11	23.80 - 24.90	13	24.99 - 25.27	4

The metrics used to describe the call intensity here are the maximum tonal spectral level in the respective frequency band for the tone, and the signal to noise ratio (SNR) of the maximum level in-band compared with the maximum, of the median level in the upper or lower frequency band used (values subtracted in the dB domain). The maximum level tracks the energy of that particular call type but has no set lower level (zero calling from that species) as the signal falls into the noise

which is variable. The SNR on the other hand does have a zero value (no calling) but suffers from variable noise levels (through natural or man-made causes) shifting the SNR up and down.

The presence of this deep sound channel in the open ocean makes an enormous difference to background noise regimes in the frequency band 10-100 Hz as the duct allows energy from thousands of km to add to background noise. McCauley et al (2015) have highlighted this for receivers set on the shelf slope of the Great Australian Bight compared to receivers set on the continental shelf, with ambient noise up to 30 dB higher in the 10-100 Hz frequency band on the shelf edge compared with back on the continental shelf.

2.5 Acoustic measures and analysis

A definition of acoustic units is given in Appendix 1. Air gun signals were analysed for levels using the algorithms defined in McCauley et al. (2003). Pertinent units here are sound exposure level or SEL (dB re 1µPa^2·s) which is the best measure for impulse, or short (say < 1 s) signals. Sound pressure levels, or SPL (dB re 1µPa) for air gun signals were defined as the square root of the mean pressure squared, over the time bands defined by the 5 and 95% values along the cumulative $P^2 \cdot s$ curve, with the ambient noise contribution removed (see McCauley et al. 2003). Sound pressure levels for continual noise have a defined time averaging period presented.

Ambient noise levels are presented in spectral level units (dB re 1µPa^2/Hz) or presented as broadband levels (dB re 1µPa), generally calculated as the total intensity above the 7.81 Hz centre frequency 1/3 octave band, or > 6.96 Hz. Unless otherwise stated, broadband levels have been calculated from the time averaged spectra made across a single sample.

2.6 Units and data sources

Bathymetry here used the 0.0025^o Geoscience Australia grid (Whiteway, 2009, ~ 280 m resolution). Spatial analysis uses the MATLAB (The MathWorks Inc.) mapping toolbox using latitude and longitude with WGS 84 chart datum. Nautical charts were generated in MATLAB from Australian Hydrographic Service charts under Seafarer GeoTIFF license No 2618SG (Curtin University). Time of sunset was derived from the Geoscience Australia website, astronomical calculator, which returned the time of the suns' upper limb crossing below the horizon. Ocean sound speed profiles were based on winter average salinity and temperature with depth retrieved from the 2005 World Ocean Data Atlas (NOAA, https://www.nodc.noaa.gov/OC5/indprod.html).

2.7 Estimation listening ranges

Noise logger listening ranges were calculated to define the detection area 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 blue whales and the spot call. 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. Bathymetry paths were truncated when the water depth reached 50 m or less.

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 sound field to be calculated (usually around a one m vertical step) out to the range limit set (500 km unless the path ran into shallow water). 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. The 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 calculations the ambient noise level may be set slightly higher than the noise level as measured if the appropriate search algorithm did not detect calls down to the background noise state (the algorithms have a threshold 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 results. The search areas were calculated from the poylgons 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.

The ambient noise for each call type was derived by taking the averaged power spectra for each sample at a 1.464 Hz resolution, removing sections which were influenced by the respective call type (bandwidths used of 5-15 Hz, 30-63 Hz and 70-90 Hz) then fitting a linear fit to this curve. The ambient noise values for the respective call type were then interpolated from this fitted curve at the desired frequency for the call type (averaged across several frequencies if the call type was not tonal). The resulting values were then filtered such that only fits with a correlation coefficient of $r^2 > 0.7$ were used and the resulting points smoothed using a running liner fit (4 hour smoothing). This ambient noise curve was then interpolated at a 15 minute interval and statistics of the ambient noise at the desired frequency for that call type obtained.

3. Results

3.1 Air gun signals

Air gun signals were present at the KI location during the first few months of recordings. They were never detected at high levels, always being only a few dB above no-seismic ambient levels. An example of a spectrogram of one, five minute sample with air gun signals is shown on Figure 5. The levels of 688 signals received at the KI location which were sufficiently above the ambient noise were calculated, with the distributions of their levels shown on Figure 6. Mean sound exposure levels were 113 dB re 1µPa^2·s and mean sound pressure levels were 109 dB re 1µPa, with these signals recorded at 551 to 638 km range.

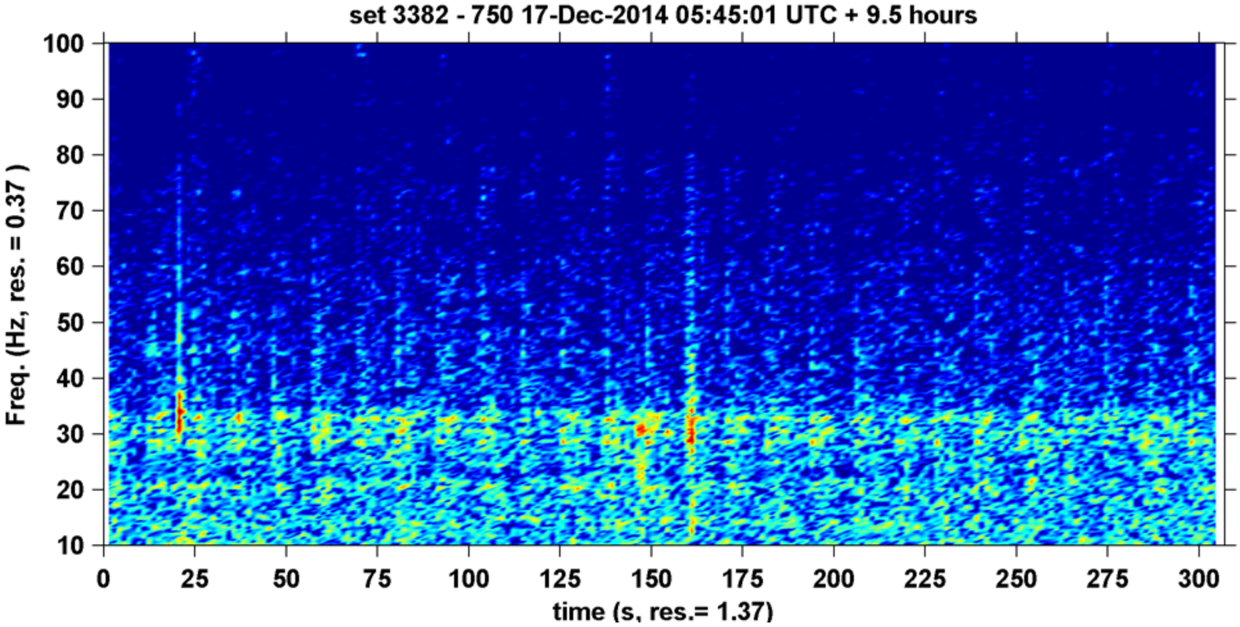

Figure 5: Example of a sample with distant air gun signals present (several s long, repeated every ~ 10 s, most energy 10-35 Hz). The downsweep at ~ 23 s is possibly produced by a whale.

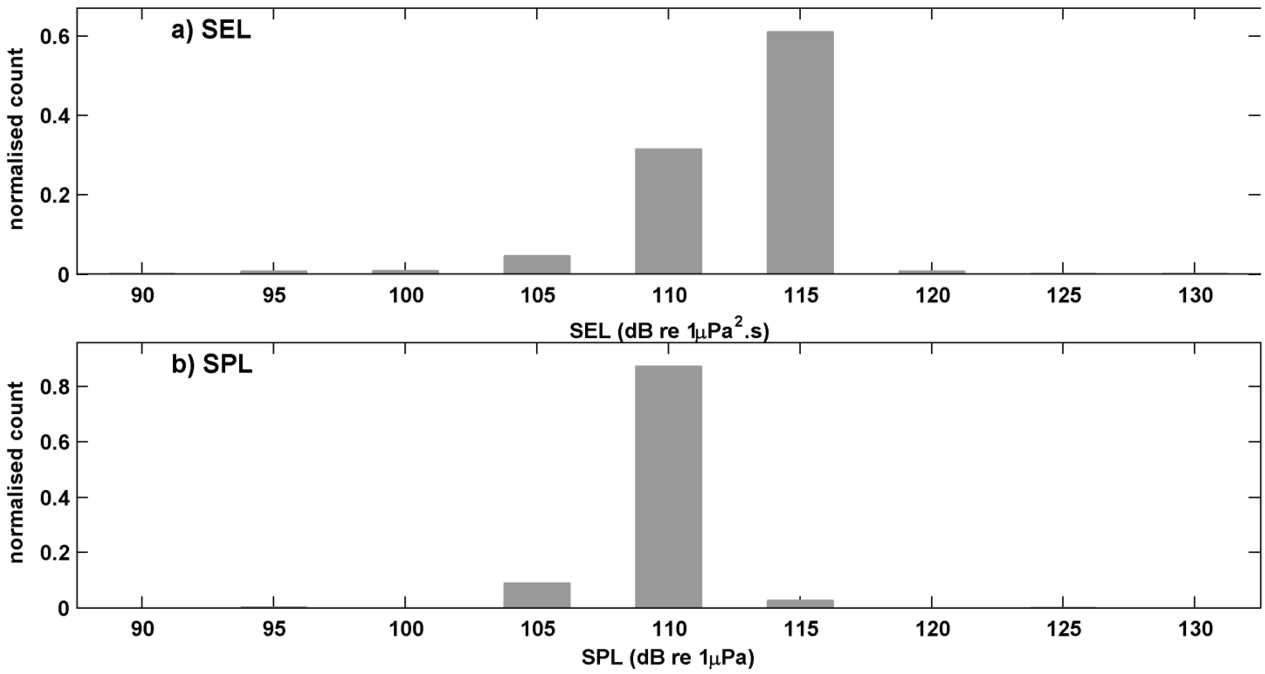

Figure 6: Distribution of received air gun signal measures at KI for (a) sound exposure level and (b) sound pressure level. A few outliers were found but most signals were close (within 4-6 dB) to the ambient noise.

The calculations for air gun signals given by McCauley et al. (2003) subtract the mean noise level, calculated for each individual signal. The mean noise level for the 688 signals analysed was 105 dB re 1µPa (same units as SPL) or only 4 dB below the average air gun signal level (comparing with mean air gun SPL which was calculated similarly but only over the air gun signal duration).

The relatively small contribution of the air gun signals to the ambient noise regime at KI can be seen on Figure 7. The air gun signals input into ambient noise up to approximately 400 Hz, with their influencing depending on background wind noise with high wind noise (from high wind speeds) masking the air gun signals. A period of air gun operations, with a line approaching the receiver up until 11:55 on the 22-Jan can be seen on Figure 7 (a) followed by relatively low wind noise then the air gun starting again at approximately 14:30 on the 22-Jan.

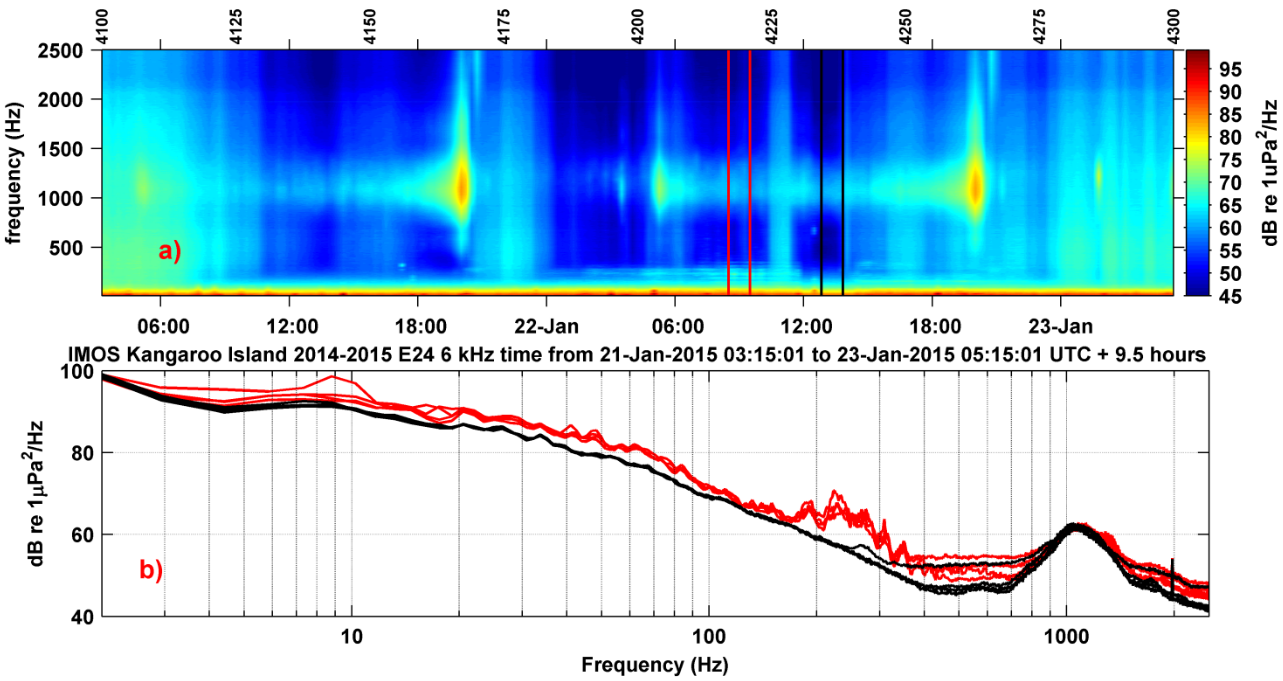

Figure 7: A 50 hour spectrogram of sea noise at KI over 10 Hz to 2.5 kHz (a) and the frequency spectra (b) averaged for each five minute sample and shown for four samples in two time periods, delineated by the red and black lines on (a). A fish chorus dominated at 1 kHz.

The influence of wind on background noise and for the presence of two fish chorus types can also be seen on Figure 7. One fish chorus was present all day but at a much higher level over 18:00-21:00 (centred around 1 kHz) and one fish chorus was present ~ 2 hours post dusk for a short period with energy mostly > 2 kHz. These are discussed below.

The seismic source detected by the KI receiver was believed to be operating at the western end of the Great Australian Bight over late 2014 into 2015, as shown on Figure 8, along with the locations of signals analysed. For the signals analysed, the minimum range of source to receiver was 551km and the maximum range 638 km. The bathymetry profiles for the shortest and longest range signals analysed are shown on Figure 9.

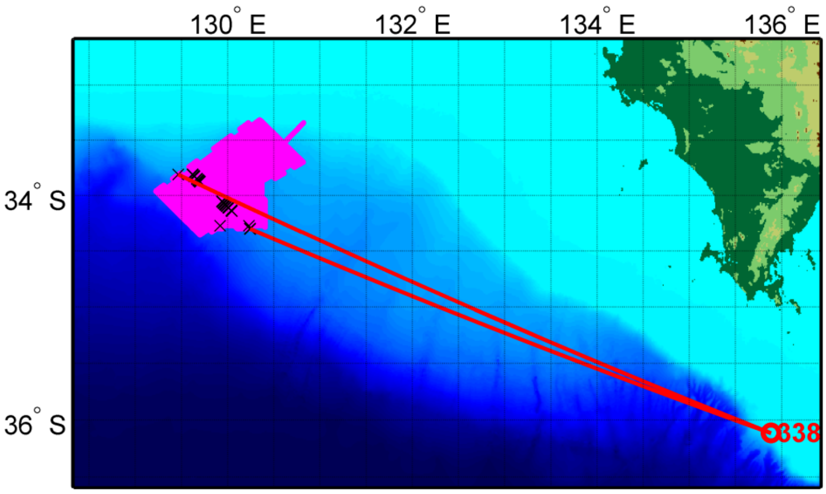

Figure 8: Location of KI receiver (red circle, RHS), seismic lines (magenta lines), analysed air gun signal locations (black crosses) and travel paths for shortest and longest range shots analysed (red lines).

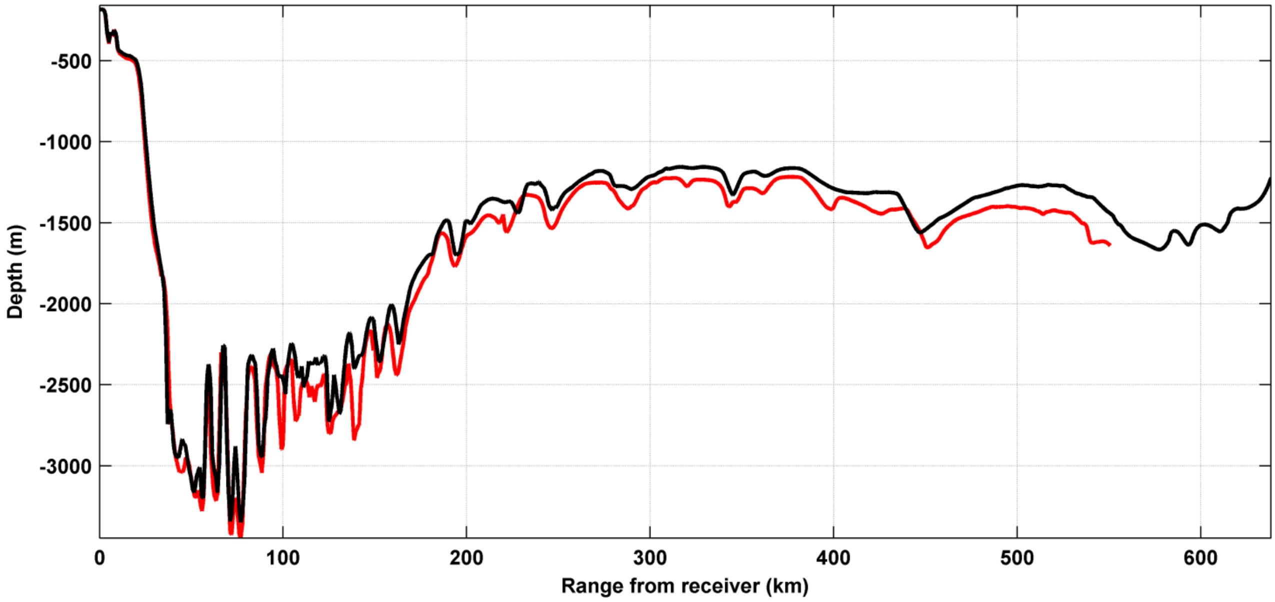

Figure 9: Bathymetry profiles paths along paths of shortest (red) and longest (black) range air gun signals analysed,

3.2 Ambient noise

Statistics of spectral level values of ambient noise averaged for each month at the KI site, in 1/3 octave frequency bands are given in Table 11, Appendix 1. The distributions of broadband ambient noise for the full KI recording period, for the period of seismic operations (up to 04-Apr-2015) and post 04-Apr-2015, are shown on Figure 10. The proportions of time ambient levels exceeded a set value for the KI site using all data, seismic period, and no-seismic period are shown on Figure 11.

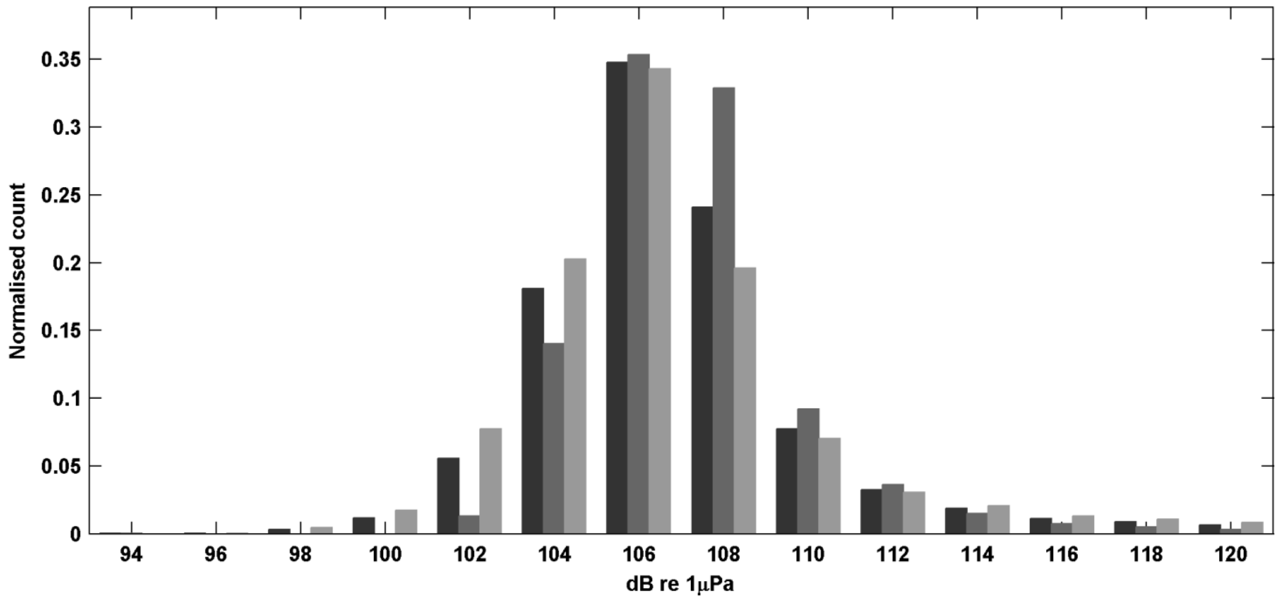

Figure 10: Distribution of broadband ambient noise from KI site, with the dates split such that: darkest bars are full period; intermediate bars are period of seismic survey; and lightest bars are period post 04-Apr-2015 with no seismic.

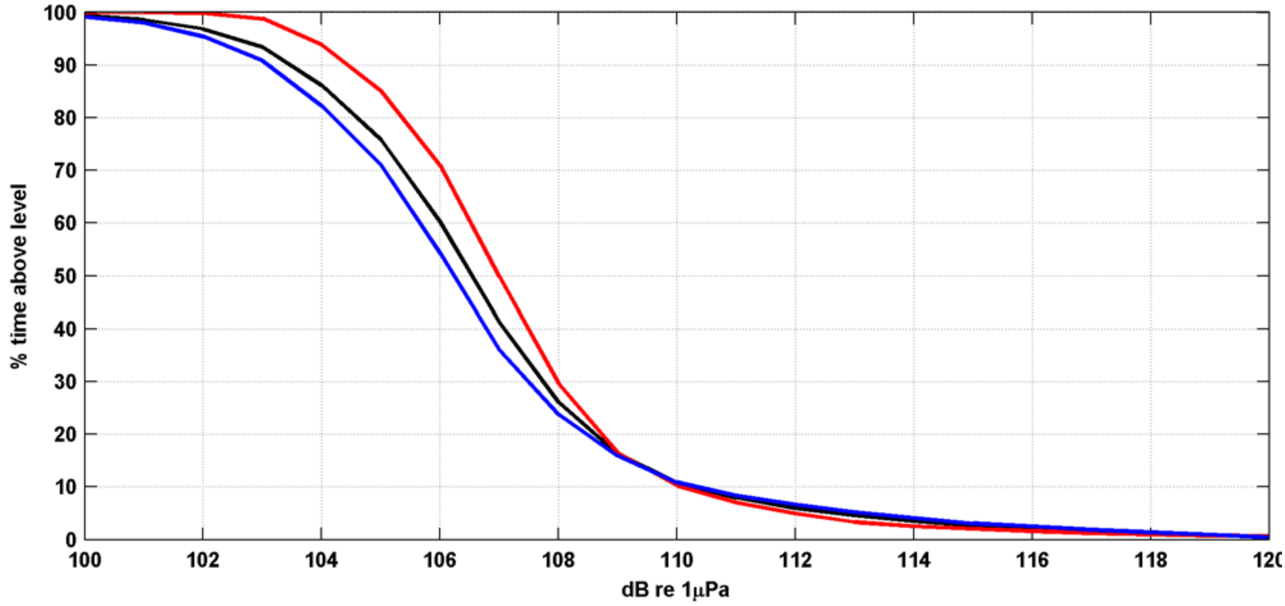

Figure 11: Proportion of time (%) broadband ambient noise exceeded a set value at the KI site, split for the full period (black), period with seismic (red) and period post seismic (blue, or > 04-Apr-2015).

3.3 Biological signals

Call types from five whale species multiple fish choruses and signals possibly from large fish were detected in the 2015 Kangaroo Island data set. Whale species detected by their vocalisations at KI included: Eastern Indian Ocean pygmy blue whales (*Balaenoptera musculus brevicauda*); Antarctic blue whales (distant calling only, *Balaenoptera musculus intermedia*); an unidentified great whale call type possibly from southern right whales (the 'spot' call); Antarctic minke whales (*Balaenoptera acutorostrata*); and humpback whales (*Megaptera novaengliae*) .

No sperm whale (*Physeter macrocephalus*) signals were located at KI although they were detected at Portland and Bremer in 2015. While the 6 kHz sample rate was low for detecting sperm whale clicks, previous measures at other sites in northern and southern Australia have detected sperm whale clicks at this sample rate. Example spectrograms of whale and fish calls are shown on Figure 12. A summary of results for different species is presented below. The analysis of using tonal levels to track a species presence was carried out simultaneously for pygmy blue, Antarctic blue and the spot call so is presented independently.

At Portland in 2015 a third blue whale sub-species, the NZ pygmy blue whale, (*Balaenoptera musculus brevicauda*) was also detected. Fin whales were detected from Portland and Bremer in 2015, but not KI. Trends in these whale species are not reported here.

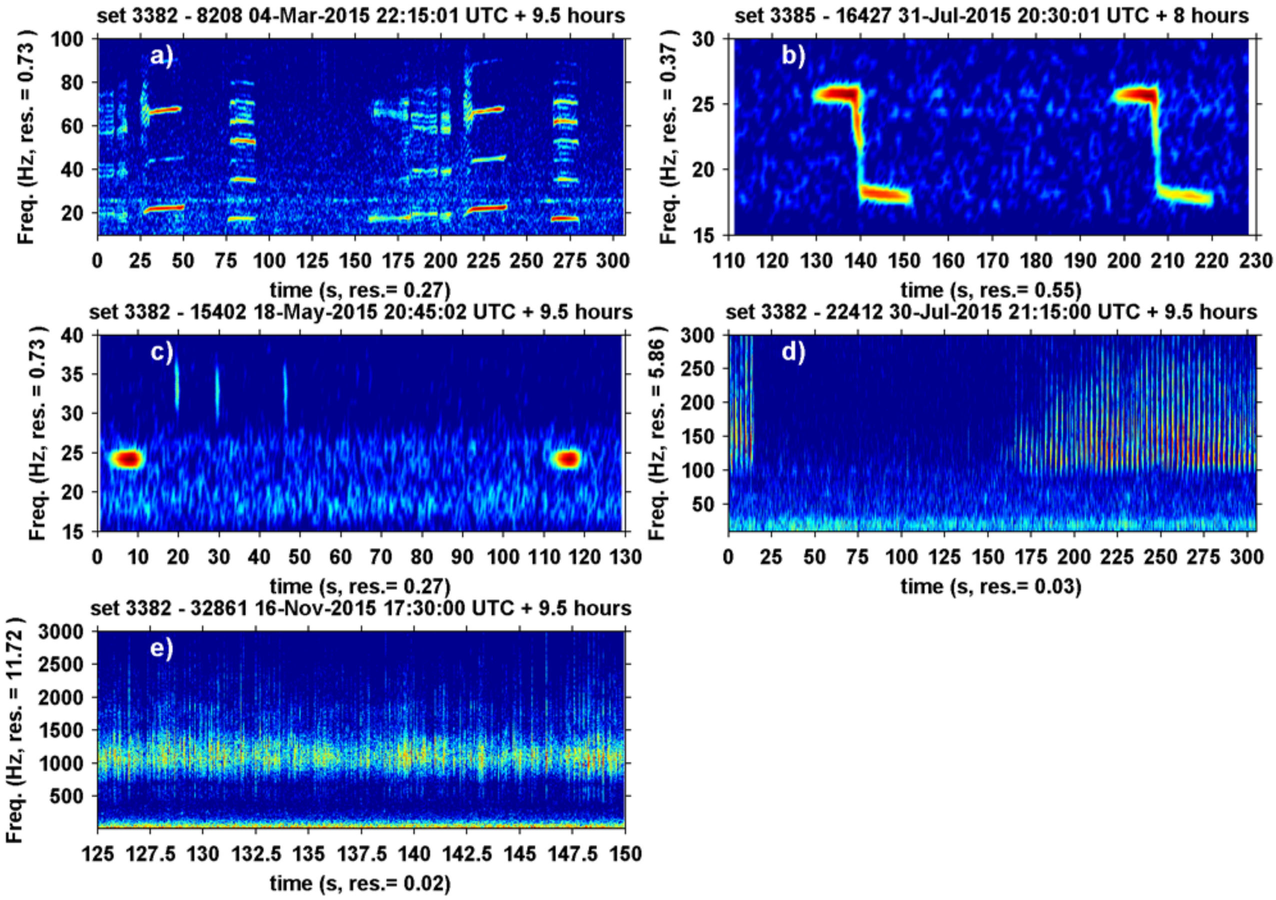

Figure 12: Spectrograms of signal types analysed here, showing: a) pygmy blue whale calls (a 'song' is over 150-300 s); b) Antarctic blue whale calls (Bremer); c) unidentified call, termed 'spot'; d) Antarctic minke whale calls (one call from 150 s onwards); and e) the most common and dominant fish chorus.

3.3.1 Blue whale signals

In 2015, based on call types received (direct or long range energy), three sub species of blue whales were present at Portland and two at KI and Bremer. Call types from the New Zealand (NZ) pygmy blue whale, Antarctic blue and Eastern Indian Ocean (EIO) pygmy blue whales were detected at Portland while the Antarctic blue and EIO pygmy blue whales were present at KI and Bremer. An example of the NZ call type shown on Figure 13, the Antarctic blue on Figure 14 and the Eastern Indian Ocean pygmy blue on Figure 15.

For the EIO pygmy blue whale the song type II component as shown on Figure 15, was searched for. The upper harmonic (centred at around 67.5 Hz in 2015) is the song component which shows best for long range calling. This upper harmonic of the type II EIO pygmy blue call is of lower source level than the 18-22 Hz portion of the call, but the ambient noise level is considerably lower at the frequency of the upper harmonic thus it tends to show up better at long range.

At KI, EIO pygmy blue whale calls were rarely detected at short range and commonly at long range as given by their low received level. Instances of whales moving past the receiver can be seen by plotting level against time, as shown on Figure 16 using data from the KI and Bremer Bay receivers. The lower levels plotted on Figure 16 were set by the ambient noise regime which can be seen to drop considerably at Bremer in December 2015. Several instances of EIO pygmy blue whales apparently moving by the receiver as given by the regular increase then decrease in levels, can be seen at both sites on Figure 16.

The relative abundance of EIO pygmy blue whales was given as counts of the number of individual whales instantaneously calling, averaged over a 24 hour period from 12:00 hours one day to 12:00 the next day. The averaging removed any diurnal differences in call rates, as found by McCauley et al (2001) in the Perth Canyon for EIO pygmy blue whales. The relative abundance estimates are shown for the Portland, Bremer and KI sites on Figure 17, noting the Portland data set was only manually checked into early June, thus beyond this time point the data has many false detections.

No incidences of nearby Antarctic blue whale calling were observed from the KI data set, although they were observed from Bremer in 2015 (ie. Figure 14). A detection algorithm was run across the Portland and KI data sets for Antarctic blue whale calls but was confounded by the tonal energy produced by long range Antarctic blue whale calling triggering large numbers of false detections. Given time constraints the algorithm was not modified and energy in the tonal frequency band has instead been used to track Antarctic blue whale calling, as described below. Tonal energy was also used to track trends in EIO pygmy blue whales and the 'spot call.

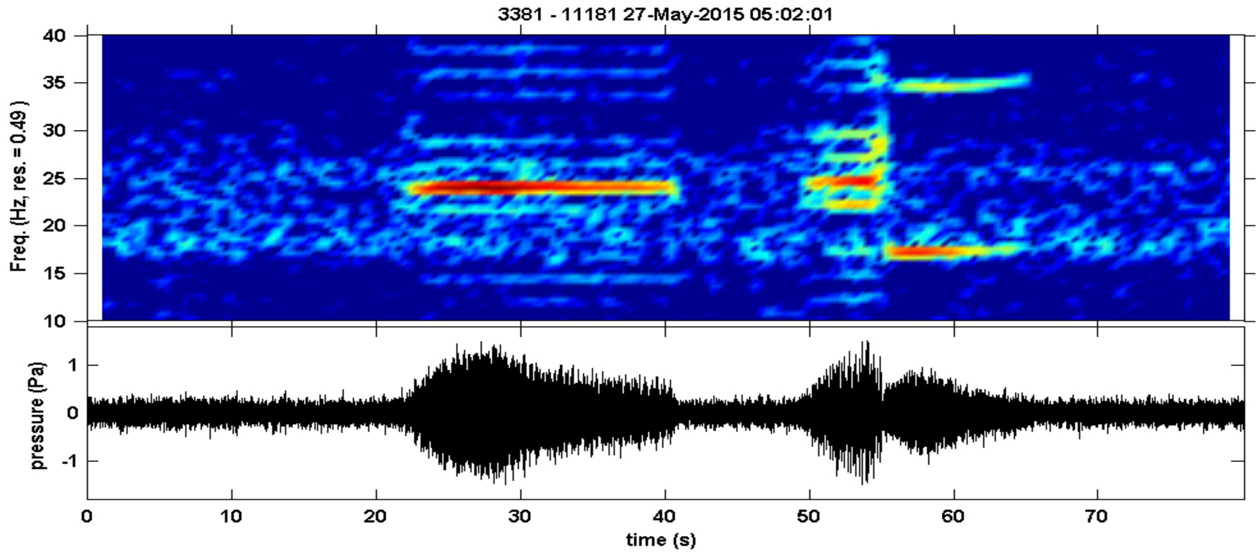

Figure 13: Spectrogram (top) and waveform (bottom) of a NZ blue whale call type from Portland in 2015.

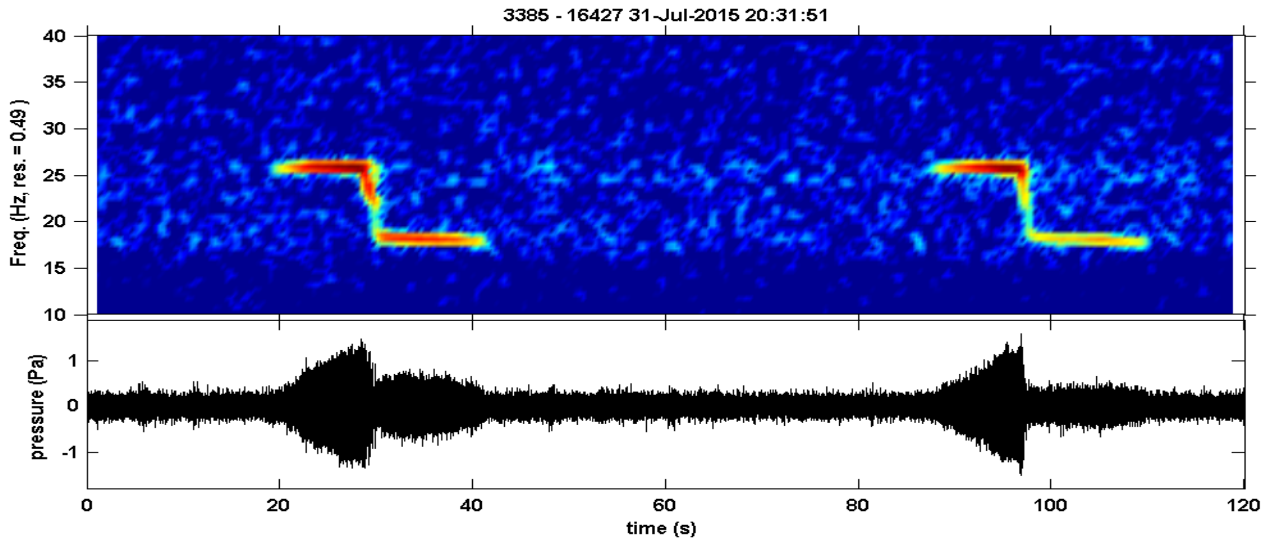

Figure 14: Spectrogram (top) and waveform (bottom) of an Antarctic blue whale call type from Portland in 2015.

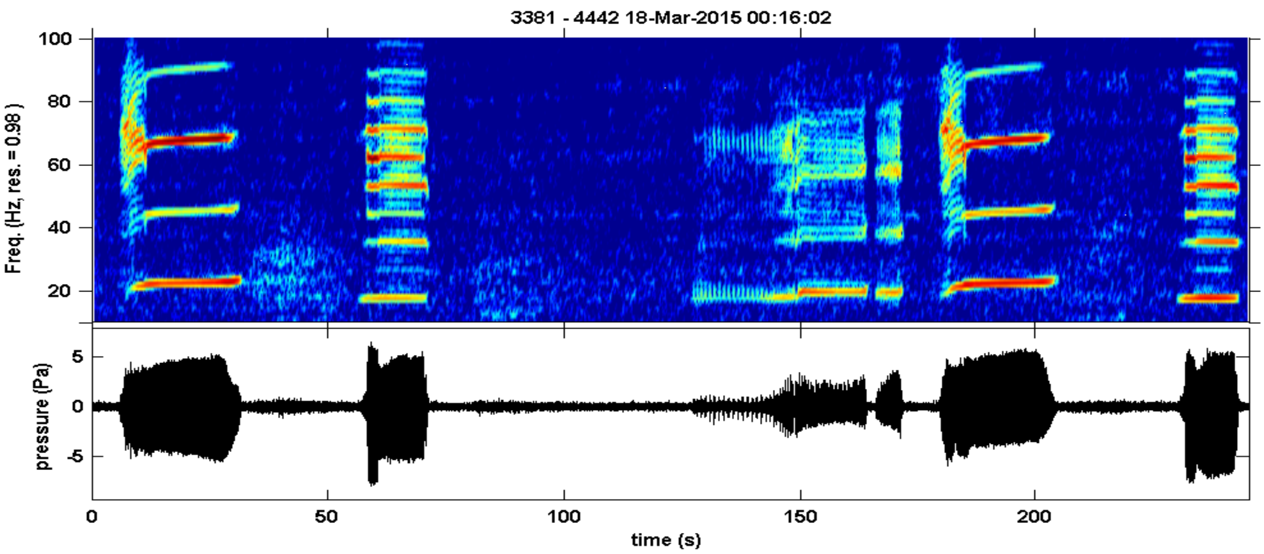

Figure 15: Spectrogram (top) and waveform (bottom) of EIO pygmy blue two (0-70 s) and three part song (120-250 s) from Portland in 2015. Note the pygmy blue type II component, that searched on here, is shown at 0-40 and 170-210 s.

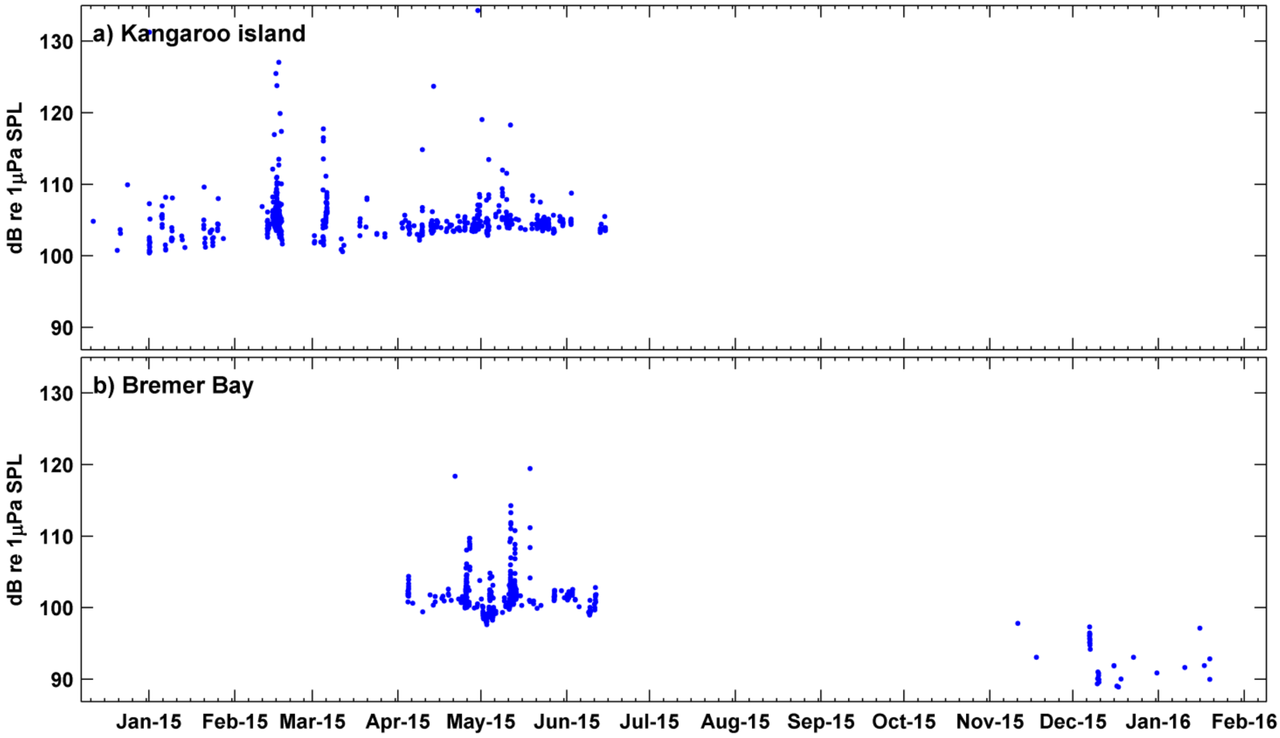

Figure 16: Received levels of EIO pygmy blue whale calls at Kangaroo Island (a) and Bremer Bay (b).

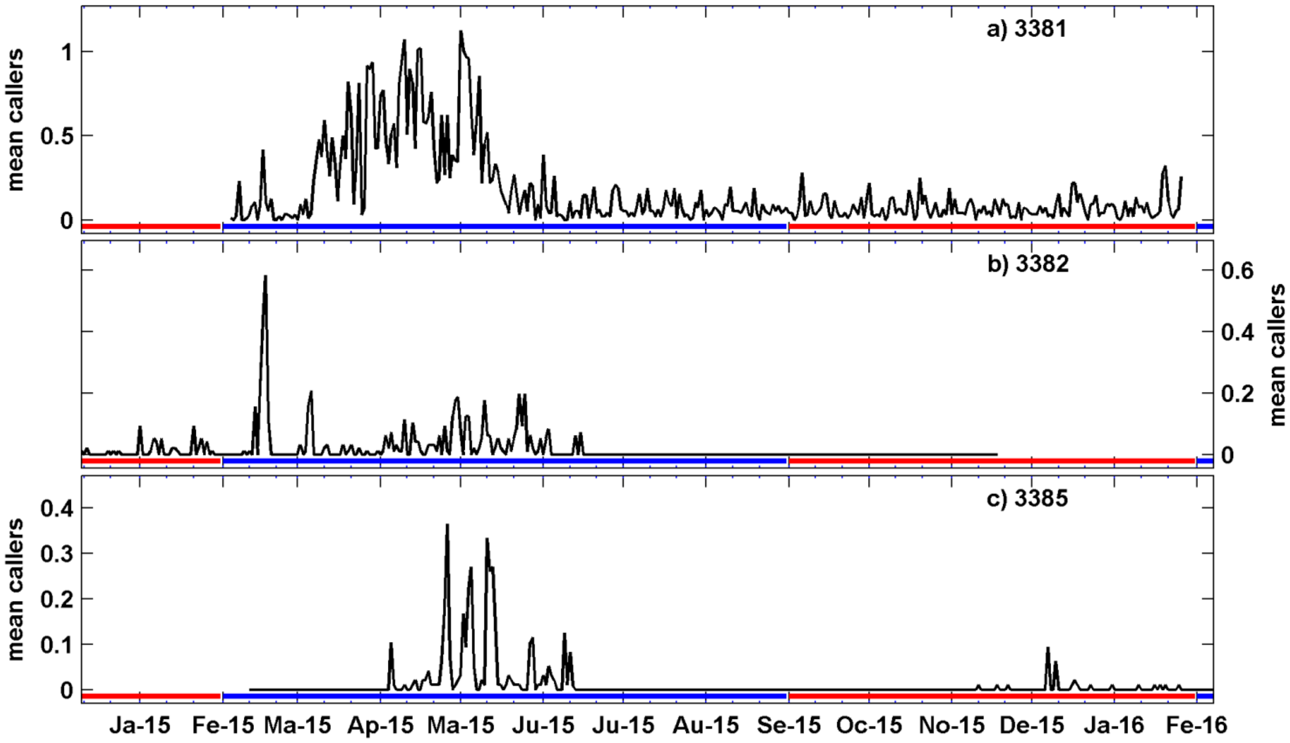

Figure 17: Averages of the number of EIO pygmy blue whales calling per 24 hours for Portland (a), KI (b) and Bremer Bay (c) over late 2014 to early 2016 The blue lines represent the pygmy blue whale north bound season at latitude 32° S on the west coast (Perth Canyon). Note that the Portland data set (3381) was only manually checked up to the beginning of June 2015, the records beyond this data are likely false detections.

3.3.2 Antarctic minke whales

Calls from Antarctic minke whales (*Balaenoptera acutorostrata*) were detected at KI on several occasions, 29-Jul-2015 to 01-Aug-2015 (in 12 of 299 samples across this period) and over 09-Sep-2015 to 11-Sep-2015 (in 38 of 149 samples). An example of their call type was shown on Figure 12 (d). The frequency content of several calls and the mean spectral content of these calls is shown on Figure 18. An indication of their presence across the 2015 sampling period at KI is shown on Figure 19 shown as the proportion of samples per 24 hour period with calling present.

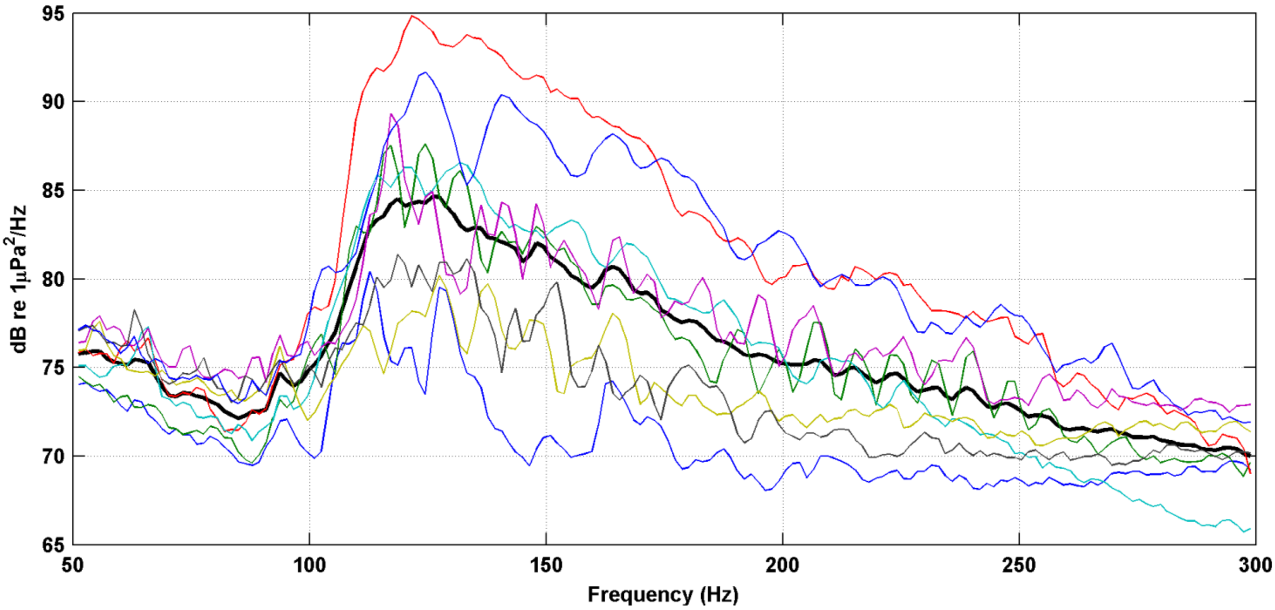

Figure 18: Frequency spectrum of Antarctic blue whale calls, with the mean spectra given by the heavy black line.

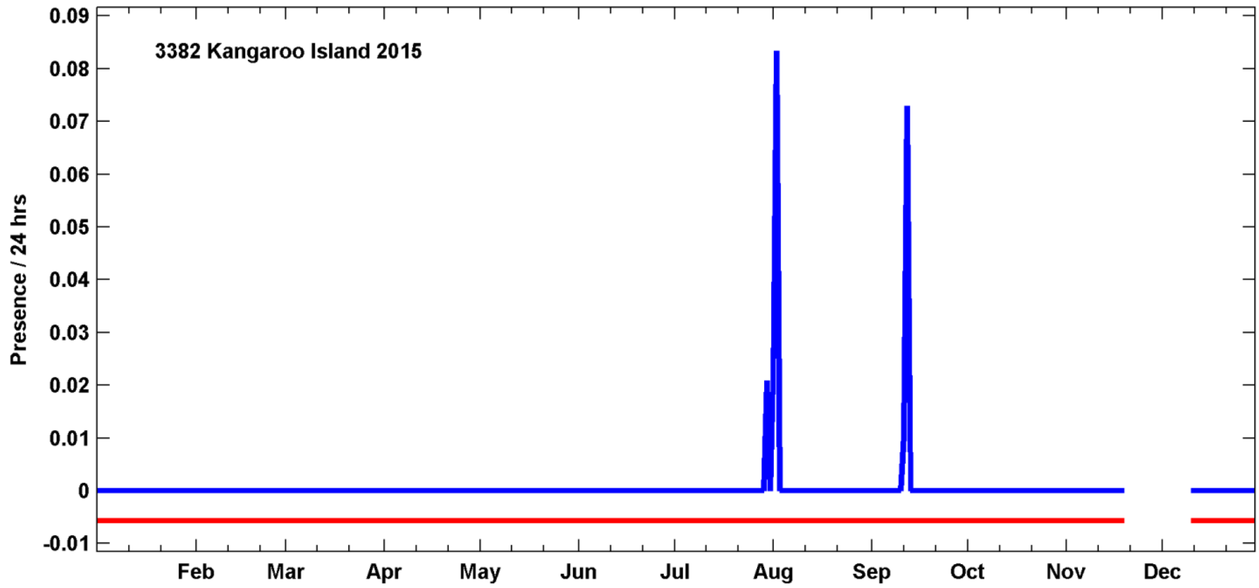

Figure 19: Presence of Antarctic minke at KI shown as the proportion of samples per 24 hours with calling present (running 12:00 one day to 12:00 the following day).

3.3.3 Humpback whales

Humpback whales were not common at the KI site, with only one calling animal detected on one occasion, over 4.75 hours from 04-Jul-2015 18:00:00 to 04-Jul-2015 22:45:01. This animal was distant from the receiver, as the call level was comparatively low.

3.3.4 'Spot' call

This call type is termed the 'spot' call as it appears as a 'spot' on spectrograms when detected from moderate to long ranges. At short range the call often has accompanying higher frequency sweeps, as shown on Figure 20. The waveform has a characteristic bell shaped form as can be seen on Figure 20, a feature which is used in the search algorithm. The search algorithm outputs, using the metric of proportion of samples per 24 hour period (12:00 one day to 12:00 the next) is shown for Bremer, KI and Portland on Figure 21.

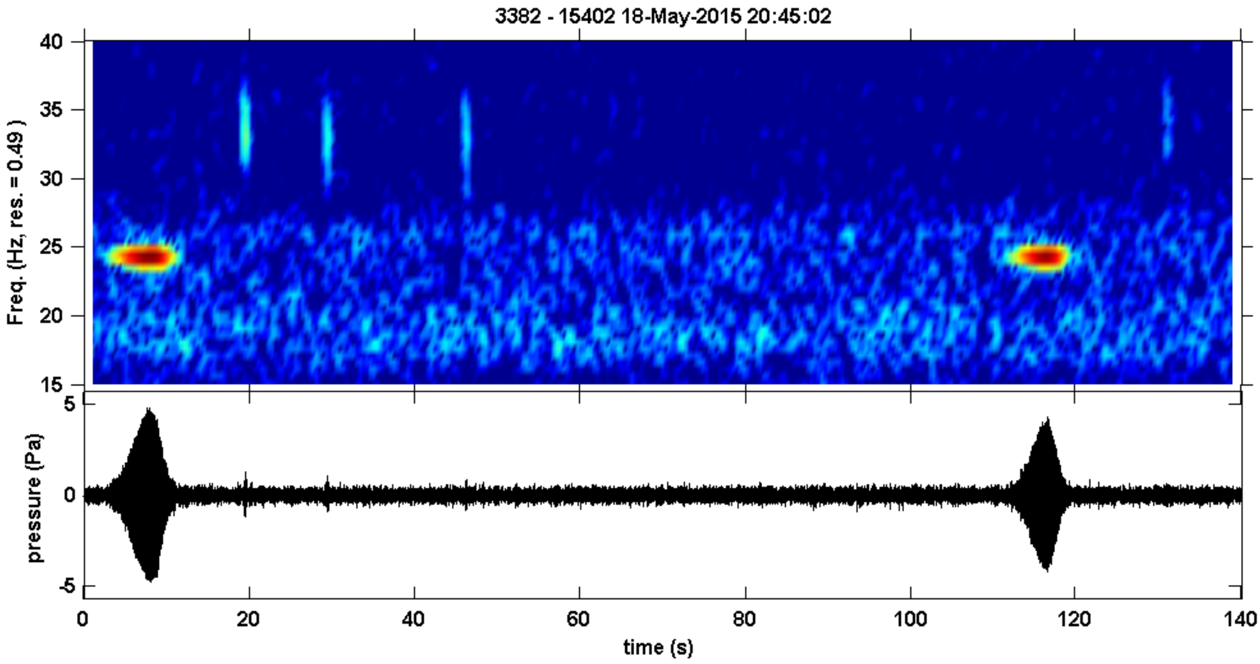

Figure 20: Spectrogram and waveform of two 'spot' calls, the first with three accompanying downsweeps.

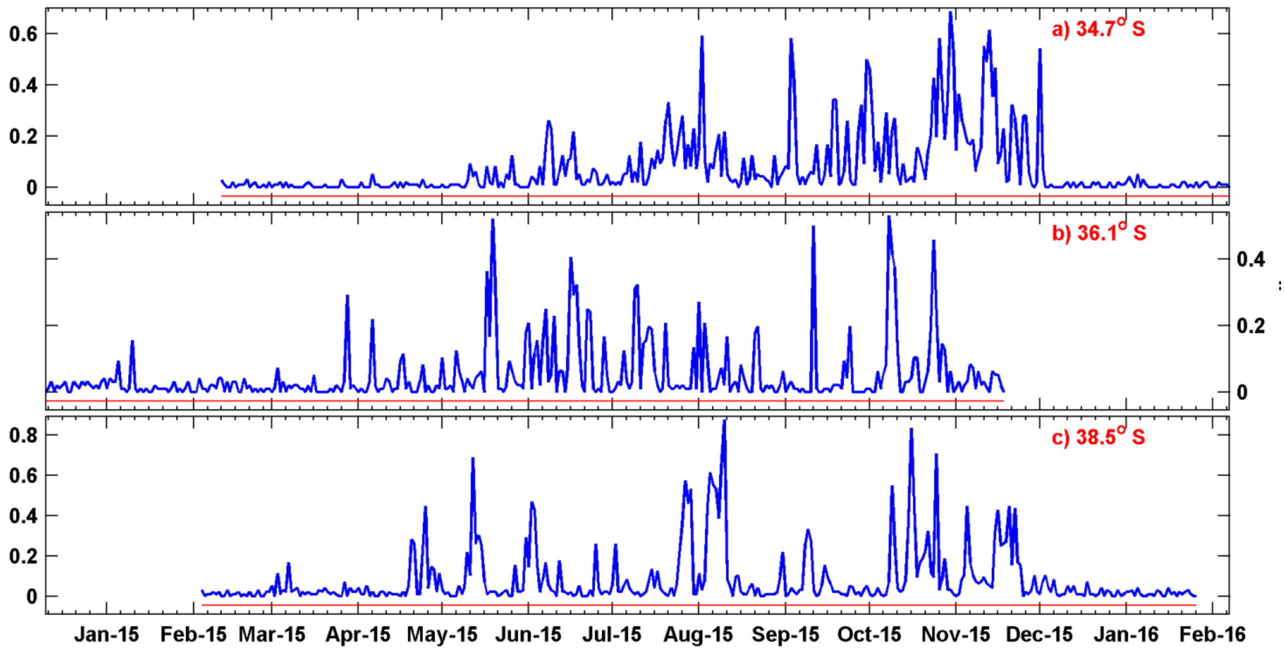

Figure 21: Proportions of samples per 24 hour period (y-axis) with 'spot' calling detected, shown for a) Bremer, b) Kangaroo Island and c) Portland.

3.3.5 Deep sound channel tone analysis, blue whales and spot call

The tonal signals which ducted in the deep sound channel were tracked across the southern Australian recording sites. Figure 22 shows the spectrograms of individual calls or songs of EIO pygmy blue, Antarctic blue and the 'spot' call, alongside a four month spectrogram from KI with all species present. The NZ blue whale did not appear in the tonal analysis, thus has not been considered here. The tonal lines in the long term spectrogram corresponding to a dominant part of the call of each species or sub-species are clear on Figure 22 (less so for the spot call). The tonal frequencies track maximum energy received via the deep sound channel for the different call types. This energy will be received from calling animals over long ranges, potentially out to 1000 km from the receiver location, thus the intensity is akin to integrating whale calling activity across a wide area in the deep ocean, south of Australia.

Measures of tonal intensity and the signal to noise ratio for that tone are plotted on Figure 23 for the EIO pygmy blue whale, Antarctic blue whale and the 'spot' call. The signal to noise ratio (SNR) gave the least ambiguous definition of the source presence. A 12 hour averaged spectra with all sources present is shown on Figure 24. The technique of obtaining the SNR involved subtracting (in the dB domain) the highest of the mean ambient noise in defined frequency bands above and below the tonal frequency, from the maximum tonal level. Given that the normal slope of ambient noise in these frequency bands always increases with decreasing frequency and calling whales increase levels immediately about the tonal frequencies, then an alternative derivation of the tonal level may involve defining the normal ambient noise curve across the frequency band of interest without the contribution of whales, then subtracting the level at the tonal frequency of this curve from the maximum tonal level.

The SNR of the tones produced by different species for Portland, KI and Bremer are shown on Figure 25.

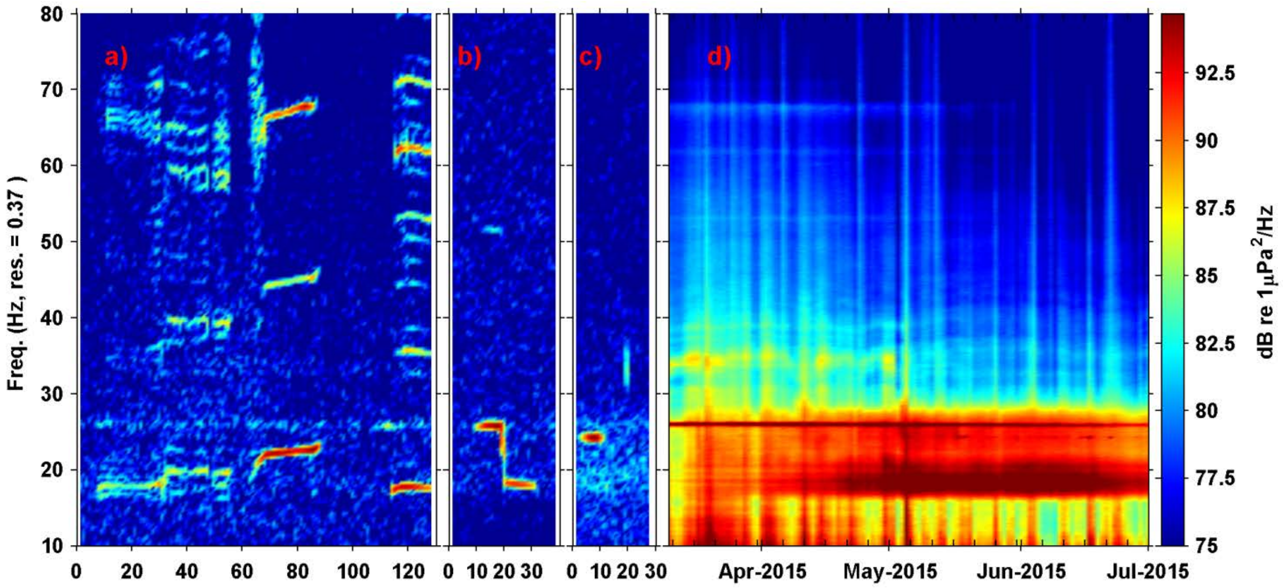

Figure 22: Spectrograms of pygmy blue whale song (a), Antarctic blue whale call (b), and unidentified great whale call (c) shown alongside a four months section of sea noise for KI (d). The spectrograms are made at 0.37 Hz resolution for a), b) and c) and at 0.092 Hz resolution for d).

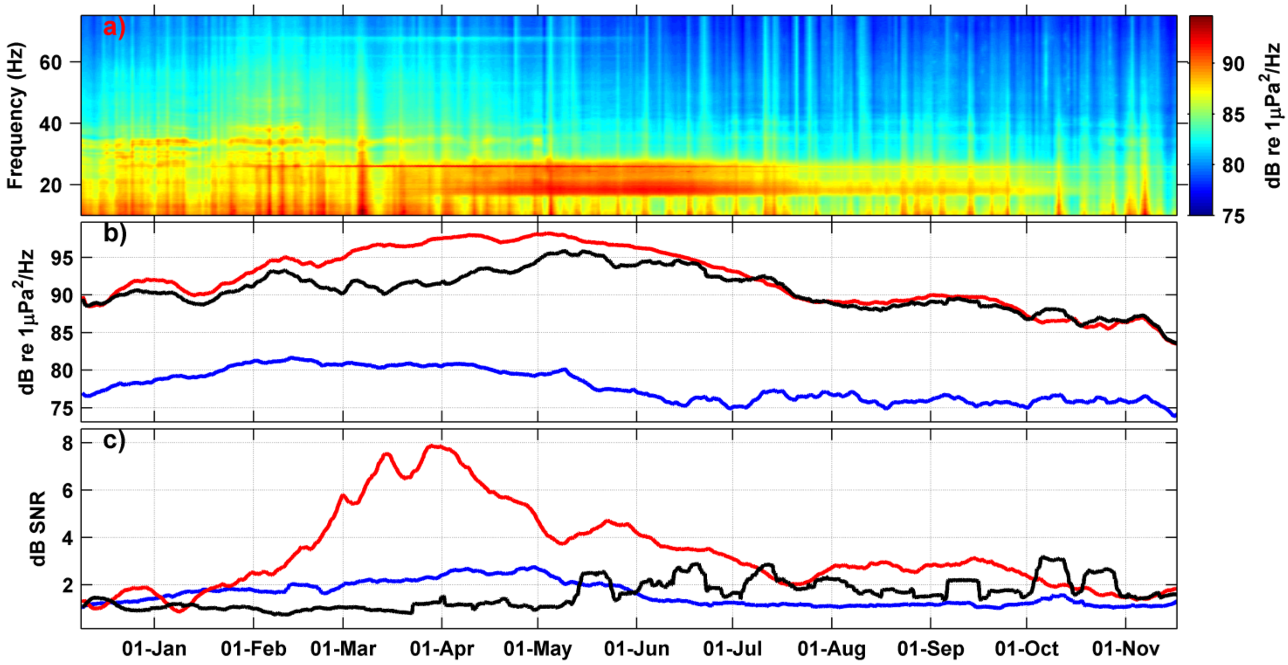

Figure 23: a) Spectrogram of KI site for full year at fine frequency resolution (0.097 Hz); b) level of tones belonging to pygmy blue (blue curve, 66.6 to 68.4 Hz), Antarctic blue (red curve, 25.4 to 26.8 Hz and 'spot' call (black curve, 23.8 to 24.9 Hz; and c) signal to noise ratio of the tones for each species.

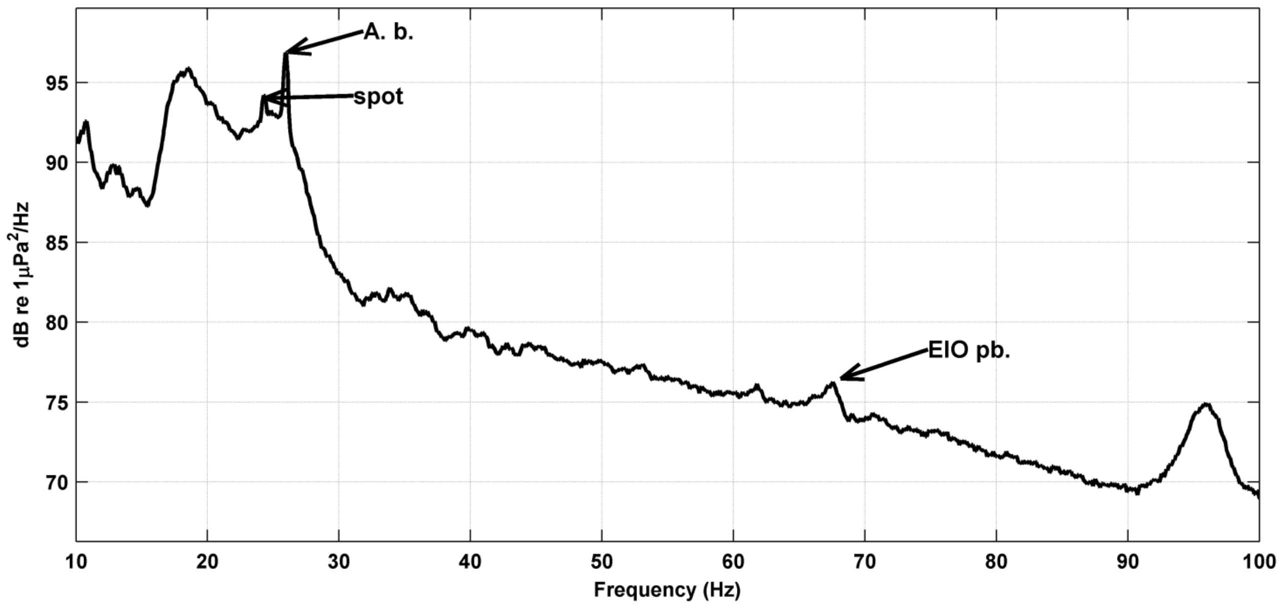

Figure 24: Frequency spectra at 0.092 Hz resolution showing frequency peaks due to long range deep-ocean coupled calling by EIO pygmy blue whales, Antarctic blue whales and the 'spot' call (average of 48 samples, over 14-May-2015 12:00 to 24:00). It is not clear what the frequency peak at 96 Hz was caused by.

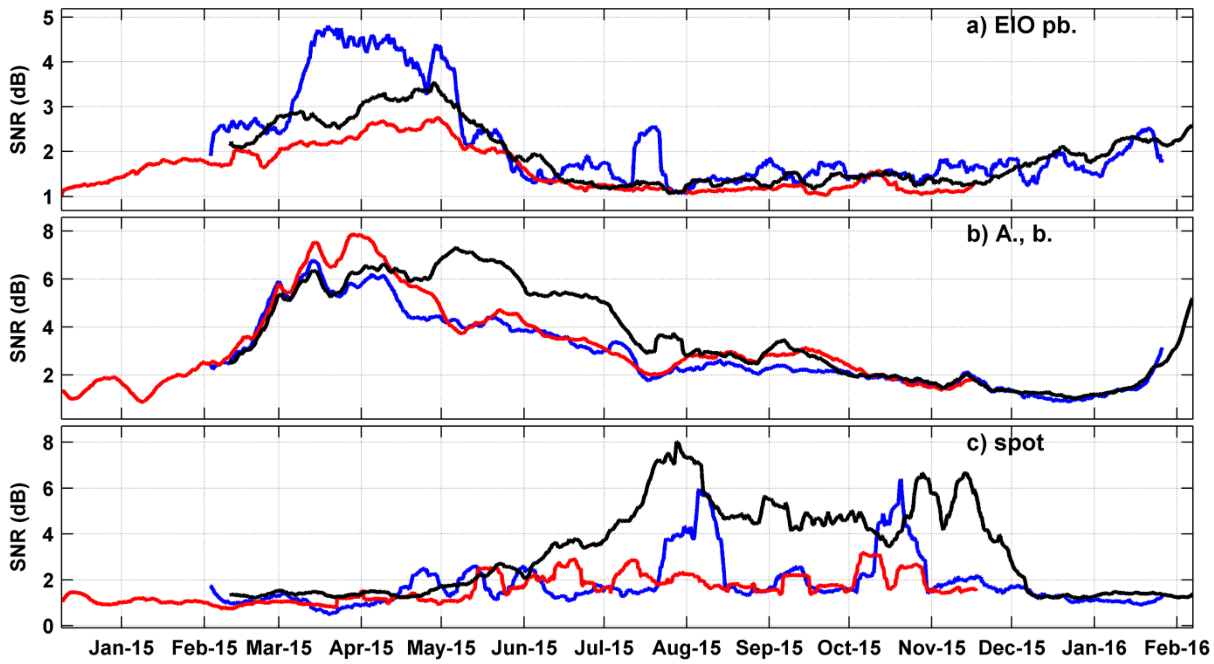

Figure 25: Calculated 2015 signal to noise ratios for a) EIO pygmy blue whale, b) Antarctic blue whale and c) 'spot call', with receiver locations colour coded as: blue - Portland; red - KI; and black - Bremer.

3.3.6 Fish calling

Calling by individual fish and different types of fish choruses were present. One chorus type dominated sea noise over the 1-2 kHz band, with an example of two days of calling shown on the spectrogram of Figure 26. This chorus was often present during the day at some level but dramatically increased in noise level at dusk, then usually had a lower level, pre-dawn peak. A second, weaker fish chorus type with most energy at ~ 300 Hz, harmonics present, and calling centred around dusk can also be seen on Figure 26. A third chorus type, at higher frequencies and occurring around two hours post dusk was occasionally seen. This third chorus type was the same source as reported by McCauley and Cato (2016) and attributed to Myctophidae fishes.

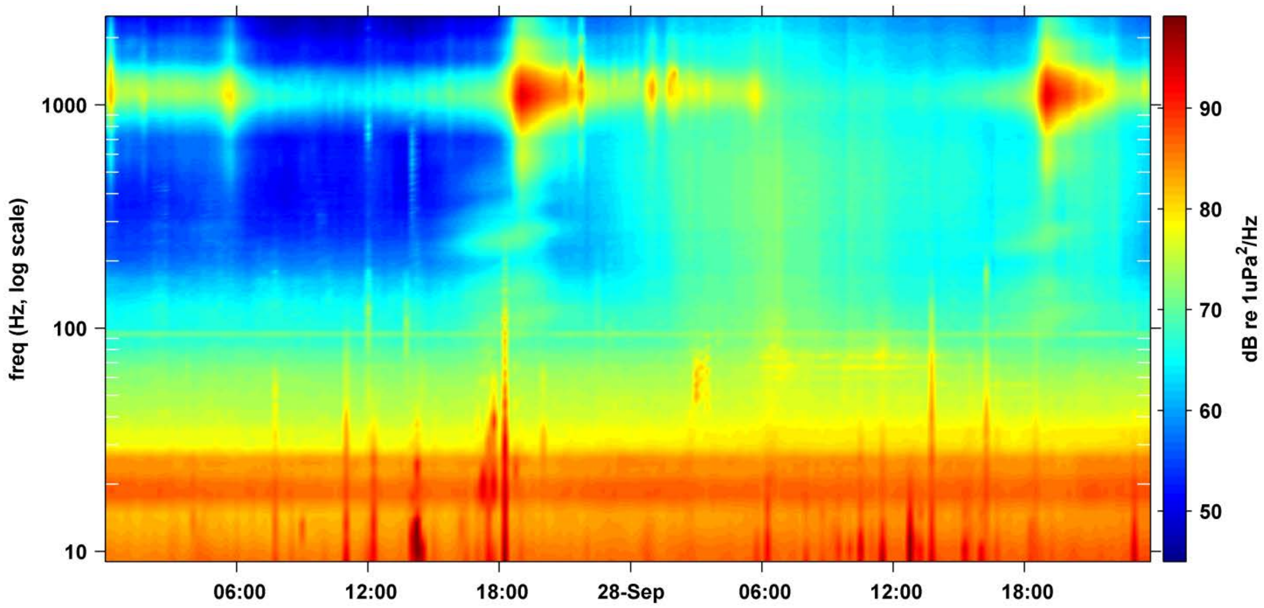

Figure 26: Two day spectrogram (log frequency scale) over 27-29 September 2015 from KI, showing the dominance of one fish chorus type centred at near 1200 Hz. Another faint chorus type was also present here centred at ~ 300 Hz with harmonics.

The high level chorus had a spectral peak at ~ 1094 Hz, thus its trend through time was tracked by following the 1 kHz 1/3 octave band, which had frequency limits of 891 to 1122 Hz. The 1 kHz 1/3 octave band was averaged across each day, with the evening time base zeroed to time of local sunset, to give the general time of the chorus peak at 23 minutes past sunset each evening (N=343 days, 95% 2.5 minutes, SD 23.5 minutes), as shown on Figure 27. The intensity and level of this choruses across the full KI data set is shown on Figure 28. The chorus had a strong seasonal trend.

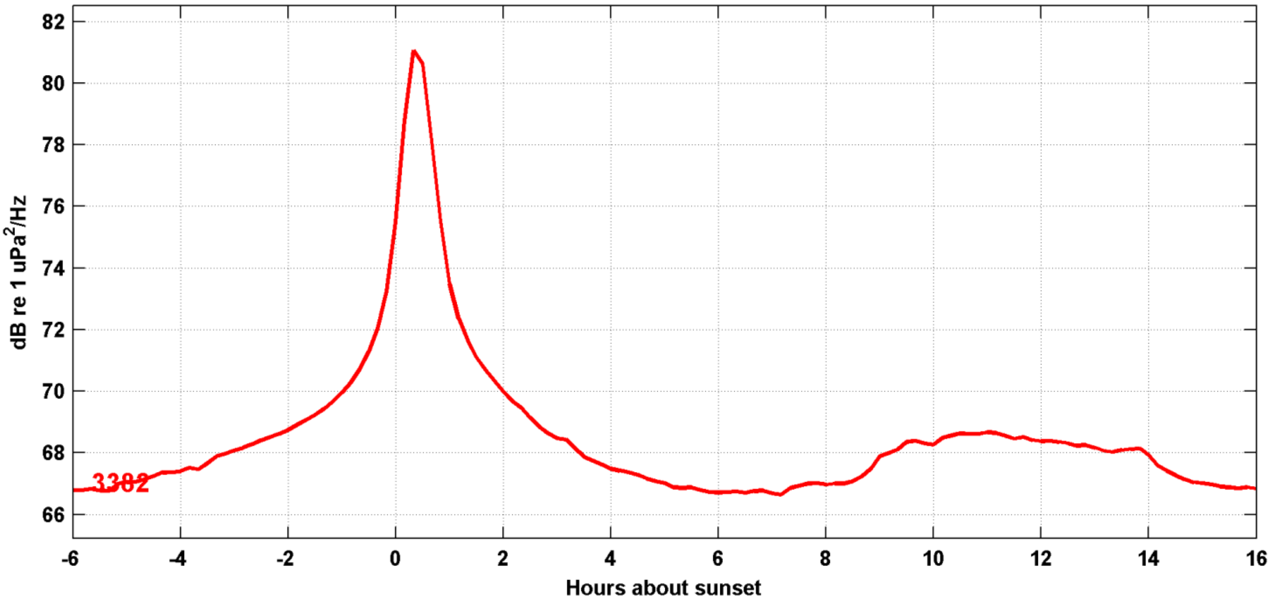

Figure 27: KI 1 kHz, 1/3 octave band level averaged across full data set to show the average time of the fish chorus.

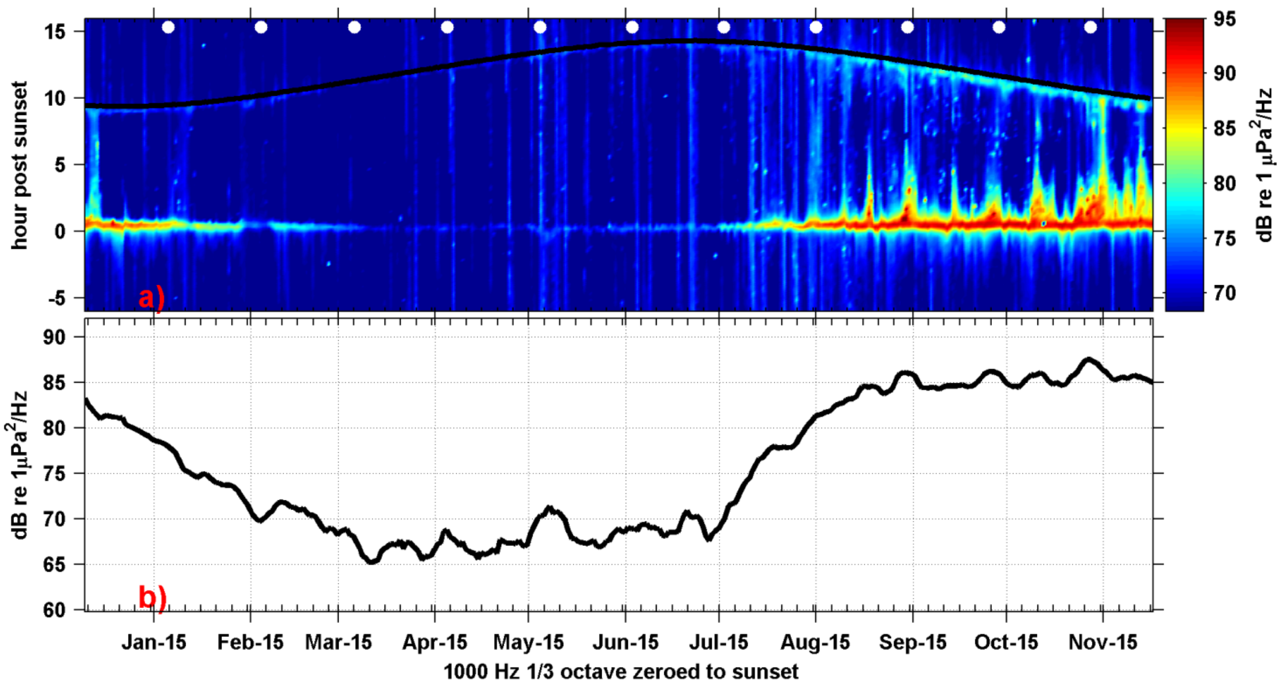

Figure 28: KI fish chorus as tracked by 1 kHz, 1/3 octave band level, with a) the intensity each evening zeroed to time of local sunset and b) the averaged level across 1 hour pre, to 3 hours post dusk. The top panel shows time of sunrise as the black curve and dates of full moon shown by the white circles.

3.5 Whale calling detection ranges

Details of how whale calling detection ranges were calculated are given in the methods. Bathymetry profiles were calculated along the great circle arcs shown on Figure 30 to give the profiles shown on Figure 31. The profiles were truncated when they reached 50 m water depth. Details of each bathymetry path (range and minimum water depth along path) are listed in Table 5. The sound speed profile was the winter mean for waters off the shelf, as shown on Figure 29. The seabed geoacoustic parameters used in the sound transmission modelling are listed in Table 6. The parabolic equation model RAMSGeo was used to estimate propagation loss on the shelf (paths 0-90°) which correctly accounted for shear waves. This model broke down travelling up the shelf slope so the model RAMGeo was used for headings 135-315°. The model RAMGeo does not account for shear waves (no models which can be run in a reasonable time frame can currently adequately model steep bathymetries and include shear wave effects). As most of the transmission on these headings was in deepwater this should not be a large error. The model was run in reciprocity mode, with a source depth of 181 m used (the actual receiver depth) and source depths of 20-40 m assumed (the calculations retrieved a 2D grid with full water column depth). The frequencies and source levels used in modelling are listed in Table 7.

Table 5: Bathymetry profiles, path lengths and minimum water depths along path for which transmission round the KI site was calculated.

Heading (°)	**Max. range (km)**	**Min. depth (m)**
0	127.6	-181
45	119.7	-181
90	69.8	-181
135	500	-5452
150	500	-5600
180	500	-5680
225	500	-5711
270	500	-5635
295	500	-3249
315	327.7	-831

Figure 29: Sound speed with depth profile used in modelling.

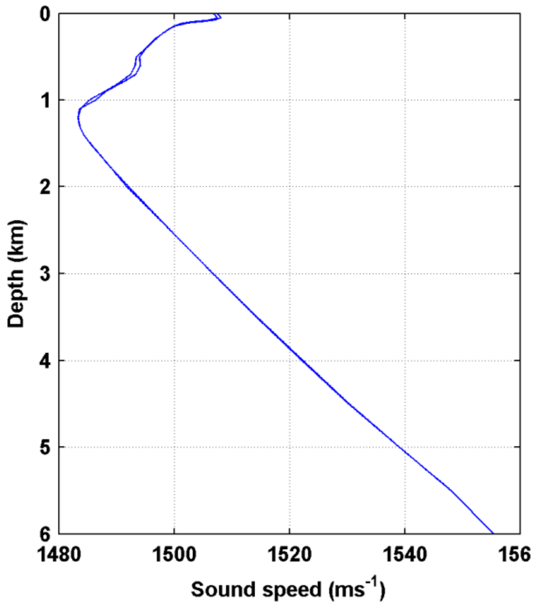

Table 6: Seabed acoustic properties used in modelling sound propagation. Values in brackets were graded by the model from the first value at the upper boundary to the second value at the lower boundary.

Layer thickness	**material**	**Density (kg.m^{-3})**	**Compressional wave speed (ms^{-1})**	**Compressional wave attenuation (dB per wavelength)**	**Shear wave speed (ms^{-1})**	**Shear wave attenuation (dB per wavelength)**
	Water column	1024				
50	sand	[1600 1750]	1620	[1 0.9]	[90 110]	[2 2.5]
> 50	basement	3500	4500	0.2	2500	0.1

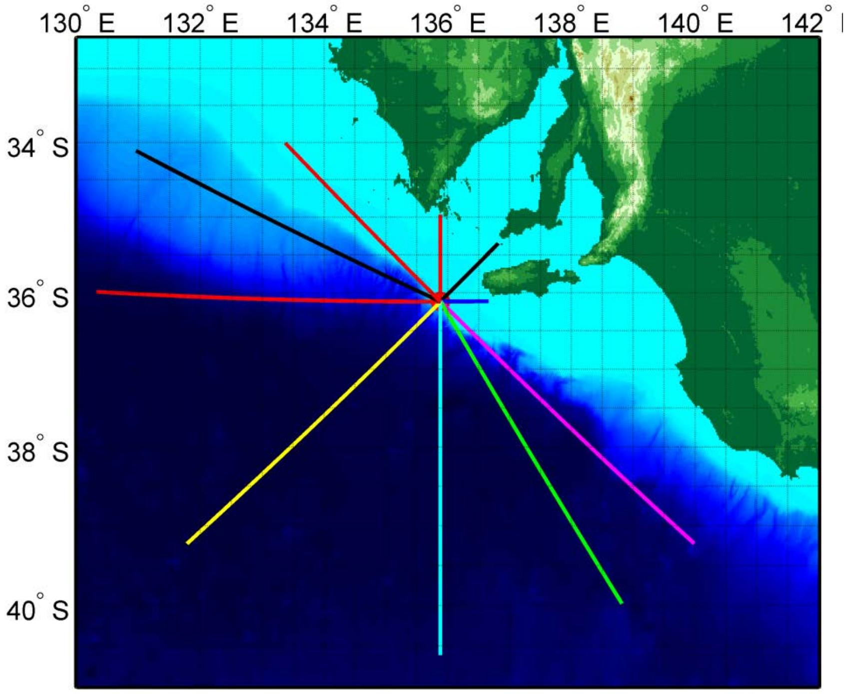

Figure 30: Tracks along which bathymetry was calculated. Lines are colour coded as: 0° to 127 km is red; 45° to 120 km is black; 90° to 70 km is blue; 135° to 500 km is magenta; 150° to 500 km is green; 180° to 500 km is cyan; 225° to 500 km is yellow; 270° to 500 km is red; 295° to 500 km is black; and 315° to 328 km is red.

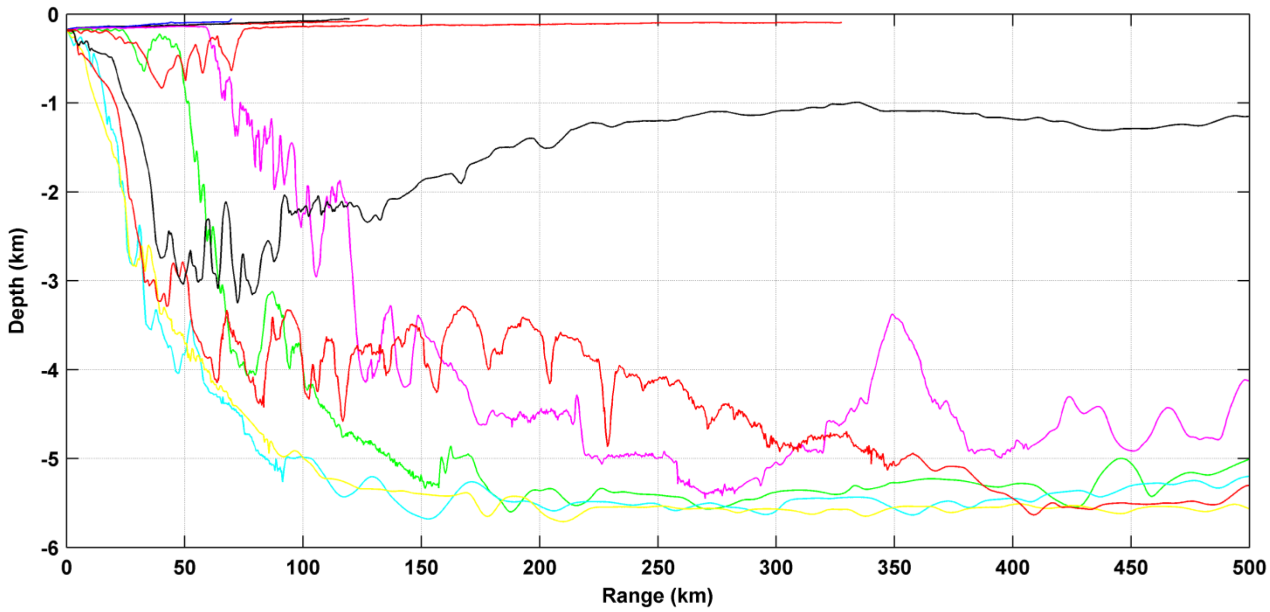

Figure 31: Bathymetry contours along lines shown on Figure 30. Lines are colour coded as: 0° to 127 km is red; 45° to 120 km is black; 90° to 70 km is blue; 135° to 500 km is magenta; 150° to 500 km is green; 180° to 500 km is cyan; 225° to 500 km is yellow; 270° to 500 km is red; 295° to 500 km is black; and 315° to 328 km is red.

Most of the studies which have defined depths of calling baleen whales have returned ranges of 20 to 40 m (ie. Thode et al. 2000, Oleson et al. 2007). A calling baleen whale will be restricted in its workable depth by constraints on the physics of oscillating the lung space (Jones et al. 2003). If the whale dives deeper the lung space resonant frequency and efficiency will increase. Given that the great whales produce such pure tones then they likely match the calling depth to the bubble (lung) volume to optimise efficiency and reduce the call output bandwidth. If the animal decreases depth its resonant frequency and efficiency (and so source level) will decrease. Thus it is likely great whales call at quite restricted depth ranges, within the bounds of those identified. To account for potential differences in calling source depth the transmission loss grids were averaged in source depths over 20 to 40 m.

The frequencies used in modelling call propagation for the Antarctic blue, EIO pygmy blue and 'spot' call correspond to the tonal peak frequencies, as listed in Table 4 (in-band frequencies).

For north pacific blue whales, call source levels have been estimated at 188 dB re 1μPa at 1 m by Cummings and Thompson (1971) and 186 dB re 1μPa at 1 m by McDonald et al. (2007). For Antarctic blue whales call source levels have been estimated at 189 dB re 1μPa at 1 m by Širović et al. (2007). For EIO pygmy blue whales an estimate of the source level of the type II component (that searched for here) of 183 dB re 1μPa at 1 m (sound pressure level) has been given in McCauley et al (2001) based on received levels of signals recorded in the Perth Canyon. Gavrilov et al. (2012) estimated the source level of the EIO pygmy blue whale type II song component at 179 dB re 1μPa at 1m and its third harmonic (67-68 Hz here) to contain about 1/3 of the signal energy, thus have a source level of 174 dB re 1μPa at 1 m. Thus several estimates of blue source level were used in estimating detection ranges, to check on how varying source level would alter listening range. McCauley et al (2001) showed that the highest level component of the EIO pygmy blue whale call was the type II component and that for this component the bandwidth of most energy was across 18-26 Hz. McCauley et al (2001) noted that for received pygmy blue whale signals in the Perth Canyon it was the 66-70 Hz up-sweep of the type II component which tended to be that most dominant in signals received at long range. An analysis of close, or high SNR calls, revealed that the received level of the 66-70 Hz portion of the EIO pygmy blue type II component was 9.8 dB below the total received level. Thus to account for sound transmission phenomena which may favour propagation of the 66-70 Hz tone, its source level was considered to be 9.8 dB below the maximum call source level, at around 174 dB re 1μPa at 1 m. Unpublished estimates of the spot call source level have been made using the Cape Leeuwin Comprehensive Test Ban Treaty hydrophones (Gavrilov pers. comm.) for a source level estimate of 182 ± 3 dB re 1 μPa at 1 m. The upper and lower bounds have been used in modelling here.

Table 7: Sources modelled, the frequency range used, estimates of source levels used and noise boundaries used (see Table 8 for full noise statistics).

	Frequencies used in modelling (Hz)	**Source level values (SPL, dB re 1μPa)**	**Noise threshold range used (dB re 1μPa^2/Hz)**
Antarctic blue whale	25 & 26 Hz	186 -189 (McDonald et al, 2001, Širović et al. (2007)	78 - 95
EIO pygmy blue whale	18, 20 & 22 Hz, 67 & 68 Hz	179 to 183 (Gavrilov et al 2012, McCauley et al. 2001) for full call. 174 for upper harmonic.	79 - 96 70 - 82
Antarctic minke whale	115, 120 & 125 Hz	179-183 based on other great whales.	65 - 77
'spot' call	24 & 25 Hz	182 ± 3 (Gavrilov pers. comm.)	79 - 95

No source level estimate was available for the Antarctic minke whale call thus no estimate of detection range has been presented. Give the nature of the call, (a series of damped bubble pulses as opposed to the continual oscillations for the tonal blue whale and spot call), it is likely to be considerably lower in source level than as for the species listed in Table 7. Without a valid estimate of the Antarctic minke whale call there is little point in modelling its detection range.

The ambient noise statistics for KI were calculated at the frequencies of the calls as described in the methods. The statistics calculated for KI, in spectral level units are listed in Table 8. The values used in calculations of calling ranges were spectral level values (as for Table 8) encompassing the full range of ambient noise values experienced. For simplicity the median ambient noise value has been used to display the transmission range of each call type.

Note that the call source level values are given in sound pressure levels (dB re 1µPa) and the ambient noise level values in spectral levels (dB re 1µPa^2/Hz). The propagation loss predicts a loss of energy of the call as it transmits in range (and depth) in dB values, which equates to a reduction in the source level by the loss. The difference in units is due to terminology alone, technically the source level values are of squared pressure, hence should be dB re 1µPa^2. The blue whale and spot call signal types are pure tones, thus have narrow bandwidth, so when comparing them with ambient noise only a narrow surrounding band (1 Hz here) needs to be considered. This is not the same as determining the range at which another whale will detect the calls, this requires integrating the ambient noise energy in some bandwidth about the tone (the so called 'critical ratio'), this has not been accounted for here. The detection ranges given are the ranges at which the call level equates to the ambient noise level.

Table 8: Ambient noise statistics calculated for KI, all values except the last column, are in spectral level units (dB re 1µPa^2/Hz)

Source	**Range**	**mean**	**median**	**SD**	**± 95 %**	**5 percentile**	**95 percentile**	**N**
Antarctic blue	78-95	86	86	2.8	0.0	81	92	32513
EIO pygmy blue LF	79-96	87	87	3.0	0.0	82	92	32513
EIO pygmy blue HF	70-82	76	76	2.1	0.0	72	79	32513
spot	79-95	86	86	2.9	0.0	82	90	32513
Antarctic minke	65-77	70	70	2.1	0.0	67	74	32513

The detection ranges calculated given the parameters above and as per the methods, are listed in Table 9 and displayed on Figure 32. An example of how changes in the background noise impact on the detection range of the receiver for the calculated detection area of the EIO pygmy blue whale 66-68 Hz sweep in the type II component, is shown on Figure 33.

Note that the technique used to define the calling range used a probability approach, taking the range at which 95% of received levels were above the designated ambient level. This was done as sound propagation is not uniform with range, at long range there are convergence zones were the signal may appear in a range bracket at the many tens of km scale, disappear for a similar scale, then re-appear etc. The technique used here does not account for the extremely long range transmission of fragments of call energy arriving in the deep sound channel, but is optimised for recognition of a coherent or recognisable whale call.

Table 9: Estimated outside detection ranges for different species, source levels and headings about the KI receiver and the area this encapsulates. Ranges are in km, and the area in 1000 km^2. Source level is in dB re 1µPa, ambient level in dB re 1µPa^2/Hz. Species are: PB-LF - EIO pygmy blue, low frequency type II component; PB-HF - EIO pygmy blue whale type II component, 66-68 Hz tonal; AB - Antarctic blue whale; and SP - spot call.

Heading	0	45	90	135	150	180	225	270	295	315	Area
Species, SL, Ambient											
PB-LF 179 Back 82	17.6	17.9	19.1	31.1	39.9	35.5	17.1	47.3	47.0	53.3	3.2
PB-LF 179 Back 87	13.9	14.4	13.3	25.1	35.3	19.4	11.4	16.9	21.4	21.9	1.1
PB-LF 179 Back 92	11.3	11.3	10.4	19.6	21.6	16.4	10.1	14.3	17.1	18.1	0.7
PB-LF 183 Back 82	21.6	20.6	23.4	36.5	43.3	72.3	38.6	66.0	49.3	61.0	6.2
PB-LF 183 Back 87	16.9	16.3	18.1	29.6	39.0	34.9	14.9	47.0	22.9	27.6	2.2
PB-LF 183 Back 92	13.1	14.4	12.7	23.6	24.6	19.4	11.1	16.4	21.1	20.6	0.9
PB-HF 174 Back 72	39.9	36.5	43.9	51.6	42.3	295.9	144.3	60.9	239.4	61.9	46.3
PB-HF 174 Back 76	31.6	31.3	36.0	45.3	39.3	75.8	86.3	53.5	188.4	56.6	14.3
PB-HF 174 Back 79	26.6	26.4	30.3	39.9	37.3	26.9	29.9	48.0	117.5	46.5	5.8
AB 186 Back 81	31.6	29.3	34.3	48.6	42.3	183.3	39.5	126.3	186.1	63.3	23.2
AB 186 Back 86	24.3	23.1	28.4	40.9	39.0	69.3	17.9	68.0	58.3	60.5	5.8
AB 186 Back 92	16.1	16.6	20.4	31.3	36.9	34.5	10.7	21.6	22.6	53.5	2.2
AB 189 Back 81	36.5	33.0	38.0	51.6	43.9	296.9	71.5	184.4	233.7	64.5	47.7
AB 189 Back 86	28.9	26.6	32.3	45.6	40.5	83.8	26.6	72.8	67.5	61.9	7.5
AB 189 Back 92	20.3	19.6	23.9	36.5	37.9	37.3	14.7	52.9	23.1	59.3	3.3
SP 179 Back 82	18.1	19.1	23.4	36.9	36.9	36.0	18.1	53.5	23.3	59.9	3.4
SP 179 Back 86	13.4	15.3	19.1	29.9	35.9	34.6	11.9	20.6	22.6	53.5	2.1
SP 179 Back 90	11.3	11.9	15.7	24.1	23.6	17.3	9.8	12.7	19.1	20.9	0.8
SP 185 Back 82	26.9	26.3	32.0	45.9	41.0	73.5	54.5	69.7	112.1	61.9	9.5
SP 185 Back 86	20.4	21.9	26.4	39.5	38.9	50.3	37.9	55.9	24.4	60.6	4.6
SP 185 Back 90	15.9	17.3	20.1	34.0	36.9	35.3	14.4	47.0	22.6	55.3	2.8

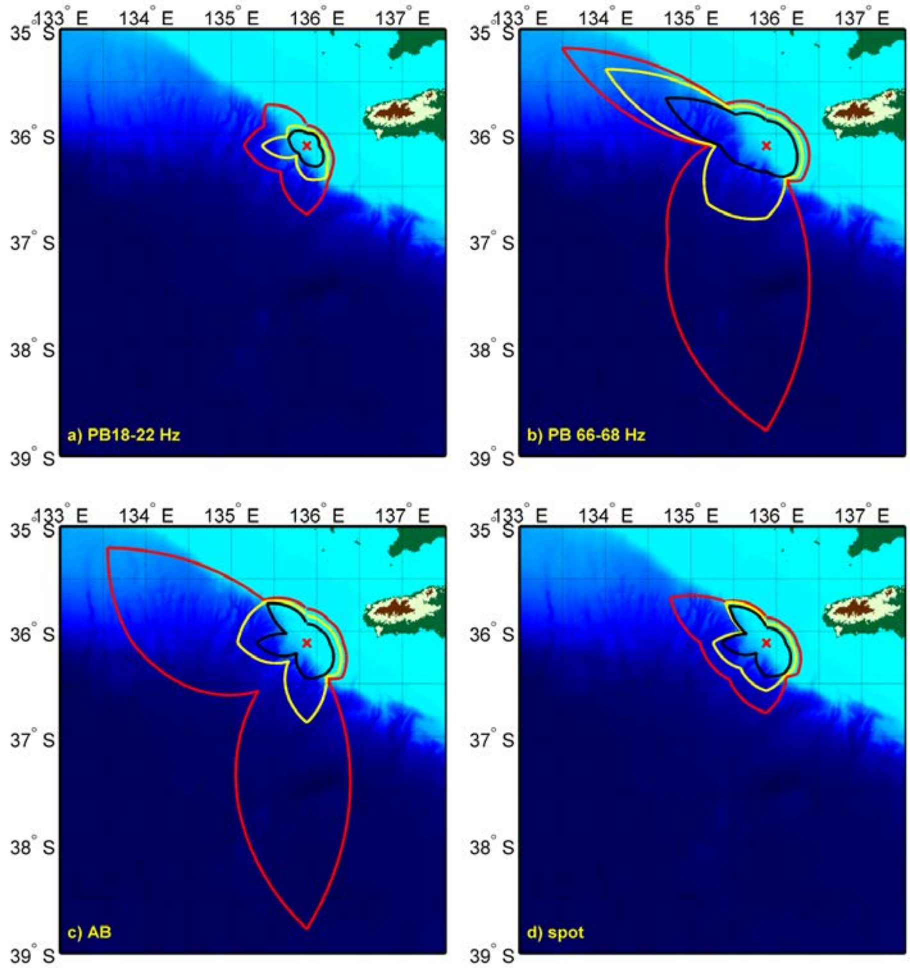

Figure 32: Estimated listening ranges at the maximum source level and median ambient noise level (yellow curves), lowest ambient noise level value encountered 5% of the time (red curve) and value of maximum ambient noise level encountered for 5% of the time (black curve), for a) the EIO pygmy blue whale 18-22 Hz sweep of the type II component; b) the EIO pygmy blue whale 66-68 Hz sweep of the type II component; c) the Antarctic blue whale; and d) the spot call. The red and black curves encapsulate ambient noise values for 90% of the recording period.

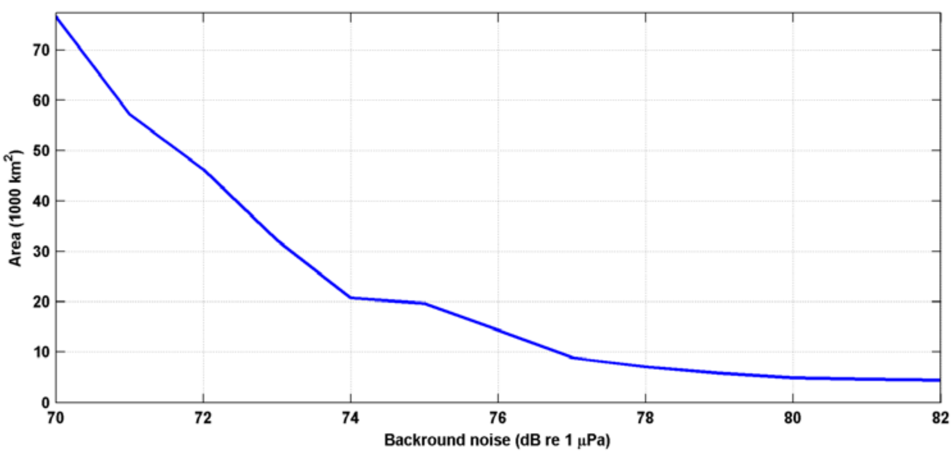

Figure 33: Change of listening area for KI with changing ambient noise. Calculated for the higher frequency sweep of the EIO pygmy blue whale type II call using a source level estimate of 174 dB re 1μPa at 1 m.

4. Discussion

A diversity of biological sources were present in the KI data set. Trends in the great whale species identified and the most common fish chorus species are listed in Table 10 for Portland, KI and Bremer and shown on Figure 34 for KI. There were other great whale calls detected, but which are currently not attributed to a species so these have not been included. The 'spot' call is again, believed to be produced by southern right whales although despite searching, we are yet to obtain a positive identification.

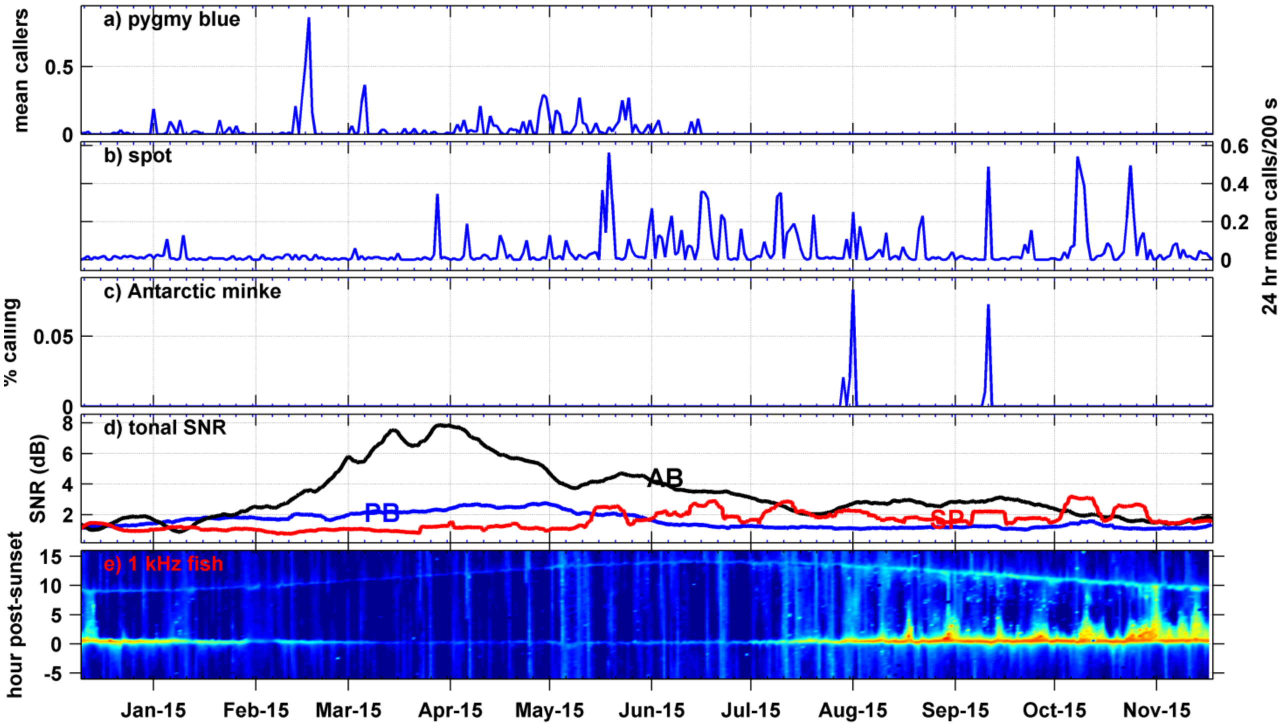

Figure 34: All acoustic detections from KI, with: a) pygmy blue whale mean calling individuals / 24 hour period; b) 24 hour mean of calls / 200 s; c) proportion of a 24 hour period with Antarctic minke whales present; d) the SNR for Antarctic blue whales (black), pygmy blue whales (blue) and the 'spot' call (red); and e) the 1 kHz 1/3 octave band levels as an indicator of the most common fish chorus type.

Apart from the low frequency portion of sperm whale calling, toothed whale calls are not covered by the bandwidth recorded here. The hardware to record one year duration (the IMOS practical minimum) at a bandwidth of say 96 kHz, which would record all whistle types, currently would only allow very sparse sampling duty cycle. Hardware to sample at this rate was not available at all for a reasonable cost at the IMOS inception and is still limited currently in batteries required and sample duty cycle.

Table 10: Presence of various whale types at Portland, KI and Bremer with seasons detected.

Site	Humpback	Dwarf minke	Antarctic minke	Fin whale	NZ Blue whale	Pygmy blue whale	Antarctic blue whale	Spot call	Sperm whale	1100 Hz fish chorus
Portland	Yes, winter-spring Feed Antarctic summer	Possible, not searched Satellite tracked through Bass St.	Yes, winter,	Yes, winter spring	Yes, Invasive pest Migrate west from Tasman Sea Commonly heard in Bass St, winter.	Yes, summer autumn, migrate west and north winter-spring	Yes, cross A. convergence late summer, autumn, winter	Yes, Winter, spring Probable heads south summer	Yes, autumn winter	Yes
KI	Yes, rarely Feed Antarctic summer	No	Yes, winter	No	No	Yes, summer autumn, migrate west and north winter-spring	Yes, cross A. convergence late summer, autumn, winter	Yes, Winter, spring	Not detected	Yes, maximum levels spring summer
Bremer	Yes Feed Antarctic summer	No	Yes, winter	Yes, winter spring, heard up the WA coast	No	Yes, summer autumn, migrate west and north winter-spring	Yes, cross A. convergence late summer, autumn, winter	Yes, Winter, spring	Yes	

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Appendix 1. Acoustic units and definitions

- **dB re 1µPa^2/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 1µPa^2.s SEL & dB re 1µPa *spl*–** 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* or *sound pressure level* (**MSP or *SPL***) 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 (say > 1 s) the ***SPL*** level is often quoted. For air gun signals, the ***SPL*** values calculated here were averaged over the time taken for 90% of the impulse signals' energy to pass.

Appendix 2. Mean monthly ambient noise levels.

Table 11: Mean monthly ambient noise levels in spectral level units (dB re 1µPa^2/Hz) and 1/3 octave frequency bands with centre frequencies from 5 to 2500 Hz. The number of samples used to derive each months averages are given as the final row.

CF	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	All
5	93.5	95.5	94.8	92.9	91.8	91.4	90.3	89.5	90.0	88.5	90.9	93.8	92.3
6	94.2	95.2	94.0	92.1	90.7	89.9	89.1	88.5	88.9	87.4	89.6	94.7	91.6
8	94.4	95.7	94.7	92.5	91.1	90.0	89.7	89.0	89.4	88.1	90.0	95.3	92.0
10	93.4	94.6	93.8	91.9	90.6	89.4	89.3	88.5	89.0	87.5	89.6	94.3	91.5
12	91.7	93.0	92.1	90.2	88.8	87.4	87.4	86.8	87.2	85.7	87.5	92.1	89.6
16	89.8	90.7	90.1	90.3	90.8	90.4	88.2	86.8	86.9	84.7	85.5	89.9	89.5
20	88.6	89.8	90.1	92.7	94.5	94.4	90.8	88.7	88.6	85.2	84.4	88.8	89.8
25	88.4	90.0	90.2	91.5	92.3	91.4	88.0	86.2	86.1	83.7	83.5	87.8	88.9
31	87.7	87.8	85.8	84.6	83.1	82.7	81.5	80.8	81.0	80.1	81.4	87.3	83.7
39	83.6	85.0	82.9	81.8	79.9	79.3	79.0	78.9	78.8	78.2	78.9	82.2	80.7
50	80.9	82.3	80.7	79.6	77.9	77.1	76.6	76.9	76.7	76.5	77.0	79.7	78.6
63	78.5	79.7	78.6	77.6	76.0	74.8	74.9	74.9	75.0	74.7	74.9	77.1	76.6
79	75.0	76.0	74.7	73.9	73.2	72.3	72.7	72.4	72.0	71.9	71.6	73.7	73.6
99	71.4	71.9	71.0	70.9	72.0	71.3	71.8	71.5	70.6	70.2	68.9	70.0	71.1
125	69.0	68.8	67.6	67.6	69.7	67.4	70.2	69.8	68.8	68.6	66.8	67.4	68.5
157	68.0	67.0	65.1	65.7	69.1	65.7	69.5	68.5	67.2	67.3	65.2	66.2	67.0
198	67.6	66.2	64.3	65.1	68.8	64.9	69.1	67.6	66.1	66.5	64.6	65.3	66.3
250	67.8	66.3	64.5	65.4	69.0	65.1	69.3	68.2	66.6	67.0	65.2	65.5	66.7
315	68.3	66.9	65.3	66.2	69.5	65.9	69.8	68.4	66.7	67.3	65.7	65.8	67.1
397	68.3	66.9	65.5	66.4	69.5	66.3	69.8	68.4	66.7	67.5	66.1	66.1	67.3
500	68.1	66.8	65.6	66.5	69.4	66.4	69.7	68.6	66.9	67.9	66.8	66.2	67.4
630	67.5	66.3	65.1	66.0	68.8	66.0	69.2	68.2	66.7	67.6	66.8	65.8	67.0
794	66.9	65.7	64.5	65.2	68.0	65.5	68.7	68.3	67.1	67.6	67.3	65.9	66.7
1000	67.5	66.5	64.8	65.4	68.0	67.1	70.2	71.2	70.3	69.9	70.5	67.6	68.2
1260	66.6	65.4	63.7	64.3	67.1	66.1	69.6	70.9	70.2	69.3	69.8	66.8	67.4
1587	64.1	62.8	61.5	62.3	65.1	62.7	65.8	66.1	64.8	64.6	64.5	63.2	64.0
2000	61.8	60.5	59.3	60.4	63.2	60.6	63.7	63.3	62.0	62.3	62.0	60.7	61.7
2520	59.3	58.1	57.1	58.1	60.9	58.2	61.2	60.4	59.2	59.8	59.2	57.9	59.1
N	2879	2590	2880	2783	2877	2783	2877	2878	2783	2879	1536	2015	32816

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