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BLUE WHALE CALLING IN THE ROTTNEST TRENCH - 2000, WESTERN AUSTRALIA

By:

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Abstract

Through January-April 2000 research was carried out off the Rottnest trench to search for blue or pygmy blue whales. A consortium of researchers carried out aerial surveys, boat surveys and acoustical measures. Historical records led us to believe that a Western Australian population of pygmy blue whales (*Balaenopteridae musculus brevicauda*, sub species of the true blue whale, *B. m. musculus*) existed, while a preliminary boat survey in 1994 suggested that some of these animals aggregated in the Rottnest trench west of Perth. This was confirmed in the 2000 observations, aerial surveys sighted up to eight blue whales/flight within the trench and in 30 days boat searching 17 blue whales were sighted. Five thousand acoustic records were made, many of which had blue whale calling in, some having up to nine animals calling at once. Although of a slightly different format, the calls recorded were of a similar character to those described from other blue whale populations. A call comprised three components, the first (type I) dominated by a 19 Hz tone for 21 s followed by a jump to a 21 Hz tone for a further 22 s. Five to ten s later the second component (II) followed which was dominated by a long frequency upsweep, beginning near 20 Hz and increasing to 26 Hz over 23 s. Approximately 23 s later the third component followed, this dominated by a 20 s, 19 Hz tone. Harmonics were evident in each component. At least one secondary source was evident in all components, consisting of a pulsed 65 Hz signal. This was especially strong in the type III component. A call thus totalled around two minutes, repeated at intervals of 78 s. The type II component had the highest source level and was the most obvious signal received at long range. Propagation modelling indicated that the components could transmit extremely well along the continental shelf edge, with a bottomed logger in 450 m of water receiving calls from in excess of 50 km and probably into the hundreds of km. Calling showed strong day night patterns, being 2.2 times greater at night than during the day. Although searching was concentrated in the Rottnest trench region, the distribution of received call levels and the propagation modelling suggested calling animals were spread relatively evenly over a large range, probably many hundreds of km along the continental shelf edge. Limiting received calls to within the Rottnest trench indicated a maximum number of calling animals/90 s sample/day from 1-5 with a mean at 2.2 ± 0.34, or less than 28% of the minimum population estimate for the trench region (eight, from the aerial surveys and assuming no corrections for sighting bias). Also extremely common in recordings were 20 Hz 'clicking' calls of individual pulses of several hundred ms length. These occurred in bouts ranging in length from one sampling period (ten minutes) to days, with bouts comprised of multiple sources. The low frequency (< 100 Hz) sea noise spectra from a series of 90 s recordings made every 10 minutes for 33.5 days was dominated by the tonal blue whale calling and 20 Hz clicking.

Acknowledgments

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Contents

1) Introduction

In the southern hemisphere two subspecies of blue whale are recognised, the 'true' blue whale (*Balaenoptera musculus intermedia)* and the 'pygmy' blue whale (*Balaenoptera musculus brevicauda*). The 'true' blue whale is the larger of the two and may be found south of the Antarctic convergence zone, particularly along the ice shelf edge feeding on euphausiid krill, whereas the slightly smaller pygmy blue whale is preferentially found further north (Bannister et al 1996). The two subspecies are extremely difficult to discern in the field. Based on Russian whaling data Zemsky and Sazhinov (1994) presented the distribution of pygmy blue whales as being primarily in the Indian Ocean, along the African east coast, throughout the lower part of the Indian Ocean, along the Western Australian coast north to Indonesia, and along the Australian southern coast and east to encompass New Zealand (as displayed in Figure 1). The migratory patterns and movements of the blue and pygmy blue whale are poorly understood although each are known to undertake extensive migrations between warm water (low latitude) breeding areas and cold water (high latitude) feeding areas (Bannister et al 1996).

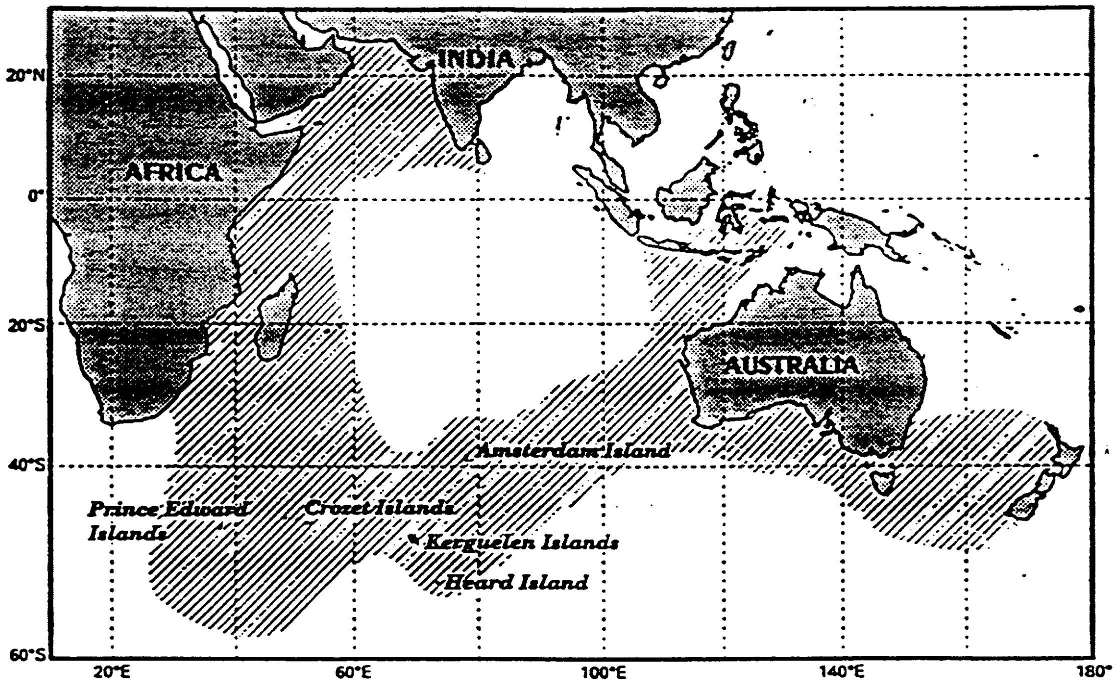

Figure 1: Pygmy blue whale distribution shown as shaded area, from Zemsky and Sazhinov (1994).

These populations were heavily hunted during the whaling decades of the 1950 and 1960's. An international ban on blue whaling was established in 1966 due to alarmingly declining numbers, although it now known that illicit catches of blue whales continued up to the mid 1970's (Bannister et al 1996). The 'true' blue whales were almost driven to extinction during this period. From an estimated pre-whaling population of southern hemisphere 'true' blue whales of around 160,000-240,000 animals, whaling reduced numbers to < 1000 animals, which is still 34 years after the official cessation of whaling, near the estimated current population size of 1000-2000 animals (Bannister and Burton 2000). Pygmy blue whale stocks were less heavily exploited and dropped from an estimated total population size of 12,500-13,000 animals pre-whaling (Zemsky and Sazhinov 1994), with an estimate of the current population at 6000 animals (Bannister et al 1996).

Along the Western Australian coast both true and pygmy blue whales have been sighted and taken. A USSR factory whaling ship captured 269 animals along the coast from Albany to Exmouth in 1965, most of which were believed pygmy blue whales (Bannister and Burton 2000). True and pygmy blue whales were sighted to 45^{o} S of WA in February-March 1993 (Bannister 1993). During a dedicated IWC blue whale cruise in 1994 up to five blue whales per day were sighted off Rottnest Island. Most of these were believed to be pygmy blue whales (Kato et al 1996). What are believed to be pygmy blue whales are regularly sighted off Dunsborough in the states south-west (Bannister and Burton 2000).

Given the historical records, the observations of blue whales off Perth in 1994, and the dearth of information on true and pygmy blue whales, a consortium of WA researchers carried out concurrent aerial surveys, boat based observations and acoustic surveys to study blue whales west of Rottnest Island. The aerial surveys began in January 1999 and were to be carried out on a monthly basis until mid 2000. Weather and aircraft availability restricted the number of successful flights. Over the period January-1999 to February-2000 eight flights were carried out during which 16 blue whales were sighted (Bannister and Burton 2000). Boat based observations in the region of the Rottnest trench were carried out through January-March 2000. In 30 days of searching 17 blue whales were sighted (data of C & M-N Jenner). Concurrently with the boat based observations, acoustic records were made. Blue whales are known to produce intense low frequency signals (eg. Cummings and Thompson 1971). Several workers have used these signals to track animals using arrays and to gain insight into the animals underwater behaviour (eg. D'Spain et al 1995; McDonald et al 1995; Stafford et al 1998; Thode et al 2000).

In this project the acoustic monitoring work was attempted primarily as a censusing technique, that is to determine if the animals were present, approximately how many calling animals were present at any given time within some range of the hydrophone, and how these characters varied with time. Factors which are crucial in using passive (listening) acoustics to census marine animals include:

- a good definition of the types and variability of the signal being listened for;
- a knowledge of the call source, that is attributing a call type to a species;
- information on call source levels and inherent variability;
- knowledge of what proportion of a population is calling at a specified time;
- an ability to discriminate multiple callers;
- any daily, lunar or seasonal differences in call rates;
- knowing where in the water column the source calls from (as this greatly effects the call horizontal transmission);
- and knowledge of the local sound propagation characteristics.

Very little of this information was available at the projects inception. Thus this document attempts to address each of the factors listed.

As it transpired the results obtained offered a wealth of information, not only for blue whales but also for several other whale species. The recordings, particularly those from a bottom mounted receiver deployed over a 34 day period, provided a rich source of information on the behaviour of several species in the area, as well as physical sea noise sources. There were instances of calling blue and possibly other baleen whale species passing within a few km of the recording gear, providing several high signal to noise ratio (SNR) signals.

All of the recordings described here were made using single hydrophones. For three or more hydrophones separated in space and logged simultaneously, time of arrival and level differences can be used to localise calling animals. Except where multipath signals can be discriminated, localising calling animals is not possible using a single hydrophone.

2) Methods

The study site was located in the region of the Rottnest trench, an indentation in the Western Australian continental shelf which begins approximately 22 km WNW of the western end of Rottnest Island. The shelf slope in the trench region drops steeply to 1000 m depth. The general location of the study site is shown on Figure 2, while the deep and indented nature of the trench can be seen on Figure 3. Along the Western Australian continental shelf between the 100-500 m depth contours, flows the Leeuwin current, a southerly current of warm tropical water approximately 50-200 m deep. Over the study period of early January to April 2000, the Leeuwin current was particularly strong, with current speeds estimated at up to1.5 knot (0.75 ms^{-1}) based on observations of moorings and drift rates. The sharp indentation of the trench lying across the path of the Leeuwin current may be expected to give rise to complex oceanographic conditions in the area.

Thirteen sets of recordings were made. The details for each set are listed in Table 1. Eleven sets were made with a drifting package (shown by the circles on Figure 2) and two with moored equipment (shown by the square and triangle on Figure 2). The drifting package used a Massa TR1025C hydrophone suspended from a housing containing a purpose built pre-amplifier (40 dB gain) and Sony TCD D-8 digital tape deck operated at 32 kHz sample rate to give 4 hour recordings per tape. System response was linear from 20 Hz to 14.5 kHz. To reduce surge from the surface gear and flow noise from cable strum, the hydrophone cable was spirally wrapped with twine and suspended on rubber strops from the housing while the housing was suspended from a rope weighted and buoyed to create a catenary. A depth meter attached to the housing was used to log the housing, and hence hydrophone, depth. Under most conditions the hydrophone was at 55 m depth. Drifting sets were made during daytime, concurrent with the boat based observations.

A moored system was set at the head of the trench (eastern trench end, square symbol, Figure 2, set 2459 Table 1) in 160 m water. This comprised the same hydrophone and electronics as the drifting system, but with the tape deck operated by timer on a 3 minute sample time every 44 minutes. The gear was suspended from the mooring surface floats. Sixty samples were collected over a two day period (10-12th January).

A second moored system comprising a deepwater housing (the '*bluey*' logger, set 2466 Table 1) was set on the bottom in 450 m of water on the northern trench edge (large triangle symbol, Figure 2) through 8th March to 10th April. This system comprised a General Instruments C-32 hydrophone connected to custom built electronics comprising an A-D converter and microprocessor controlled sampling and storage system (10 kHz sample rate, 90 s samples every 10 minutes, 9.1 GByte SCSII storage disk). The frequency response of this system was calibrated from < 1 Hz to 3.5 kHz. This system retrieved 4827 samples over 33.5 days.

Continuous sections of sea noise from the DAT tape decks was digitised at 651 Hz using a calibrated DataPhysics DP430 spectral analyser card installed in a 166 MHz PC. The digital data from the '*bluey*' logger was transferred to an IDE disk on a PC. All data analysis was then carried out in the Matlab environment.

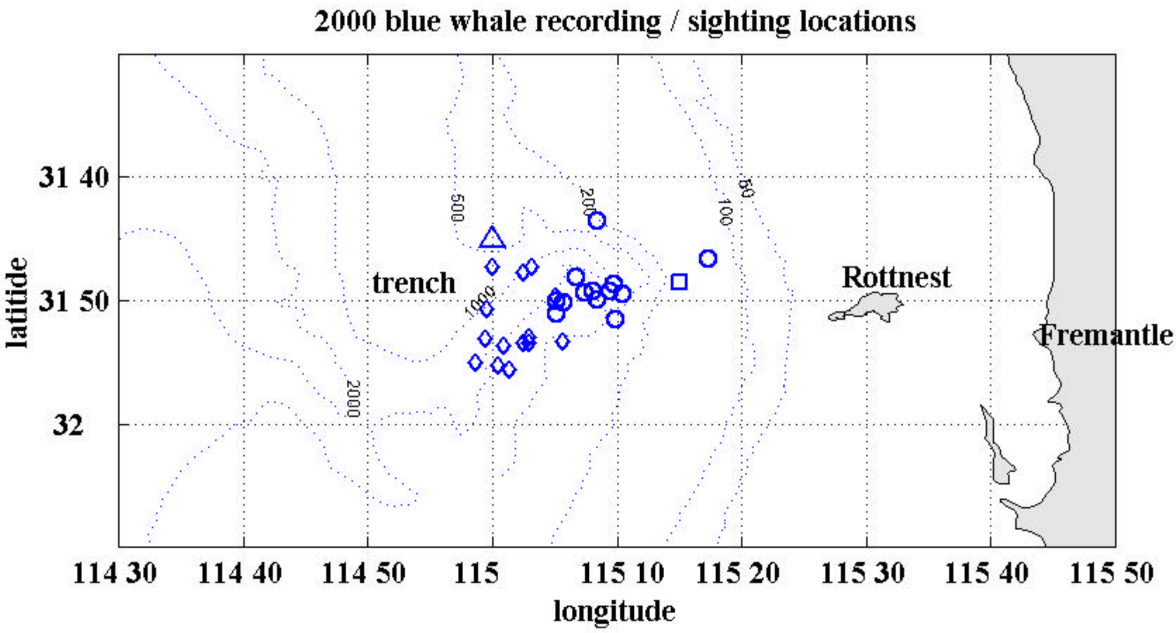

Figure 2: Location of the Rottnest trench region, west of Rottnest Island Western Australia. Recording locations are shown by the circles (drifting gear), square (inshore moored gear sampling over three days) and large triangle (moored gear sampling over 33.5 days). Whale sightings from the boat observations are shown by the diamond symbols. Depths in metres.

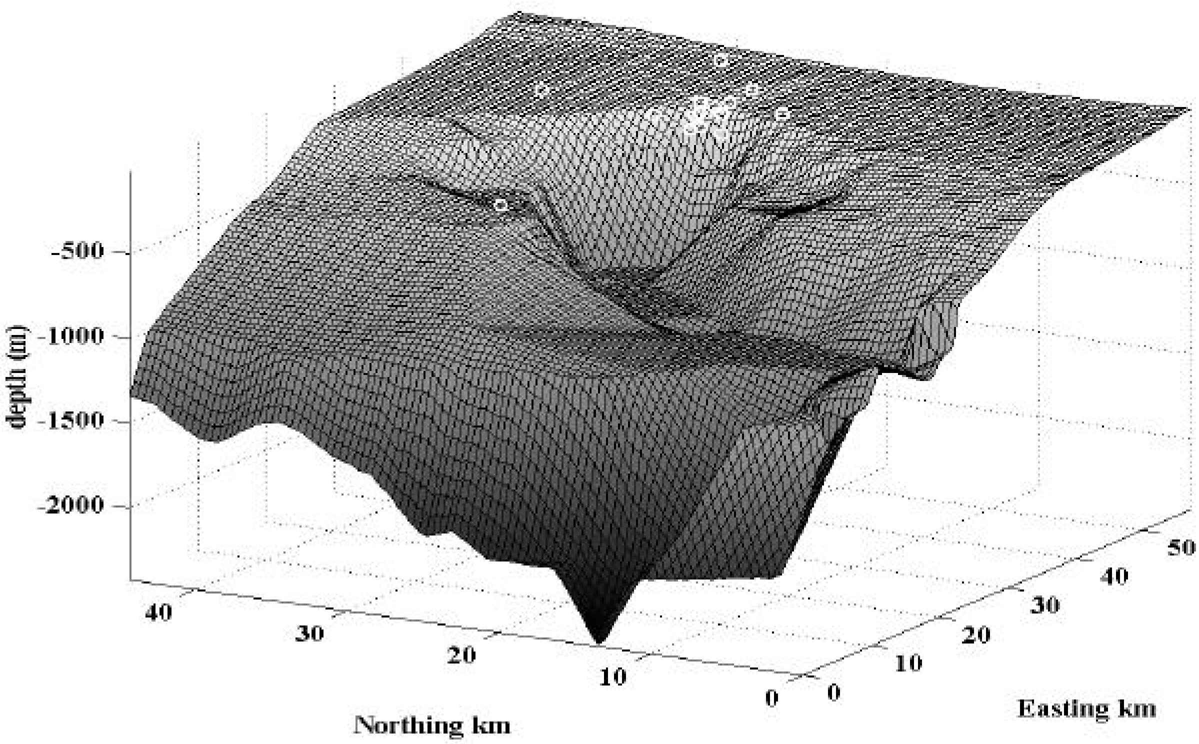

Figure 3: Surface representation of the trench bathymetry, showing the location of recording sites (white circles). The image is looking NE into the trench from the western side (zero point = 32^o 12' 114^o 45').

Table 1: Details of recordings made. Abbreviations or superscripts are: 1 - finish date given only for sets with repetitive sampling as opposed to a single drift sample.

Set #	**date start finish**[1]	**useable time start / stop**	**# records / sample increment**	**type**	**lat in**	**long in**	**hyd depth (m)**	**water depth at hyd (m)**
2456	10-Jan	09:20-10:58	1	drift	31 58.62	115 09.77	55	860
2459	10-Jan 12-Jan	12:08 (first) 09:56 (last)	60 / 3 min every 44 min	moored	31 58.49	115 15.07	45-60	160
2460	13-Jan	09:56-13:15	1	drift	31 58.08	115 06.72	55	1000
2461	18-Jan	09:17-13:26	1	drift	31 53.5	115 08.38	55	230
2462	28-Jan	08:38-12:49	1	drift	32 01.49	115 09.85	55	430
2463	29-Jan	09:21-13:25	1	drift	31 59.25	115 09.34	55	780
2464	12-Feb	13:27-16:05	1	drift	31 56.55	115 17.25	55	125
2465	14-Feb	08:26-11:55	1	drift	32 00.07	115 05.71	55	830
2467	17-Feb	08:23-09:00	1	drift	32 01.07	115 05.08	55	790
2468	27-Feb	09:12-12:38	1	drift	31 59.22	115 08.05	55	770
2469	28-Feb	09:34-13:45	1	drift	31 59.85	115 08.40	55	660
2466	8-Mar 10-Apr	00:10 8-Mar 12:30 10-Ap	4827 / 90 s every 10 min	moored	31 55.13	114 59.96	450	450
2470	13-Mar	12:20-13:00	1	drift	31 59.96	115 5.06	55	920

Salinity, temperature and depth profiles were taken opportunistically with a Marimatech HMS 1820 CTD profiler with a nominal maximum depth rating of 250 m, although it was used to 300 m depth. The Leeuwin current was a consistent feature throughout January to April. CTD profiles showed a warm body of water at 21-22.5^{o} C from the surface down to between 70-200 m where a sharp thermocline existed. Two examples are shown in Figure 4 from a site at the trench head and the '*bluey*' logger deployment site on the day of recovery. Water temperatures dropped steadily below the base of the Leeuwin current, with one record showing 10^{o} C water at 300 m depth but most settling between 13-19^{o} C at 250-300 m depth. On the last sample taken on the 10-April at the *bluey* logger site (square Figure 1) the Leeuwin current extended to 200 m depth below which the temperature steadily dropped. All sound speed profiles showed a sound speed maximum at the base of the Leeuwin current of between 1530-1532 ms^{-1}.

In the deeper waters of the trench it would be expected that cold-deep oceanic water would occur. Thus below the Leeuwin current, the temperature and salinity would be expected to steadily drop as observed, until the deep ocean temperature and salinity where met, then remain relatively constant to the bottom. An idealised sound speed profile based on this scenario using the 200 m thick Leeuwin current profile shown in Figure 4-bottom and a sound speed structure below this depth as for the deep sea at the appropriate latitude (from Urick, 1983), is shown on Figure 5.

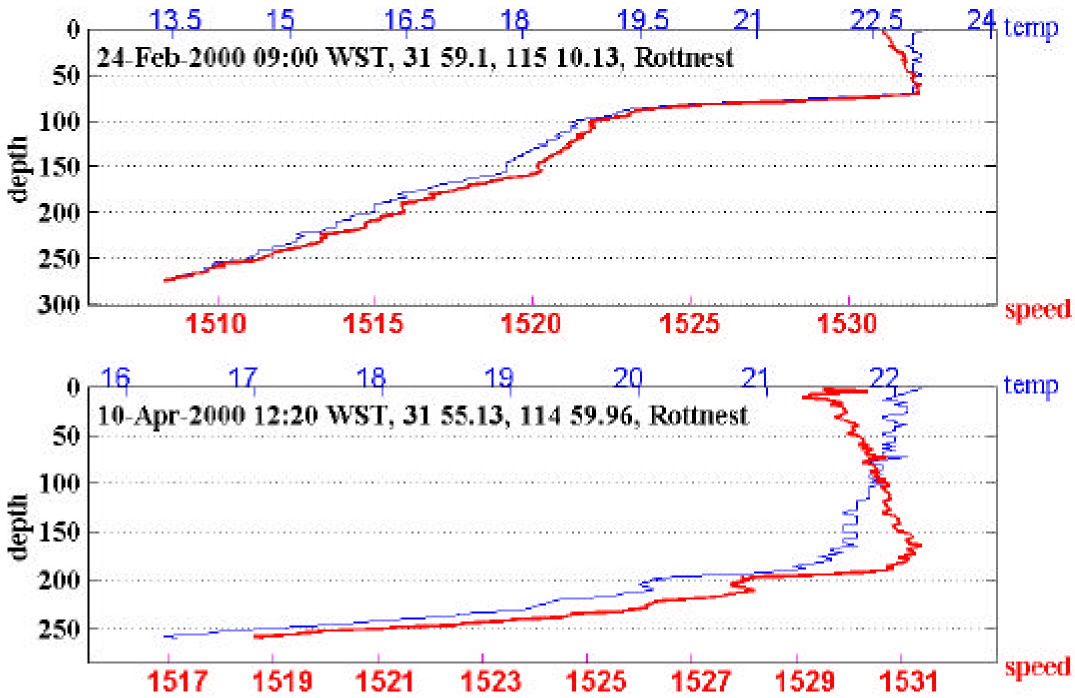

Figure 4: Examples of temperate (thin lines) and sound speed profiles (thick lines) taken across the trench. For clarity salinity is not shown. The Leeuwin current was evident as the warm surface layer. The thick lines and the lower y axis, represent the sound speed structure.

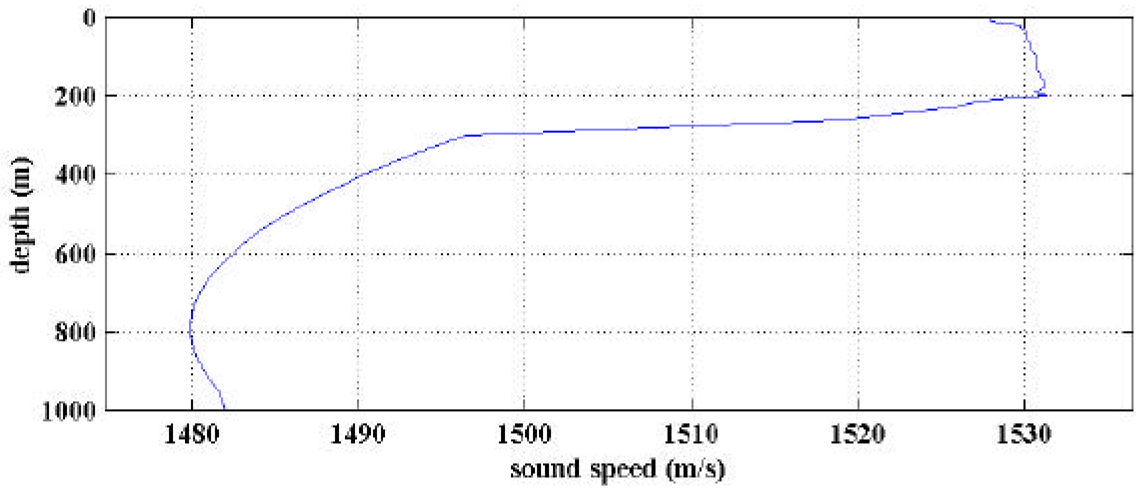

Figure 5: Idealised sound speed profile to 1000 m depth using a 200 m thick Leeuwin current from a CTD cast and a 'typical' deep water profile.

3) Results

3.1) 'Blue' whale calls

3.1.1) Call / Component structure

The most common low frequency signals observed with typical 'blue' whale characteristics (based on literature comparisons of blue whale spectrograms), was a sequence of three long tonal signals with most energy in the band 16-100 Hz. These three '*components*' always occurred in a set sequence. The nomenclature used in this document is that together the three components made a single call. Calls were repeated in a stereotyped pattern at a consistent interval between the end of one and the start of the next, with the interval at 70-85 s (mean at 78 ± 8 s, 95% confidence limits). An example of five call sequences repeated over 15 minutes is shown on Figure 6. Although these calls display 'typical' characteristics of previously reported blue whale calls, in the presence of very long (> 10 s), intense, narrow band tones with most energy in the range 10-30 Hz (ie. Cummings and Thompson 1971; Cummings et al 1971; McDonald et al 1995; Stafford et al 1999), there are no published calls which match well with those reported here. This reflects the difficulty involved in correlating calls with sources in the marine environment combined with the low effort and difficult logistics of describing the calls of southern hemisphere oceanic baleen whales. Given the strong parallels with other blue whale calls, then at the minimum the calls described here are attributable to blue whales. It is believed from the boat based studies run concurrently, that the blue whales observed in the Rottnest trench over the study period were principally pygmy blue whales. Biopsy samples of seven whales were taken in 2000 and genetic analysis of these samples should determine if the whales sighted were true blue or pygmy blue whales. For the duration of this document they are simply referred to as blue whales.

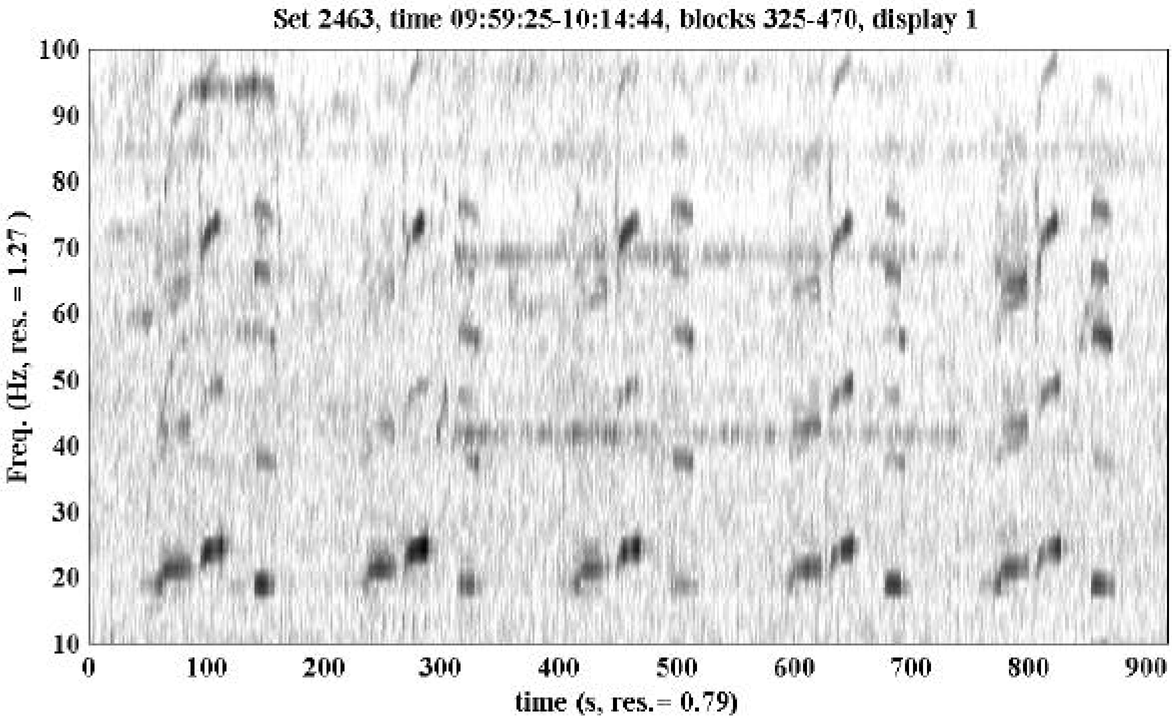

Figure 6: Example of five sequences of the three component blue whale calls, over a 15 minute period. The horizontal bands were tones from a nearby small boat. The blue whale calling had most energy between 18-26 Hz but also displays harmonics and a secondary call source up to frequencies of 100 Hz.

The first call component, referred to here as a type I, was the longest of the three components. A high signal to noise ratio type I component and its waveform is shown on Figure 7 (over 3-50 s, SNR 21 dB, mean squared pressure 120 dB re 1μPa, equivalent energy 134 dB re 1μPa^2.s, background noise 99 dB re 1μPa). This component was dominated by two tones. It began with a tone centred around 19 Hz, lasting for approximately 21 s. This leading tone showed strong amplitude modulation, beginning at a low level then markedly increasing in level after about 14 s. After 21 s the tone abruptly jumped to 21.2 Hz and continued at a comparatively high level for a further 22 s. This was the longest of the three call components, such that for high SNR components the two tones spread over 44-45 s. Since the leading portion of the 19 Hz tone was of a low level it was normally not observed in spectrograms or component waveforms and thus low SNR components appeared to be of shorter duration. Harmonics up to 80 Hz were often evident from the type I component.

The type I component was followed 5-10 s later by the type II component, a frequency upsweep as shown on Figure 7 (over 52-78 s SNR 27 dB, mean squared pressure 126 dB re 1μPa, equivalent energy 138 dB re 1μPa^2.s, noise 99 dB re 1μPa). The tonal part of this component began near 20 Hz, increased to 21 Hz over 2-3 s then slowly increased to approximately 26 Hz over a further 20 s period. Averaged over the whole component the spectral peak was centred around 24.2 Hz. Strong harmonics were evident, particularly the frequency sweep centred near 72 Hz. This component also consistently had an interesting 'blip' at the start, which can be seen over 62-93 Hz leading the type II component in Figure 7. This 'blip' was interesting as a separate signal type, with characteristics like the 'blip' only, were sometimes observed without any of the type I, II or III tones.

The type III component then followed approximately 23 s later. An example of the spectrogram and waveform of a high SNR type III component is shown on Figure 8 (over 26-48 s, mean squared pressure 131 dB re 1μPa, equivalent energy 142 dB re 1μPa^2.s, noise 98 dB re 1μPa). The type III component was dominated by an almost constant tone, centred near 18.5-19 Hz with several harmonics present. Interestingly a secondary tone and its harmonics, indicating a secondary source within the animal, was also present in this component. By selectively filtering the type III signal shown on Figure 8 using bandpass filters (5th order Butterworth), this can be seen on Figure 9 where a several second delay between initiation and end of the 19 Hz tone and the 65-66 Hz tone is evident. Amplitude modulation of each tone is evident. On a more detailed inspection of the 65-66 Hz signal it was found that it was pulsed, or made up of a closely spaced series of short pulses interspersed with multipath signals and gaps of no signal. On further analysis of the type I and type II components it was found that they also had this 65-66 Hz series of pulses. These pulses were used to return the range of nearby animals as discussed in section 3.2.

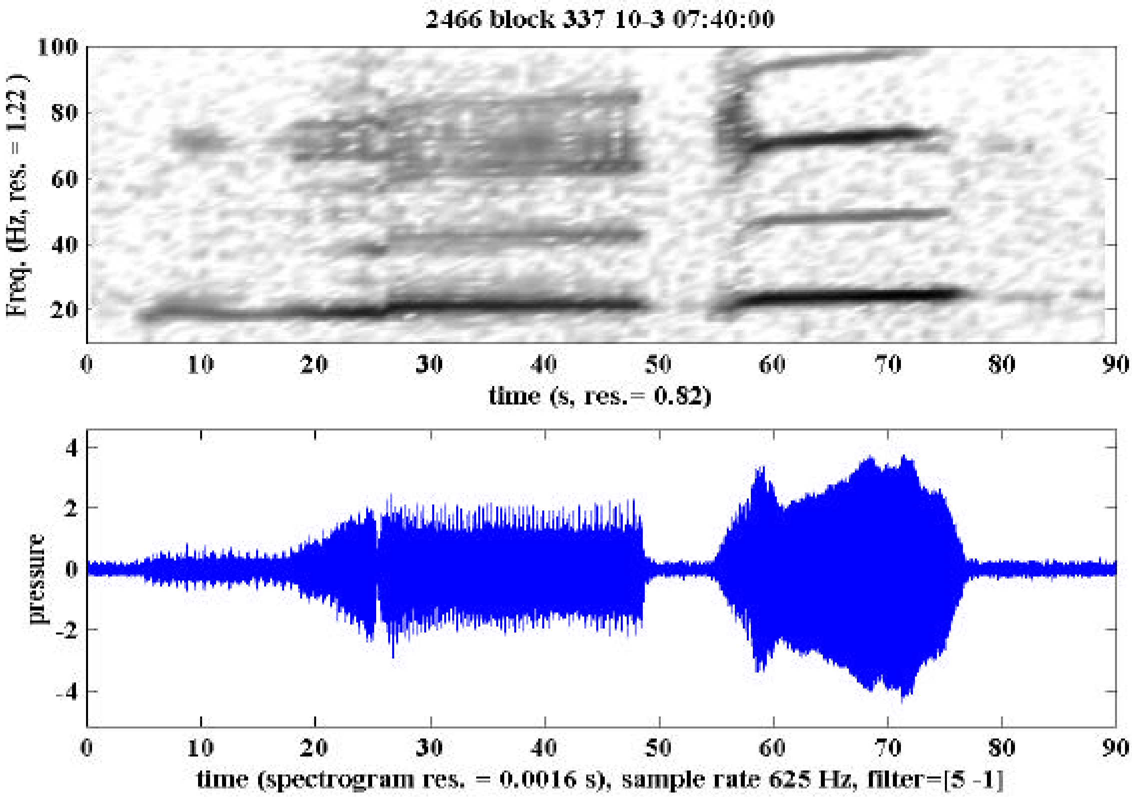

Figure 7: Spectrogram and waveform of the type I and III components. Waveform high pass filtered using a 5 Hz, 5th order Butterworth filter.

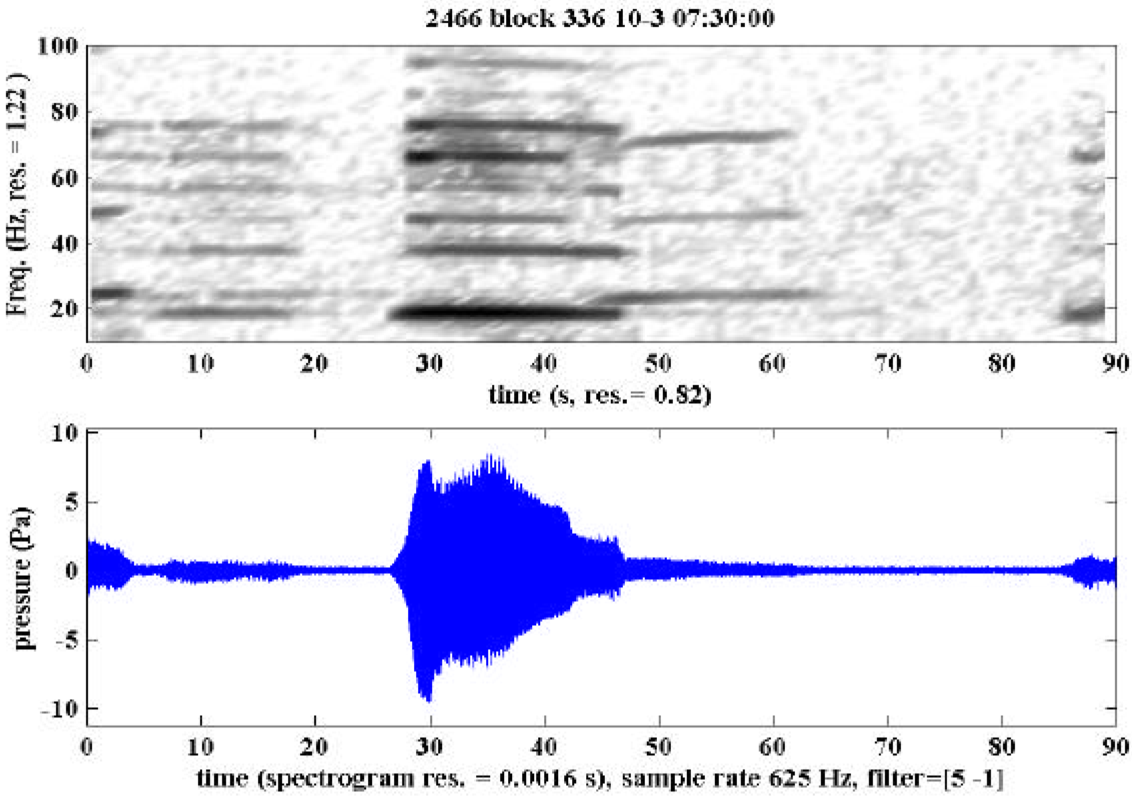

Figure 8: Spectrogram and waveform of type III component (over 26-48 s). Several other lower level component types from different singers can also be seen (for example a type II component overlapping the end of the type III component).

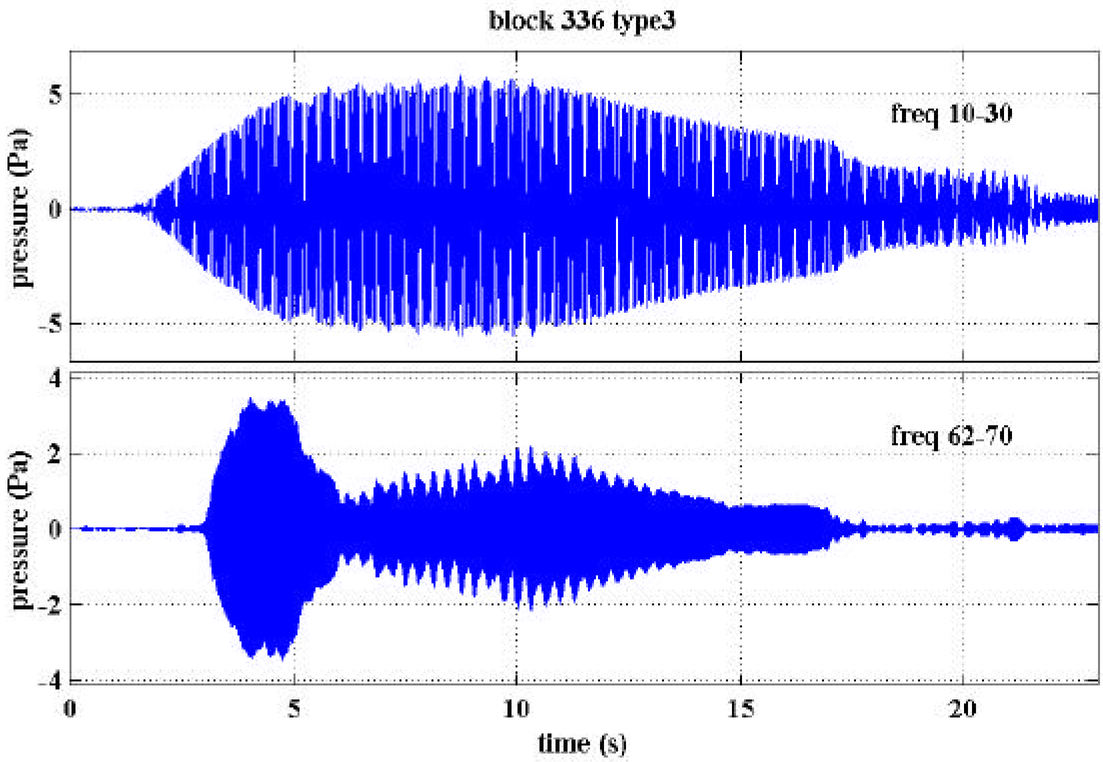

Figure 9: Bandpass filtered waveforms of type III component shown on Figure 8.

This call type is similar, although not exactly the same, to spectrograms displayed by Cummings and Thompson (1971) from blue whale calls recorded off Chile in 1970.

The three call components were remarkably stereotyped in individual structure and in the timing between adjacent components. The distribution of the spectral peak frequency of 404 components (recorded across a 7 day period from the *bluey* logger) determined from FFT averages at a resolution of 0.0763 Hz over the full duration of each component, is shown on Figure 10. The type III component spectral peak frequency was centred almost exclusively near 19 Hz, the spectral peak frequency of the type I component varied over approximately a 1 Hz band centred near 21.2 Hz (the lower level leading tone does not show in this analysis), and the type II component spectral peak frequency varied, which reflected its frequency sweep nature. The frequency spectra of three high SNR components indicating the sharp tonal nature of components is shown on Figure 11.

An example of the amplitude modulation within components can be seen on Figure 12 where a type I component displays strong sidebands which shift frequency with time.

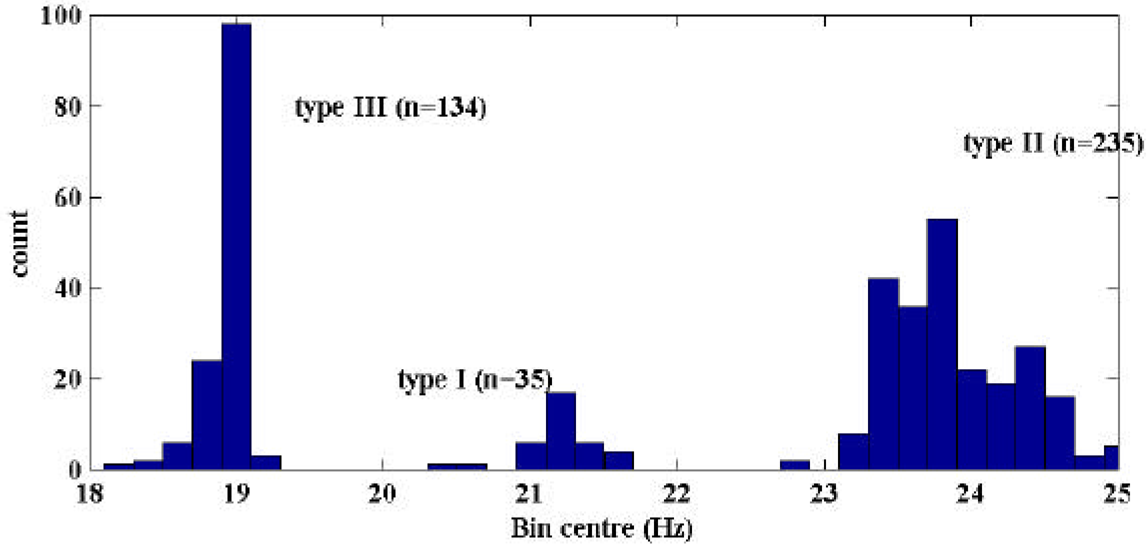

Figure 10: Distribution of the frequencies of the spectral peak for each component type, as determined by averaging the frequency content over each component duration (FFT's taken with a 0.0763 Hz resolution two averages per component, distribution shown with a 0.2 Hz bin width).

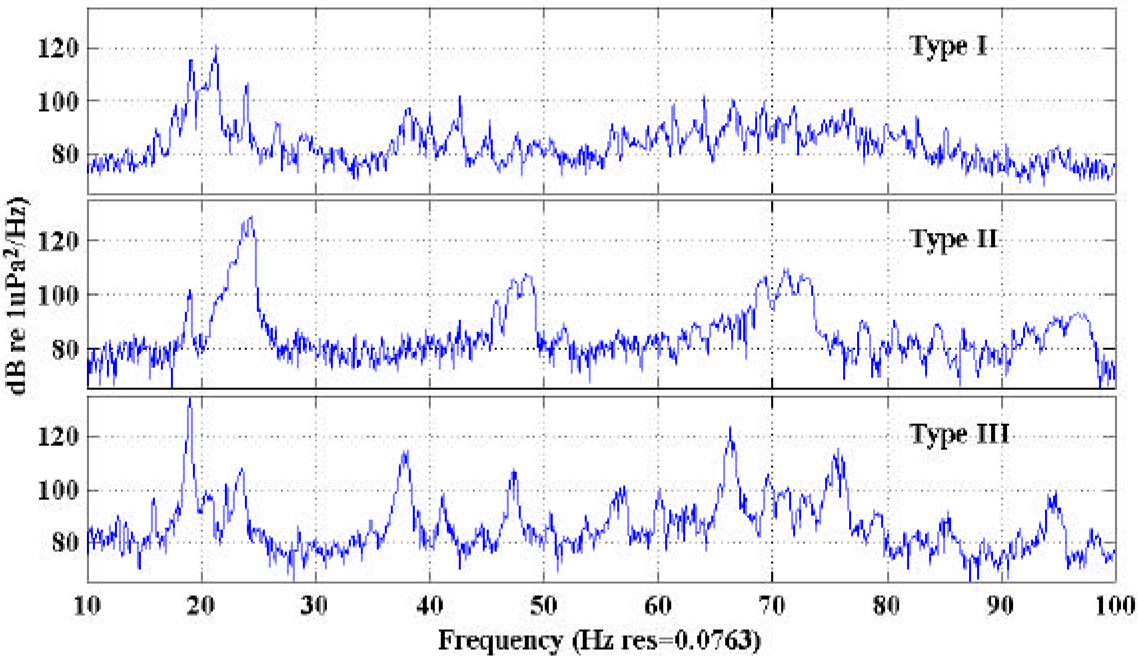

Figure 11: Frequency spectra of high S/N ratio components for each component type, over the frequency band 10-100 Hz.

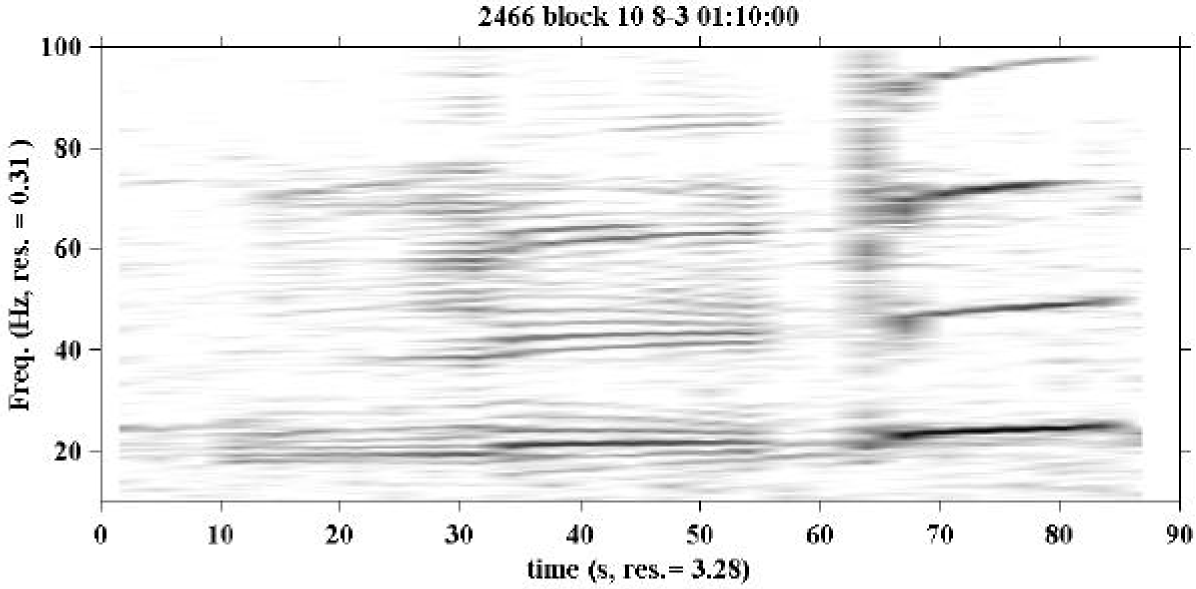

Figure 12: Spectrogram of two blue whale components (type I over 8-57 s and a type II over 61-86 s). The type I component displays sidebands associated with amplitude modulation of the carrier tone.

3.1.2) Received component levels

For the same sequence of type I, II and III components (a call), each component consistently had different received levels. Based on matched components within the same call which had no other complicating sources (ie. overlapping clicks or other blue whale calls) and using the mean squared pressure over the component duration to compare received component levels, then:

- the type II component was 3-10 dB higher in received level than the type I component (4 matched components)
- and the type II component was 0.4-3 dB higher than the type III component (seven matched components).

This implies differences in source levels for each component. The nature of received calls emphasised this, for very long range calls, or those with low signal to noise ratios, it was always the type II component which showed up best. For the deep water moored hydrophone (*bluey* logger at 450 m depth) low SNR signals displayed the 20-26 Hz type II fundamental and harmonics. For the drifted hydrophone (at 55 m depth) it was often the 60-80 Hz harmonic of the type II component which showed up best in spectrograms, with the 19-26 Hz tones often lost.

There was considerable variability of the received level through a component. Examples of this for the type II component are shown in Figure 13, where the magnitude of the Hilbert transform of several components have been overlaid. This analysis displays the positive component envelope, assuming it to be symmetric about the zero pressure axis. The envelope of the lowest level component displayed showed a bi-model peak in received level. This was common for many received signals. The highest level component displayed showed a large increase in received level towards the end of the component. Although some of this variability is under the control of the animal, (of the order of seconds) much of it is believed a function of sound propagation peculiarities for tones (of the order of the entire component length) and is discussed further in section 3.3.

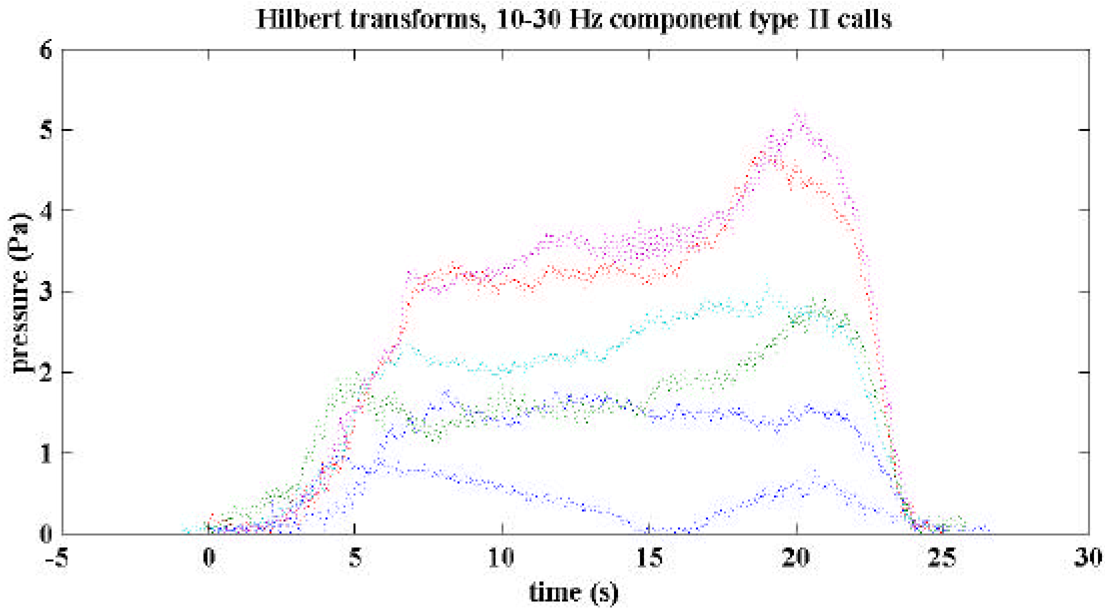

Figure 13: Magnitudes of several type II component Hilbert transforms, showing waveform envelope. The envelopes show large and variable differences in level throughout the component. This is believed partly a function of amplitude modulation of the signal under the animal control, but primarily a sound propagation effect.

3.1.3) Type II received levels

Since the type II component had the highest source level it tended to be the most common signal identifiable in received spectrograms. Thus much of the sound propagation analysis and call counting techniques were tailored for this component type. For sound propagation analysis it is necessary to consider the frequency structure of the signal propagating, since the transmission loss characteristics are frequency dependant. If the emitted sound is broadband, or has energy equally spread across a wide frequency band, then the sound propagation needs to be calculated at representative frequencies and the loss for each frequency at a specified range summed to give the resulting signal at that range.

For the type II component the signal tended to be dominated by the 20-26 Hz tone, as shown on Figure 11 (middle plot). This implies that the sound propagation modelling could concentrate on this frequency band only, and neglect all the other spectral input, such as the 48 and 72 Hz tones seen on Figure 11. If these other tones were 10 dB less than the 20-26 Hz level then they can be validly ignored, since they contribute nothing to the decibel value of the received signal level. To check if this applied across a range of signals, the start and end time of 107 type II signals with no distorting or overlapping sources (boats, other whales etc) and from the bottomed *bluey* logger, was determined and the spectral content of these components calculated, using a 0.6104 Hz resolution, Hanning window and around 16 averages per component. Only the portion of each component which included 95% of the component energy was used (with the sections averaging at 16 s each). These type II signals spanned a received level of 103-129 dB re 1µPa (mean squared pressure, see section 3.2 for definition). Using decibel statistics (or the statistics calculated on the intensities then converted back to dB), the mean difference in the level of the spectral peak between 20-30 Hz minus that between 45-50 Hz was 18.18 dB with 95% confidence limits from 16.5-19.3 dB. Using the same technique the mean difference between the level of the spectral peak between 20-30 Hz minus that between 68-75 Hz was 9.94 dB with 95% confidence limits of 8.2-11.1 dB. Thus the assumption of using only the 20-26 Hz tone in propagation modelling was considered valid.

For the final censusing technique a prediction of mean squared pressure from spectral level of the 20-26 Hz tone was required. Using the respective values calculated from the above batch of 107 signals, the trend of this prediction can be seen on Figure 14, with the fitted curve giving:

$$l_{msp} = 0 \cdot 7476 + 28 \cdot 1556 l_{s-24} \qquad \text{Equation 1}$$

where
l_{msp} = mean squared pressure level (dB re 1µPa)
$l_{s\text{-}24}$ = peak spectral level of the 20-26 Hz tone (dB re 1µPa^2/Hz).

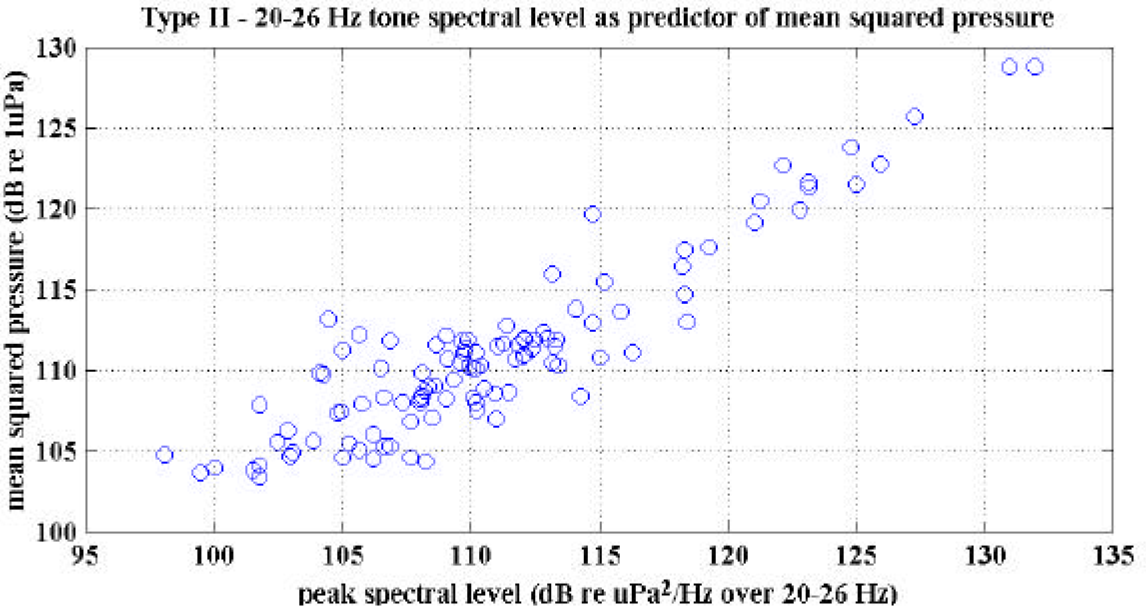

Figure 14: Prediction of type II component mean squared pressure from the peak spectral level of the 20-26 Hz dominant tone, from 107 components ranging in received level from 103-129 dB re 1µPa (mean squared pressure).

3.2) Blue whale call propagation - general and *bluey* logger site

Estimates of the how well the blue whale calls travelled in the environment of the trench are crucial in using acoustic techniques to estimate the local abundance of animals either on a relative or absolute scale. They may also provide clues as to how the animals are using their sounds. There are numerous difficulties in estimating the propagation of any signal in continental shelf waters. The primary factors are the frequency of the sound of interest, absorption losses, the sound speed structure through the water column, the signals interaction with the seafloor and its reflection off the sea surface.

For the primary frequencies of the blue whale calls (18-26 Hz, Figure 11) reflections off the sea surface can be considered to occur without loss but with a 90^o phase shift and absorption losses are negligible (Urick, 1983).

The sound speed structure within the water column is important as if it varies with depth (which other than in shallow bays, it almost always does), then downward travelling sound waves will be refracted upwards if the sound speed increases with depth, or downwards if the sound speed decreases with depth. Depending on the appropriate sound speed structure with depth, this can result in ducting where sound waves are refracted so that they remain in a duct and do not interact with the surface or bottom (as in the deep sea where a sound speed minimum at around 1000 m depth 'traps' sound waves), can result in sound shadowing if downward refraction is strong, or can result in continual interactions with the sea surface if upward refraction is strong. The presence of the warm Leeuwin current in the study region (sound speed profiles shown in Figure 4) would have resulted in upward refraction above the base of the Leeuwin current and strong downward refraction below the base, where the sound speed dropped sharply. This effect can be illustrated in a ray plot. This type of analysis treats the sound waves leaving a source as a series of closely spaced rays, then calculates the trajectory and refraction of each ray as it passes through layers of water with different sound speeds, taking into account reflections off the surface or bottom An example of the ray trajectories near the *bluey* logger site for a 200 m deep Leeuwin current (as for Figure 4, bottom plot), a source at 40 m depth (the commonly reported depth of a calling blue whale, Thode et al 2000, D'Spain et al 1995), in a constant 450 m water depth, out to 20 km, are shown on Figure 15. For simplicity the bottom reflected rays are not shown. This figure shows strong downward refraction just below the Leeuwin current such that of the rays plotted, none are evident below 100 m depth from 11 km outwards. In reality signal energy would occur in this shadow zone due to sound energy reflecting off the seabed or entering the seabed and later being refracted or reflected out of it back into the water.

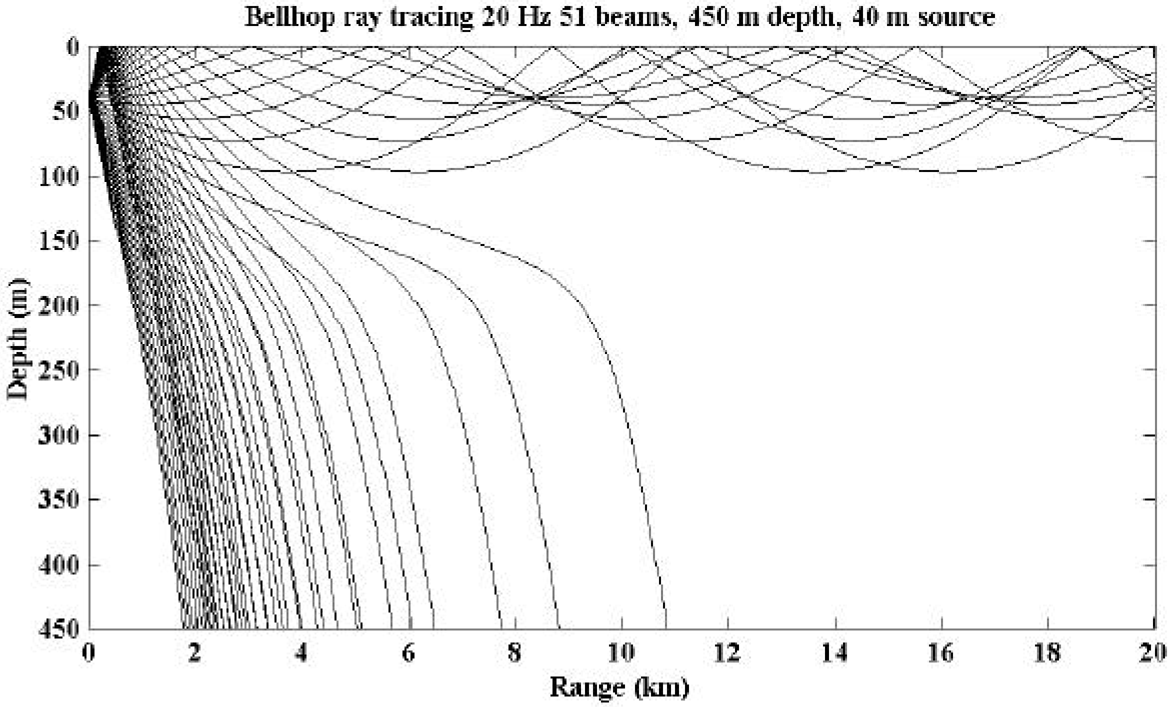

Figure 15: Ray trace for a 20 Hz source at 40 m depth in a constant 450 m water depth using the sound speed profile of Figure 4-bottom (200 m deep Leeuwin current) extrapolated as for Figure 5. Strong downward refraction is evident. Made using the '*Bellhop*' program (Porter, 1994), with only surface reflections included.

The interaction of sound waves with the seafloor is vitally important for the propagation of sound in shallow water (continental shelf and slope, waters). Sound energy may reflect off the seafloor, be scattered off the seafloor or may enter the seafloor, travel through it, then be reflected or refracted back into the water column. There are several mathematical approaches for calculating how impinging sound waves interact and refract in the sea floor. These are implemented in specialised programs which also include the surface reflection interaction and water column sound speed variations. Each of these programs has its own set of limitations and peculiarities necessary for successfully running and interpreting the outputs. All require detailed geological information on the seafloor properties. No geological information on the seafloor characteristics appropriate for sound propagation studies were available to the author for the trench region. Based on sound propagation modelling by Hoffman et al 2000 and Jones et al 2000, a set of sediment properties for the shelf above the 200 m contour, west of Rottnest was extrapolated to encompass the whole trench region. The parameters used are given in Table 2. These parameters were used for all water depths < 200 m. For water depths > 200 m the depth of the medium sand thickness was linearly increased from 0.5 m such that at 2500 m water depth its thickness was 50 m. The underlying layer thicknesses were held constant.

Table 2: Sediment geological properties used in the sound propagation modelling (from Hoffman et al 2000)).

Layer	**Thickness (m)**	**compressional sound speed (c_p m/s)**	**shear sound speed (c_s m/s)**	**compressional attenuation (dB/l)**	**shear attenuation (dB/l)**	**density (kg/m^3)**
water column	variable	re. Figure 5	-	-	-	1025
medium sand	0.5	1600	-	0.5	-	1600
boundstone soil	4	1700	-	0.5	-	1700
tamala limestone	300	2500	1100	0.1	0.2	2100
basement		3500	1500	0.1	0.2	2300

In addition to the sediment properties the bathymetry along each travel path from an in water noise source is important for lateral sound transmission. As can be seen from Figure 2 and Figure 3 the bathymetry of the trench is complex. This could be expected to have significant effect on sound travelling across the region. A program was written which used a gridded version of the digitised bathymetry chart to estimate bathymetry profiles. Eight such profile paths emanating from the deployment location of the *bluey* logger at 45° increments, are shown on Figure 16 and Figure 17 and were used in the propagation modelling.

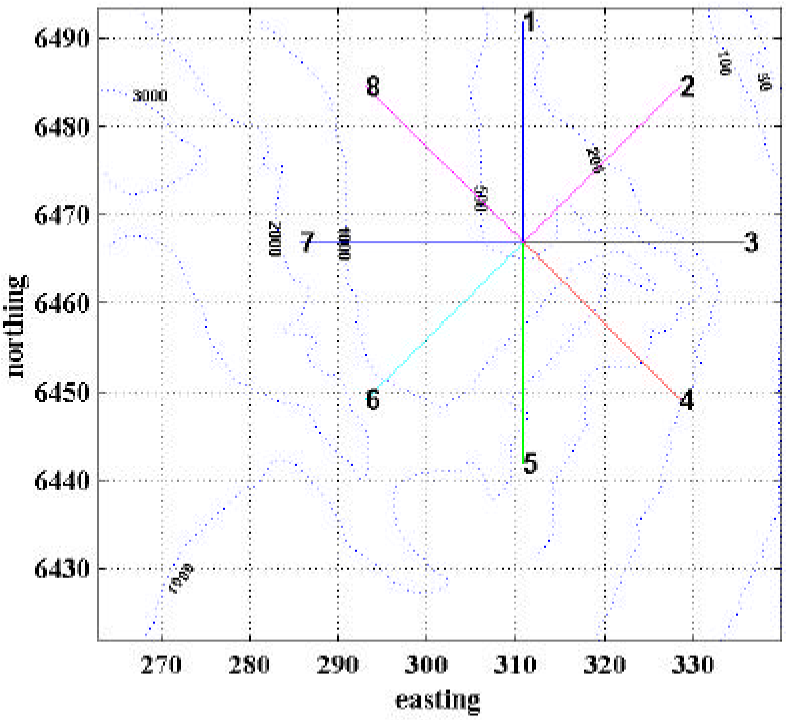

Figure 16: Bathymetry of study area with eight 25 km tracks at 45° intervals shown emanating from the *bluey* logger site.

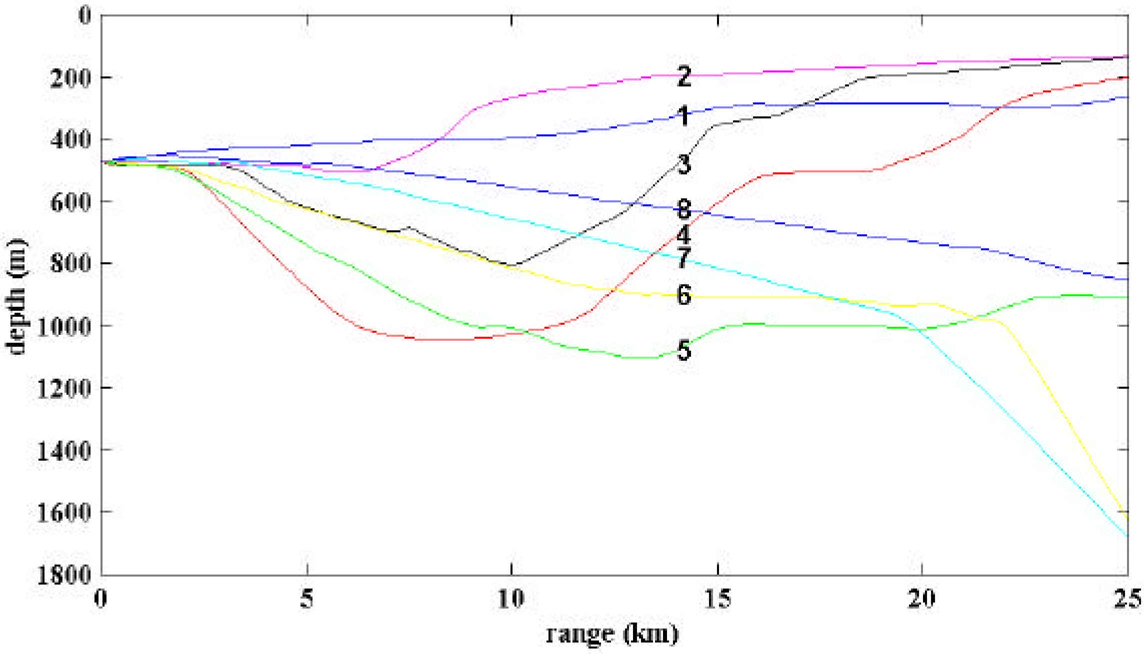

Figure 17: Bathymetry profiles for eight tracks shown on Figure 16.

As can be seen from Figure 16 and Figure 17 some of the paths cross the trench where water depths up to 1000 m are found.

Two propagation codes were readily available for modelling the transmission of signals across the trench. These were *Kraken* (Porter, 1994), a normal mode code, and *RAM* (Collins, 1993), a parabolic equation code. These were run in the PC environment on a 500 MHz Pentium machine. Each program was trialed with test, water and sediment parameters and found to give correct results. The *Kraken* program is a "range independent" program, that is it can only be set up for a single environment type of constant depth. Although the water column and seabed properties could be expected to be reasonably constant throughout the study region (with water column parameters primarily changing with depth) the bathymetry was not. Thus the *RAM* program was chosen since it is "range dependant" or can deal with changing bathymetry, water column sound speed profiles, or sediment characteristics. As a check the accuracy of the *RAM* and *Kraken* programs were compared against each other. A constant environment problem was set up using the seafloor parameters listed in Table 2, the water column sound speed profile shown in Figure 5 (or a 200 m deep Leeuwin current), a constant water depth of 450 m, a source at 40 m depth, a receiver on the seabed at 450 m depth and a frequency of 24 Hz. The outputs of the two programs over 5-10 km can be seen on Figure 18, along with an idealised case for ducted sound or cylindrical spreading ($10\log_{10}$[range]).

The *RAM* and *Kraken* transmission loss curves shown on Figure 18 show identical trends, with the small scale differences due to the different resolutions used in the calculations. Range steps of 100 m were used in *RAM* and 250 m in the *Kraken* runs.

To visualise the 2D transmission loss field the Kraken output for the above run is presented on Figure 19. It can be seen from this plot that regions of high and low transmission loss occur scattered throughout the water column, and that as predicted by the ray plot of Figure 15, the loss increases within the water column below the Leeuwin current base (200 m in the example) beyond approximately 10 km. The 'patchiness' of the loss shown on Figure 19 is due to the interference patterns produced by the multipath (bounces off the seafloor and surface) and direct signal combining. Note that for this example, beyond approximately 10 km there is no longer a direct path and that all paths have interacted with either the surface or bottom (Figure 15). The destructive and constructive effects of multipath interference are what produce the 'spikiness' which can be seen in the *RAM* output of Figure 18. For example a 25 dB drop in signal strength is observed between 7.4 and 7.6 km in the RAM output.

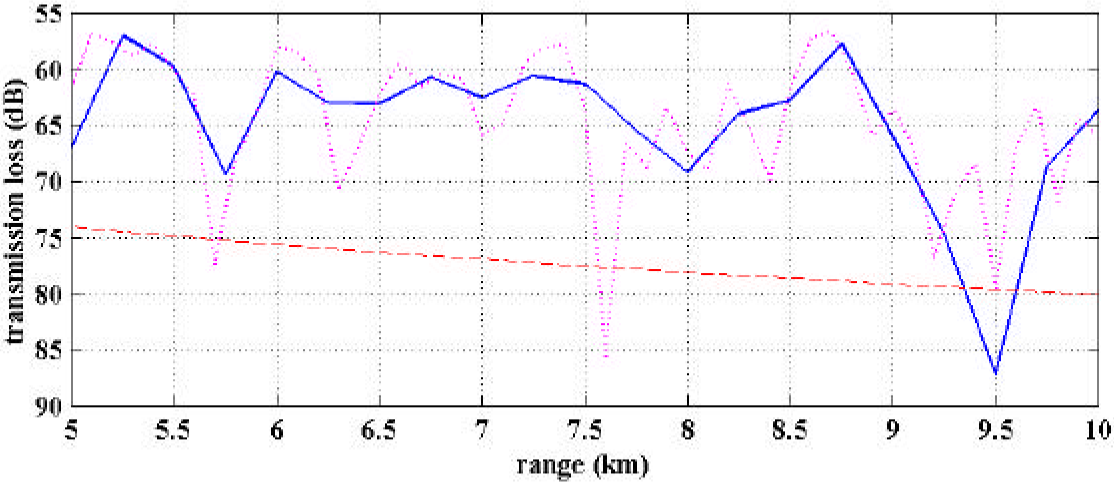

Figure 18: Comparison of *RAM* output (thick dotted line) and *Kraken* output (thick solid line) for constant 450 m depth, sound speed profile of Figure 5 and seabed parameters as for Table 2. Cylindrical spreading is shown by the thin dashed line.

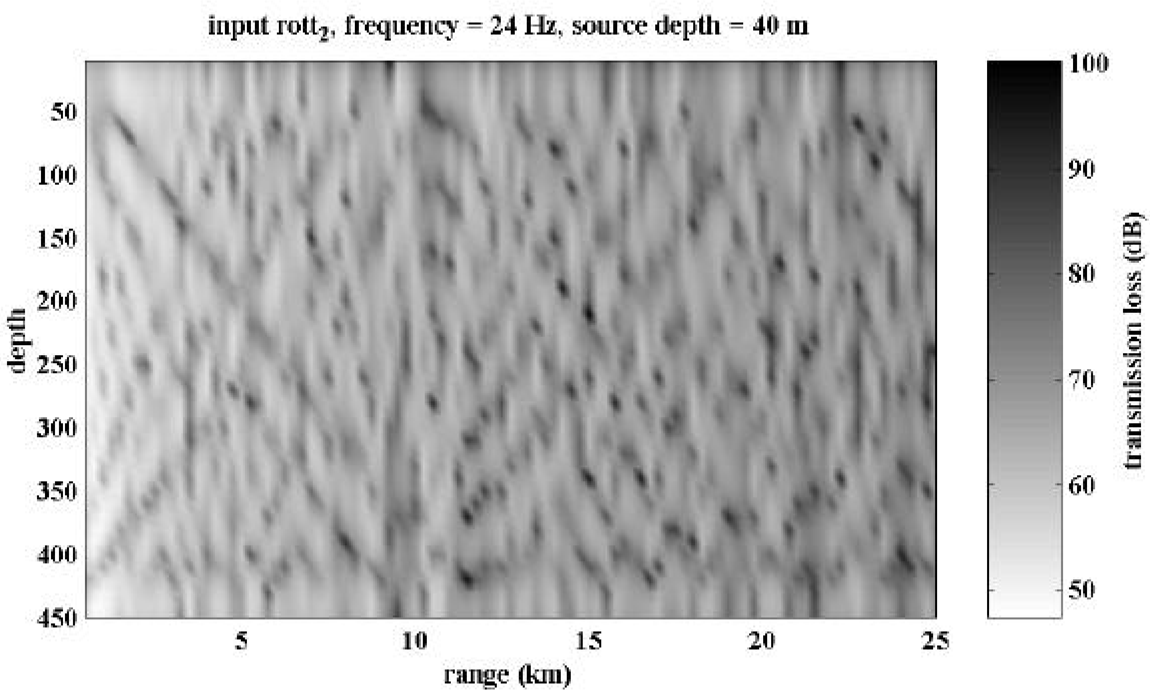

Figure 19: Transmission loss field calculated by *Kraken* in the environment of the *bluey* logger, with details as per text.

To predict transmission loss from the *bluey* logger receiver sites and properly account for the changing bathymetry, *RAM* was set up and run as per:

- a water column sound speed structure based on that shown in Figure 4-bottom (ie. a 200 & 75 m thick Leeuwin current) and extrapolated to that shown on Figure 5, and input into *RAM* at 25 m depth steps;
- the seafloor parameters listed in Table 2 with the medium sand layer thickness constant at 0.5 m for water depths ≤ 200 m then linearly increased to 50 m thick at 2500 m water depth;
- the eight bathymetry paths shown in Figure 17, with the bathymetry calculated at a 250 m interval and input into *RAM* in 500 m steps;
- the transmission loss calculated in 100 m steps out to 37-50 km (depending on which heading was used);
- using the principle of reciprocity, the *RAM* receiver placed at the actual source depth of 20 or 40 m, and a *RAM* source placed at the actual receiver depth of 475 m (the bathymetry program interpolated depth at the *bluey* logger site)
- a frequency of 24 Hz.

The output of *RAM* gave transmission loss (dB) with range, at the specified frequency, for a fixed receiver depth equivalent to the *bluey* logger location, a source depth of 20 or 40 m and for eight profiles on 45° headings from the logger location. To then convert the transmission loss estimates to a blue whale component received level at a specified range, required an estimate of the appropriate component source level. This is dealt with below.

3.3) Blue whale source levels

Three estimates of the source level (theoretical level of the noise source assuming it to be a point and the measure made at 1 m range from the point) of blue whale calls are given in the literature. Cummings and Thompson (1971) present an estimate of an average source level in the 14-222 Hz band (or encompassing all the signal energy) as 188 dB re 1µPa at 1 m, for blue whales recorded off the Chilean coast. They do not state the type of measurement so it is assumed to be the mean squared pressure or squared *rms* value of the signal, since this is the most common measurement type reported. In terms of absolute pressure this is mathematically equivalent to:

$$\overline{p^2} = \frac{1}{T}\int_{T_0}^{T_e} p_{s+n}^2(t)dt$$

where:

$\overline{p^2}$ = the mean squared pressure or the square of the *rms* pressure, reduced to an equivalent value at 1 m range from the source

T = the signal duration

p_{s+n} = the blue whale pressure signal plus the noise

In all calculations carried out in this analysis the mean squared pressure was calculated by using the portion of the signal which encompassed 95% of the signal energy (thus standardising the way T was calculated) and by subtracting the background noise component from the signal of interest (ie replacing p_{s+n}^2 above with p_s^2).

Cummings and Thompson (1971) estimated the source level using spherical spreading and visual estimates of range from calling whales.

D'Spain et al (1995) used complex localisation techniques from recordings made with vertical arrays of hydrophones to estimate the 3D location of calling blue whales off the Californian coast. Calling depths of 22-34 m, a speed of 1.8 m/s (3.5 knots) and a source level estimate for a type B call, at 169 ± 2 dB re 1μPa at 1 m (believed mean squared pressure) were estimated.

The most comprehensive analysis of blue whale source levels in the literature is that of Thode et al (2000) again for blue whales off the Californian coast. In a similar fashion to D'Spain et al (1995) they used complex sound propagation modelling techniques to localise blue whale sources in 3D space using recordings from linear and vertical hydrophone arrays. All whales tracked vocalised between 10 and 40 m depth. For one tracked blue whale they estimated a consistent maximum source spectral density level of about 185 dB re 1μPa^2/Hz at 1 m range. This is a narrow band (limited frequency range) measure of the average maximum tone level reached (with the dominant tones from 16.41 ± 2.18 Hz and 50.52 ± 1.75 Hz). They then converted this to a broadband level, giving a source level estimate for this animal of around 180 dB re 1μPa at 1 m range.

Given the variability of blue whale source level estimates, the fact that none existed for the type of calls recorded here and the vital importance of knowing the mean source level so as to allow range estimation from a single hydrophone, it was considered necessary to investigate some of the higher signal to noise ratio components recorded in this study and attempt to determine the caller location by identifying multipath signals. This technique involved discerning the direct signal, surface and bottom bounce signals and obtaining their relative arrival times and possibly their received level. An indication of some of the arrival paths available in shallow water (ignoring refraction) is shown on Figure 20. An outline of how identification of multipath signals can be used to estimate the range and elevation of calling animals from the relative arrival time and level of the direct and surface path signals is given in Cato (1998). This technique has been used to determine the location of several fish species (ie. McCauley 2000) and can be extended to use paths beyond the surface arrival.

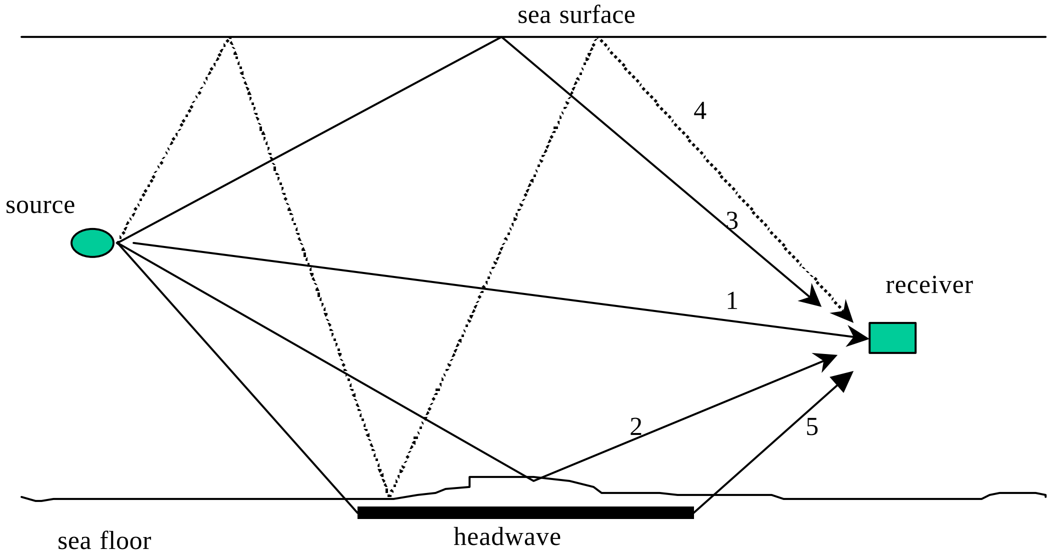

Figure 20: Some of the arrival paths received in shallow water, ignoring refraction. Paths are: 1 - direct; 2 - bottom; 3 - surface; 4 - surface-bottom-surface; 5 - headwave.

To successfully use this technique requires that the multipath signals can be discerned. Thus the long continuous tones of each component type over the 18-26 Hz frequency range were not suitable. But the pulsed 65-66 Hz signals of each component were suited to this technique. Only calls from the *bluey* logger were used in this analysis. This hydrophone was bottomed, thus the arrivals from a bottom bounce to the hydrophone were able to be ignored (ie. arrival 2 in Figure 20).

The strong refraction bought about by the change in sound speed structure with depth needed to be dealt with in estimating the multipath arrivals at any specified orientation of source and receiver. Thus a sound propagation model which predicted ray paths from a source was used. The *Bellhop* model (Porter, 1994) was run with a 75 and 200 m depth Leeuwin current (as per Figure 4 top and bottom extrapolated to depth as per Figure 5), source depths of 20 and 40 m and constant water depth of 450 m (ie. the *bluey* logger depth). The model output depth and range vectors for rays resulting from each launch angle selected. For each model run, 600 rays between launch angles of -50° (looking up) and 50° (looking down) were used. A simplified output of this model run, with the bottom bounces not shown, was presented in Figure 15 (section 3.2). Since the receiver was bottomed the *Bellhop* output was then used to find the various arrivals for specified locations along the seafloor. The travel path along each ray (or multipath signal) to the specified bottom location was calculated, as was the travel time along the ray, which was found by using the water column sound speed structure and the ray path vectors. Thus an output consisting of the horizontal range to a source at 20 or 40 m depth, and the associated travel time and travel path range, for the first eight arrivals was obtained over horizontal ranges from 400 m (direct arrival only) to 5 km. Only shallow sources were used in the *Bellhop* ray path modelling as all previous workers whom have calculated the calling depth of blue whales have reported calling depths of less than 40 m (eg. D'Spain et al 1995; Thode et al 2000).

For sources near the surface (compared to the water depth), such as the blue whale, the multiple bounce paths arrive at the receiver in groups of two closely spaced paths. This can be seen on Figure 21 where the different arrival times relative to the direct arrival for a 65 Hz signal are presented with range, and each group arrives as a 'set'.

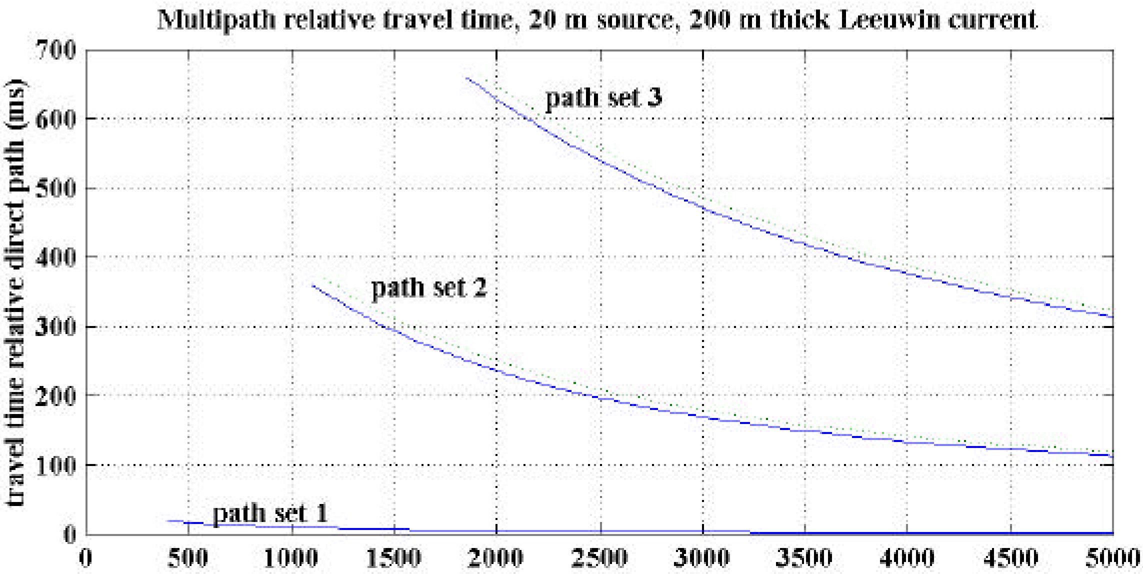

Figure 21: Arrival times of multipath signals relative to the direct arrival, for the *bluey* logger site, a 20 m source, 200 m deep Leeuwin current, at 65 Hz. The arrivals come in closely spaced pairs with the lowest arrival pair the direct (zeroed) and surface arrivals, the next group the bottom-surface and surface-bottom-surface (dotted line) arrivals, and the top group, the bottom-surface-bottom-surface and surface-bottom-surface-bottom-surface (dotted line) arrivals.

If the outgoing signal pulse is sufficiently short, or generally less than 10 ms long, the different arrivals in each path set may be resolved, but if they are not then each set of two arrivals will combine to form a received bounce path. The latter is the case with the blue whale 65-66 Hz pulses recorded, they were generally of the order of 100-200 ms long, which meant the two arrivals combined. Since the two arrivals for each path set (termed a path from here on) will be of the same frequency, different phase but similar amplitude (the path lengths for each set are similar), they will combine to form a signal which appears to have an arrival time somewhere between that of each arrival. The mean of the two arrival times making a path was used in the following calculations. From the output displayed in Figure 21 it can be seen that out to approximately 5 km (where the curves of path arrival times relative to the direct arrival, flatten out), the source range can be accurately determined from knowledge of the direct and subsequent path arrivals. Hence discerning the multipath relative arrival times can give the range to source.

The 62-75 Hz blue whale component pulses were spaced at variable repetition rates of between 200-750 ms, which mostly occurred in groups of constantly spaced pulses for several seconds before switching to a different pulse interval. The patterning of this pulse spacing was not investigated, but it is possible that information could be encoded within the various repetition patterns observed. For discerning the multipath sets widely spaced sets of pulses were required. Because of the multiple bounce paths and the relatively close spacing of outgoing pulses it was very confusing trying to accurately identify the multipath sets. One had to search for consistent (in time from outgoing pulse) bounce sets. An example of a call and outgoing and multipath signals is shown on fig Figure 22.

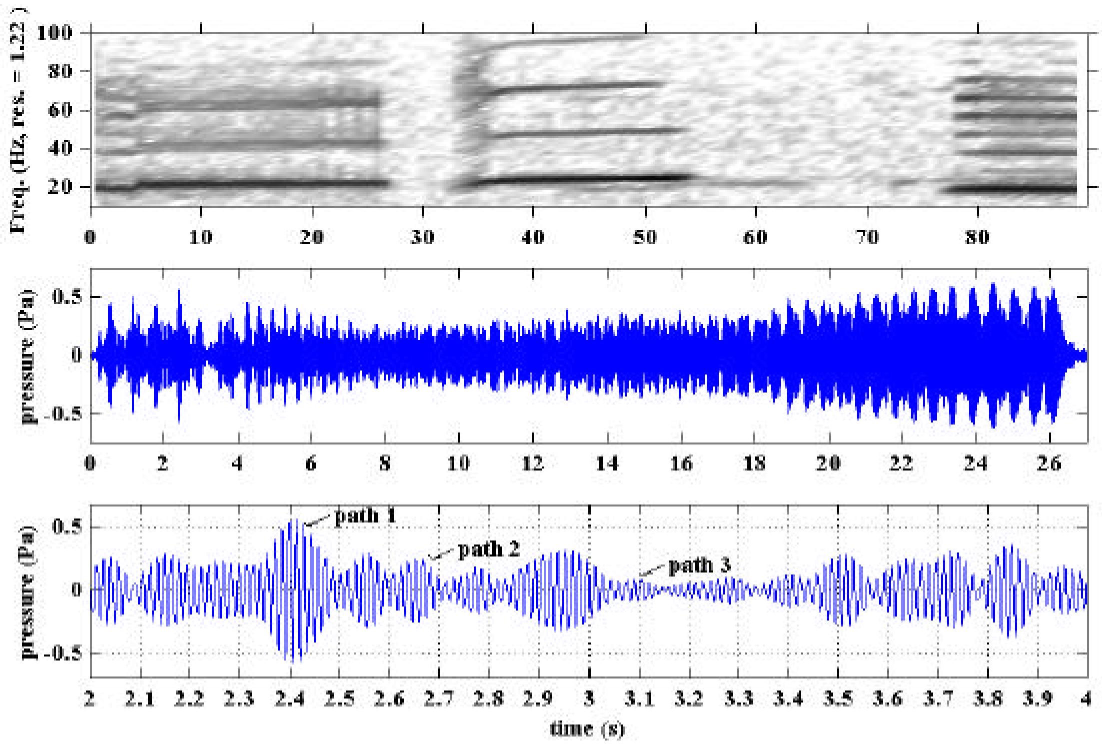

Figure 22: (**top**) Spectrogram of full block 338 with portion of type I, full type II and portion type III component, (**middle**) first 27 s showing type 1 component (bandpass filtered 62-75 Hz), (**bottom**) section showing waveform (bandpass filtered 62-75 Hz) of several pulses (first arrival) and bounce paths (path 2 & path 3).

The range of seven calling animals was determined by measuring the arrival time of the second and where possible third bounce paths, relative to the first path. The appropriate values and ranges obtained are shown on Table 3. Having determined the range to each caller it was then necessary to determine the propagation loss at this range. As can be seen from Figure 18 and Figure 19, for strong tones the loss and thus received signal, may fluctuate by 10-20 dB over short ranges (a few hundred metres). Also the transmission loss along each of the eight bathymetry paths was different, and although range from the *bluey* logger was determined it was not possible to determine the azimuth, thus there was no way of knowing which was the correct bathymetry track for each caller. Hence a matrix of possible loss values was determined, varying with: source depth; Leeuwin current depth; and bathymetry track. As an estimate of what the source level of the type II signal in each block was, the transmission loss estimates at 24 Hz for all combinations of:

- the single range estimate (Table 3),
- the eight bathymetry paths;
- a 200 m and 75 m thick Leeuwin current;
- and a source depth of 20 and 40 m

were added to the appropriate mean squared pressure of the type II signal to give 224 '*possible*' source levels. Note that some are erroneous values since eight bathymetry tracks, two source depths and two sound speed profiles were used, yet for each block only one combination is correct. Propagation of only the 20-26 Hz signal was considered, as this spectral section of the type II signal was consistently 10 dB or greater than the input from other frequencies, hence contributed all the effective signal energy (section 3.1.3). The frequency distribution of these '*possible*' source levels was plotted as per Figure 23 and the distribution bin with the highest count taken as an estimate of the type II source level, or 183 dB re 1μPa mean squared pressure at one metre.

This was considered a crude estimate but since there was no valid way of finding the true source level for each call without determining which bathymetry path the animal was along, and that an error in the range estimate of only a few hundred metres could potentially give a large difference in transmission loss, it was considered reasonable. The value is higher than the source level estimate of D'Spain et al (1995) of 169 dB re 1μPa msp, or Thode et al (2000) of 180 dB re 1μPa msp, but less than that of Cummings and Thompson (1971) of 188 dB re 1μPa msp, but these estimates are from different blue whale stocks using different methods.

The type II component source level estimate of 183 dB re 1μPa mean squared pressure at one metre has been used below in range estimation.

Table 3: Measured relative arrival times and range estimates with predicted arrival times, for seven sets of blue whale calls.

block	**path 2 / path 3 (where available) travel time, relative to path 1 (ms)**	**horizontal range estimate (m)**	**predicted path 2 / path 3 / path 4 (where available) arrival time - relative to path 1 (ms)**	**measured type II component level (msp - dB re μPa)**
10	150	3550	150 / 418 / 777	121.4
24	120	4750	120 / 331 / 625	122.7
33	170 / 430	3050	171 / 471	123.8
43	100	6200	100 / 269 / 506	121.6
335	210 / 550	2350	212 / 571	128.8
337	223 / 596	2200	223 / 596	125.7
338	254	1850	256 / 657	128.8

3.4) Transmission of blue whale calls to *bluey* site

All propagation calculations concentrated on the type II component only, as this was the component with the highest source level and which appeared best at all ranges in the spectrogram plots. Using the transmission loss and source level estimate as derived above, a plot of the resulting received level for the type II component about the *bluey* logger location, for the bottomed receiver, source at 40 m depth and a 75 m deep Leeuwin current is shown on Figure 24 (using the eight 45^{o} transmission loss tracks and interpolated between).

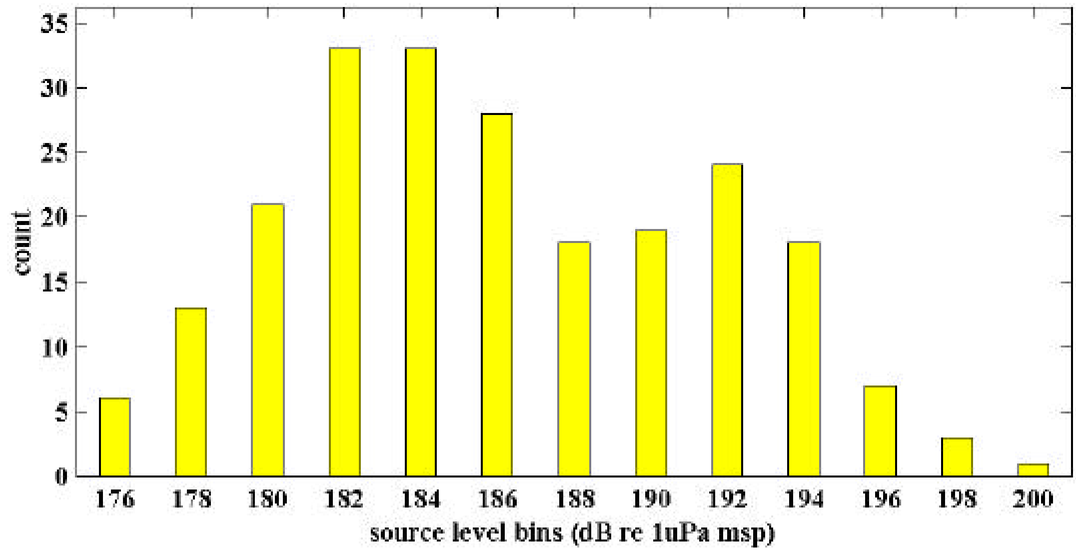

Figure 23: Distribution of '*possible*' source level estimates of the type II component.

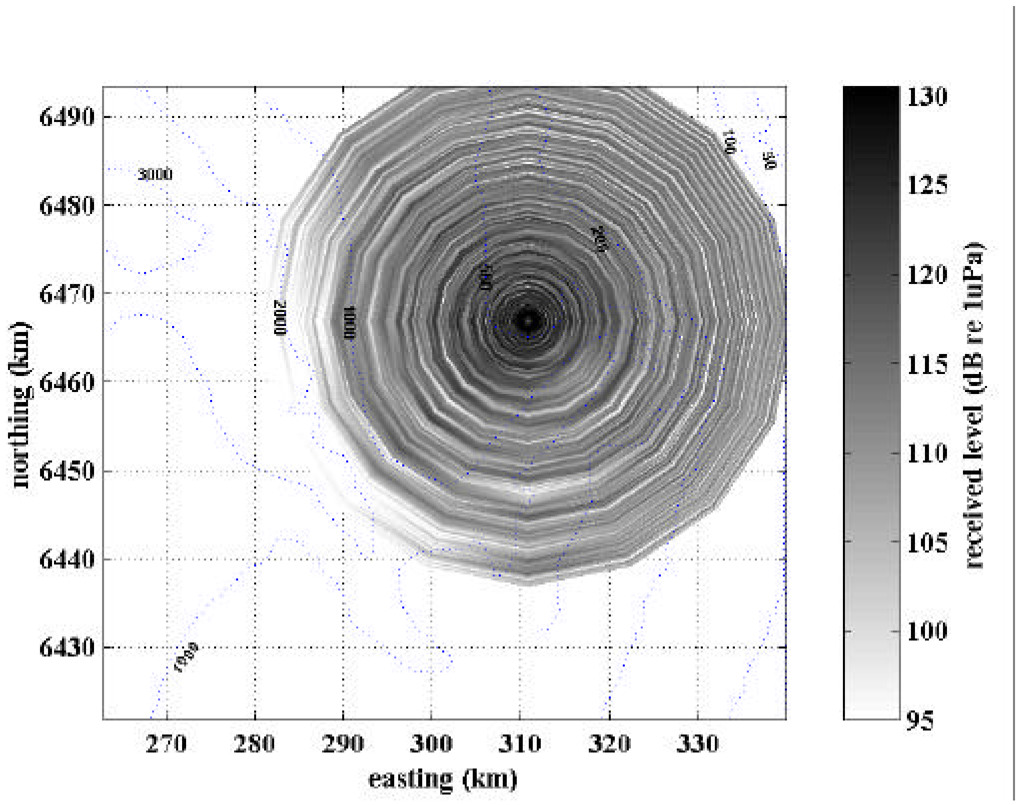

Figure 24: Predicted blue whale type II component level from the *bluey* logger site using a 75 m deep Leeuwin current and a 40 m source depth.

The received type II component level out to 50 km for tracks 5 and 6 (Figure 16) and a 200 m deep Leeuwin current are shown on Figure 25. The level can be seen to oscillate up to 20 dB over ranges of a few hundred meters. This is due to the dominance of the 22-26 Hz tone and its subsequent multipath interference patterns (the calculation were made at 24 Hz, but can be expected to be similar for frequencies within a few Hz). This oscillation presented difficulties in attempting to attribute a received level for this component to an animal at a specified calling range.

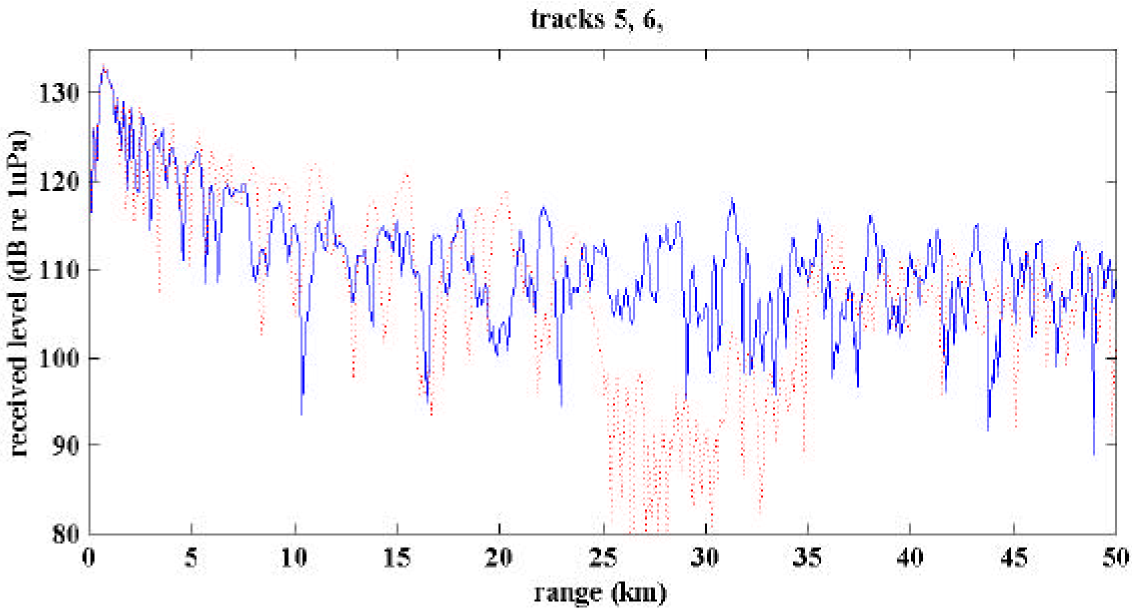

Figure 25: Output of RAM for 200 m thick Leeuwin current, 24 Hz, 450 m receiver, 40 m source and bathymetry tracks 5 (solid line) an 6 (dotted line).

To give a statistical probability that a received level was within some defined range of the *bluey* logger the following steps were taken for each of the eight bathymetry tracks (Figure 16):

- threshold received levels were chosen from 100 to 130 dB re 1µPa in 2.5 dB increments (t_i);
- for each threshold level the ranges at which the RAM predicted received level equalled or exceeded the threshold level were found (r_n);
- for each threshold level the number of RAM range points equalling or exceeding the threshold level (r_n) in 250 m bin increments from 0 to the bathymetry profile length (37-50 km) were found (n_i);
- for each threshold level the cumulative sum vector of n_i was calculated (ie $c_i = \sum_1^x n_i$ where x was the total number of bins or 250 m steps in the bathymetry path length) ;
- and the 95% point of this vector c_i found to give the range within which 95% of all components for the given threshold and bathymetry path occurred.

The resulting curves giving the 95% probability of detection range for the type II component on the eight path lengths for the *bluey* logger site and a 200 m deep Leeuwin current, are shown on Figure 26. Although for several of the paths the detection range for the lower threshold levels is dependant on the total path length used (ie. < 107.5 dB re 1µPa for > 47 km path 5), it is clear that the propagation of these signals to the *bluey* logger site is excellent. This is notable on paths 4, 5, and 6. Paths 4-6 face the opposite side of the trench on headings 135, 180 and 215 degrees from the *bluey* site respectively. Paths 1-4 all run up into shallow water thus the transmission of the 18-26 Hz signal would be expected to at some point drop rapidly, which it does.

The same propagation modelling exercise as described above was carried out for: a Leeuwin current of 75 m thickness, source depth of 40 m: and a Leeuwin current of 200 m thickness and source depth of 20 m. The resulting 95% probability of detection ranges are shown on Figure 27 and Figure 28 respectively.

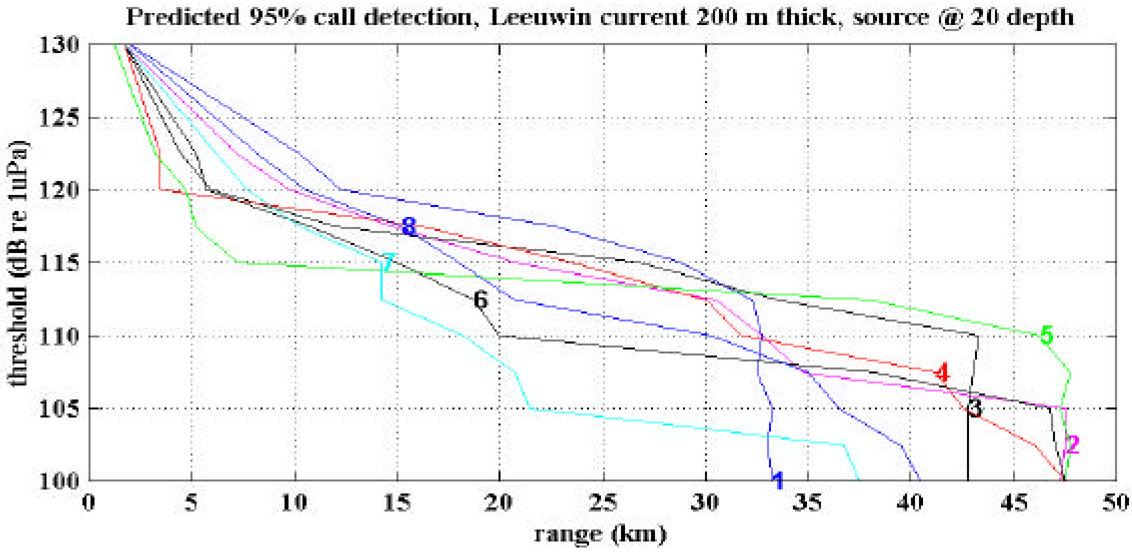

Figure 26: Predicted ranges for the 95% probability of detecting the blue whale type II component from the *bluey* logger site for a 200 m thick Leeuwin current and source at 40 m depth. Numbers represent tracks shown on Figure 16 and run from 1=north in 45^{o} clockwise steps to 8=NW.

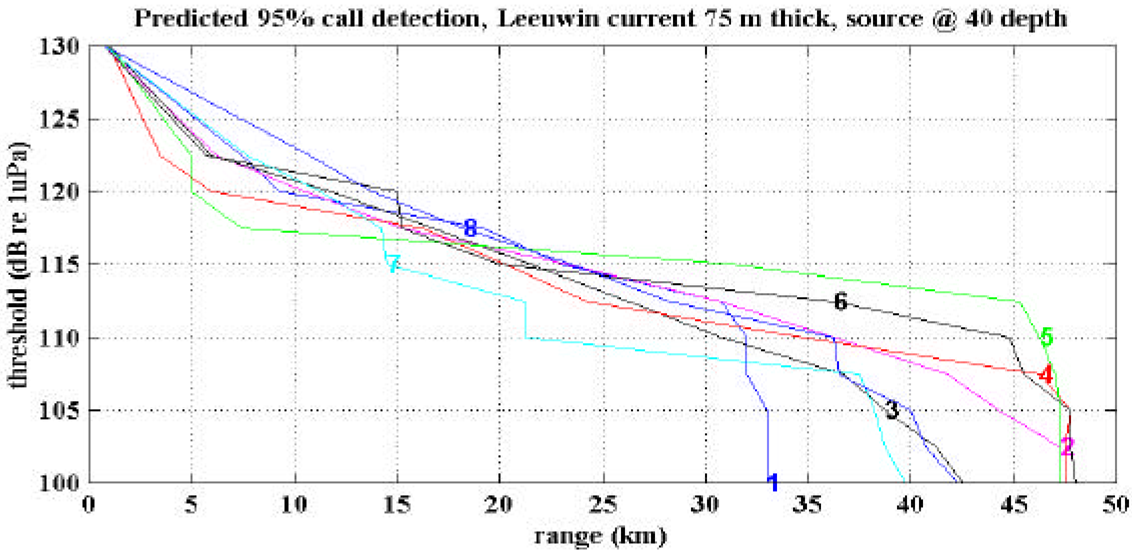

Figure 27: Predicted ranges for the 95% probability of detecting the blue whale type II component from the *bluey* logger site for a 75 m thick Leeuwin current and 40 m depth source. Numbers represent tracks shown on Figure 16.

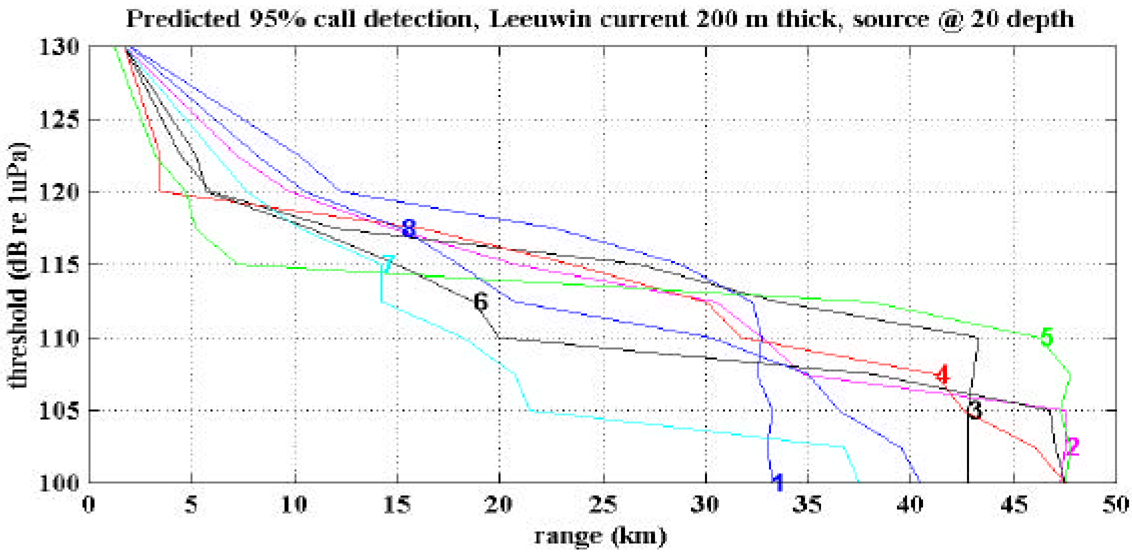

Figure 28: Predicted ranges for the 95% probability of detecting the blue whale type II component from the *bluey* logger site for a 200 m thick Leeuwin current and 20 m depth source. Numbers represent tracks shown on Figure 16.

Changing the thickness of the Leeuwin did not dramatically change the predicted 95% detection range (comparing Figure 26 and Figure 27). Changing the source depth only significantly reduced the propagation from profile 7, or to the west.

Thus the *bluey* logger was effectively sampling all of the Rottnest trench region. Given that type II signals in the range 95-100 dB re 1µPa were measured from the *bluey* logger site, then by extrapolating the trends shown on Figure 26, it is possible that the logger was sampling perhaps 50 km or more to the north, 40 km to the west and perhaps out to 100 km or more to the south of the site.

3.5) Transmission of blue whale calls to drifting site

Drifting sets were made using hydrophones suspended in the water column at mostly 55 m depth. To simplify calculations a central point near the head of the trench was chosen as representative of the location of drifting sets (31° 58' 115° 8', see Figure 2 for the drifting set locations). From this site eight bathymetry paths at 45° increments were determined (out to 50 km where possible). The rationale as used in the *bluey* logger calculations (previous sections) was then used to determine the propagation of the blue whale type II component to the hydrophone. This can be seen in Figure 29.

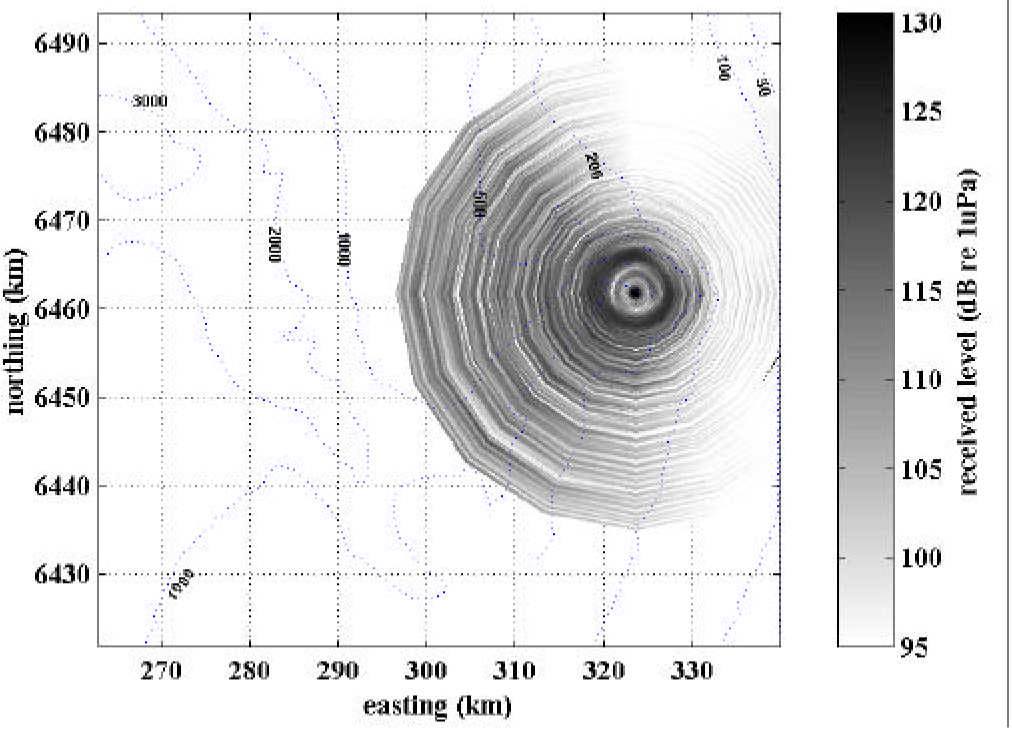

Figure 29: Predicted blue whale type II component level about the representative drifting site (hydrophone at 55 m depth) for 75 m thick Leeuwin current and 40 m source depth.

By comparing Figure 24 and Figure 29 it can be seen that blue whale calls propagated significantly better to the bottomed *bluey* logger than to the shallower hydrophone of the drifting sets. Shading by the trench bathymetry can be seen at the drifting site, with propagation to the west far better than through NE, E to SW.

The 95% probability ranges of detection for the type II component from the representative drifting site, using two source depths and Leeuwin thicknesses are shown on Figure 30, Figure

31 and Figure 32. These also display a much smaller blue whale detection range as compared to the *bluey* logger site.

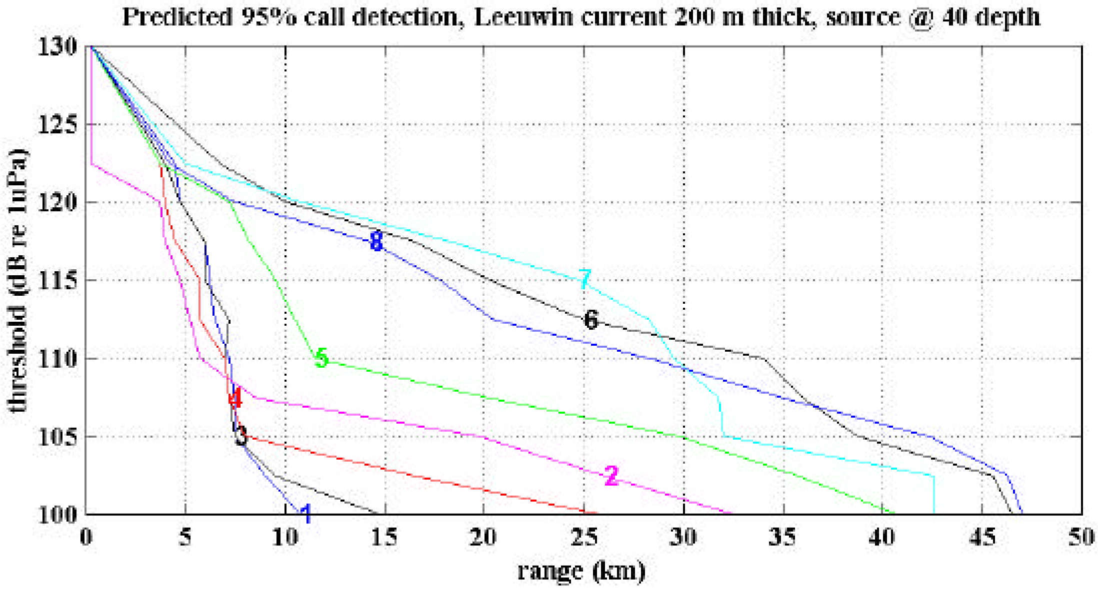

Figure 30: Predicted ranges for the 95% probability of detection of the blue whale type II component for the drifting site, a 200 m Leeuwin current and 40 m source depth. Numbers represent tracks at 45^{o} increments clockwise from north equals one.

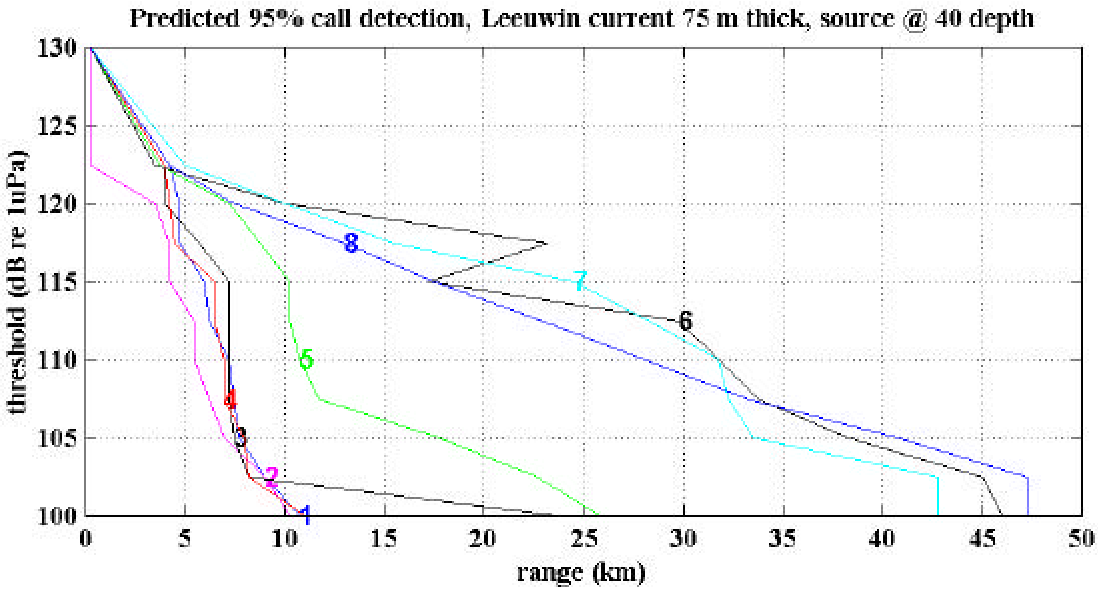

Figure 31: Predicted ranges for the 95% probability of detection of the blue whale type II component for the drifting site, a 75 m Leeuwin current and 40 m source depth. Numbers represent tracks at 45^{o} increments clockwise from north equals one.

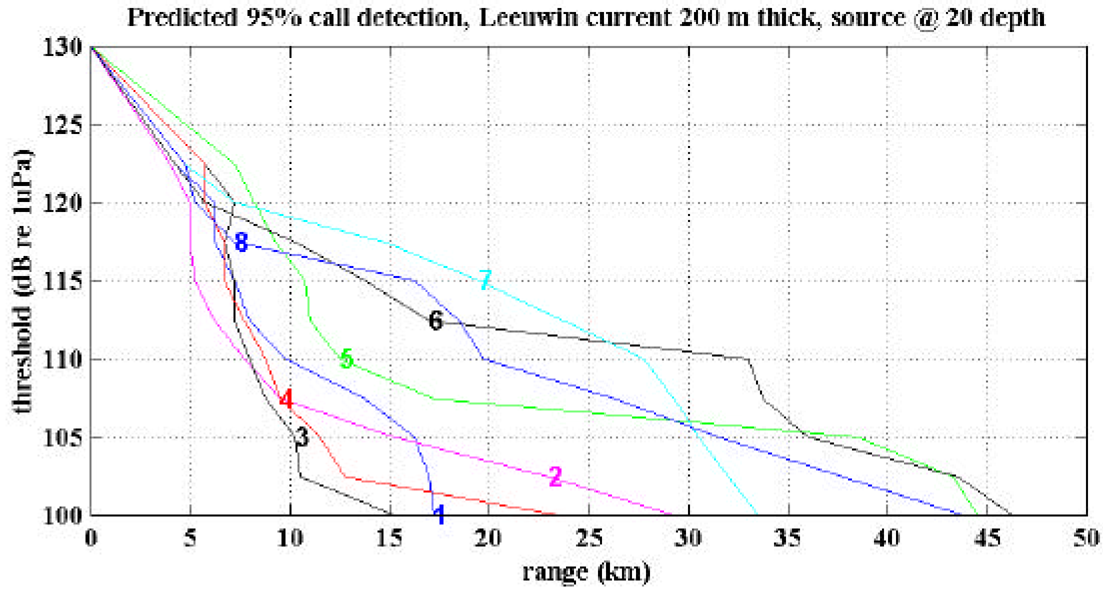

Figure 32: Predicted ranges for the 95% probability of detection of the blue whale type II component for the drifting site, a 200 m Leeuwin current and 20 m source depth. Numbers represent tracks at 45° increments clockwise from north equals one.

3.6) Other signals recorded

A number of other signals, of physical, biological and man-made origin were also recorded. Details of these signals are briefly presented below, with no further discussion.

3.6.1) 20 Hz 'clicking'

A second call type commonly observed was 20 Hz 'clicks'. An example of several click waveforms is shown in Figure 33.

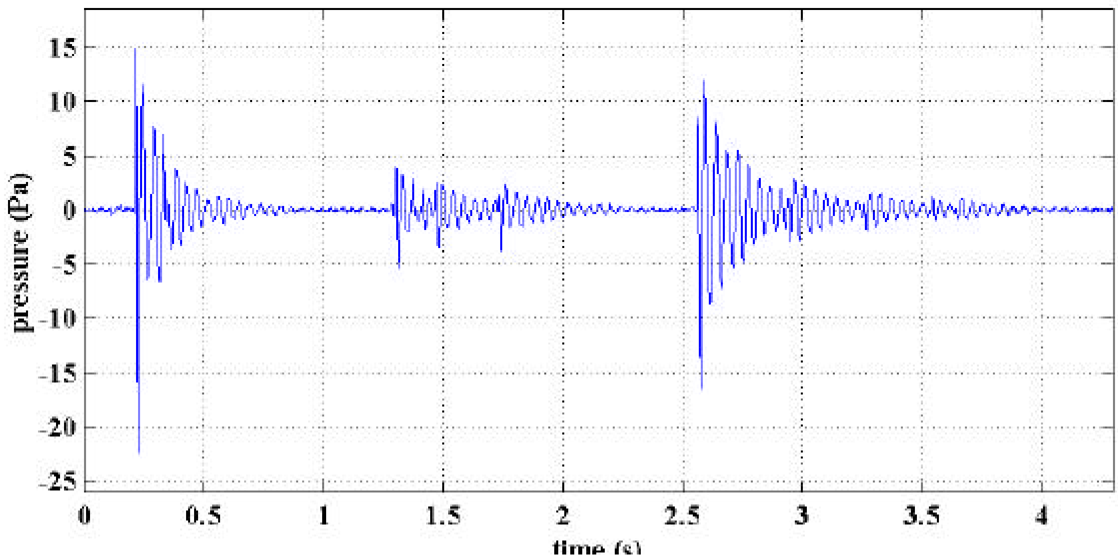

Figure 33: Example waveforms of 20 Hz clicks recorded.

These were common, occurred in bouts of isolated samples to days of clicking and were often recorded at very high levels (up to 153 dB re 1μPa peak-peak). They display several multipath reflections, from which it should be possible to estimate range and depth using an extension of the method described in Cato (1998). For example the middle call of Figure 6 was estimated to be at a depth of 286 m, and 1987 m from the hydrophone using a surface reflected time relative to the direct arrival of 82 ms and a bottom-surface reflected time of 169 ms relative to the direct arrival time and ignoring refraction effects. During clicking bouts and within a 90 s block, signals were received with a wide range of levels and separate clicks had different patterns of multipath arrivals. This indicated that several sources were active and responsible for the clicking.

3.6.2) Air-gun signals

Over some of the period of field trials, January to April 2000, a seismic vessel was working off Dongara to the north. Precise details of the air-gun source, the vessels trackline and operational schedule are not known. Dongara lies approximately 280 km (150 n mile) north along the continental shelf edge. On several occasions the air-gun signals were clearly detectable from the bottomed bluey logger and the drifting sets. An example of a set of signals is shown on Figure 34.

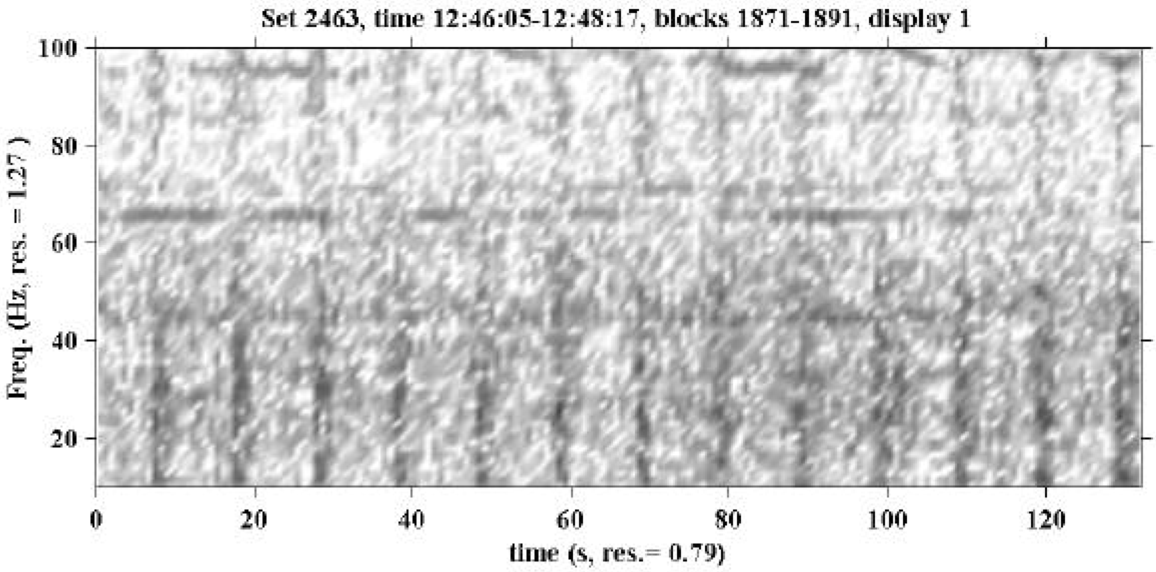

Figure 34: Example spectrogram of sequence of air-gun signals recorded from the drifting gear. The horizontal lines are from a nearby small boat moving about.

3.6.3) Twenty second 125 Hz signal

During a set of the drifting gear on the 29th January, several unknown calls of around 20 s length with maximum energy at 125 Hz were recorded, along with the blue whale tonal signals. An example of this call type, overlying a blue whale call, is shown on Figure 35.

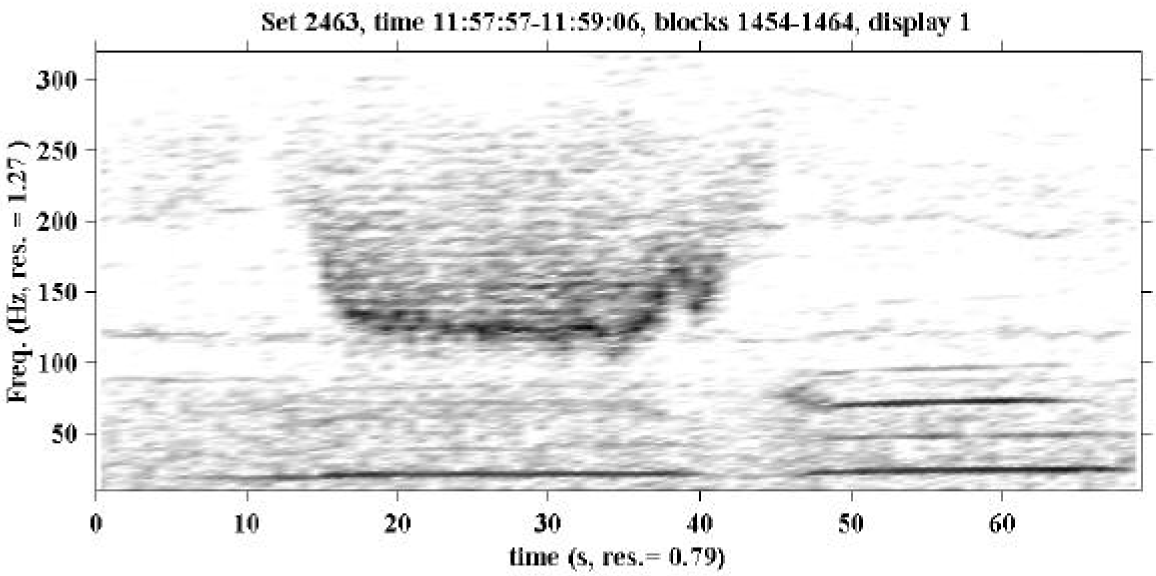

Figure 35: Example of 20 s 125 Hz signal (over 14-45 s and > 100 Hz). The call overlies a blue whale type I component, and some boat noise can be seen as the horizontal bands.

These calls were only heard in this recording session, and not again in any of the drifting sequences or from the *bluey* logger set. The gear was deployed near to a school of approximately 35 Rissos dolphins (*Grampus griseus*) but given the low frequency nature of the calls it was unlikely to have originated from these animals.

3.6.4) Four second 'chirps'

At the time of finalising this report a scaled down series of field trials was being carried out (summer 2001). A set of drifting records picked up a series of high level four second 'chirps', not seen before. Blue whales had been sighted the previous day and were sighted several days later, but not on the day of recording. These recordings had high flow noise as they were taken from a drifting dinghy. An example of this call type is shown on Figure 36.

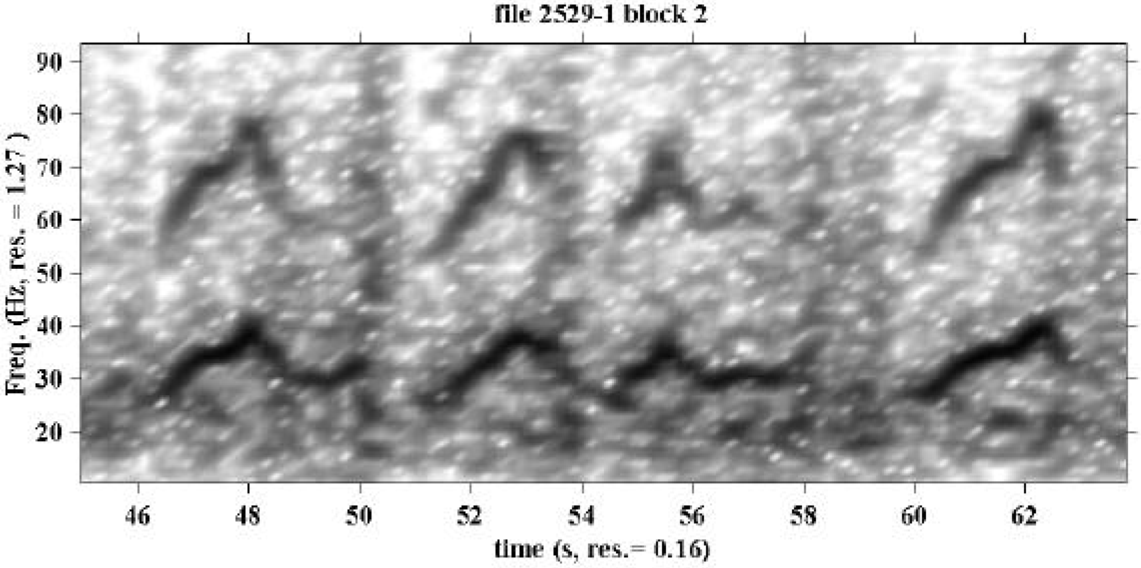

Figure 36: 'Chirps' recorded from drifting set in early 2001.

3.6.5) Dolphin signals

A large proportion of the drifting recordings contained dolphin whistles and echolocation signals. It is probable that the *bluey* logger set also had dolphin signals in it, but these were not looked for and as they were removed in the down-sampling process of the blue whale analysis, would not have been apparent in the searching that was carried out. Several species of spinner (*Stenella* spp.) and the bottlenose dolphin (*Tursiops truncatus*) were sighted in the boat surveys.

3.7) Blue whale call search techniques

Given the precise tonal character of the calls then the possibility of using spectrogram cross correlation techniques, as described by Mellinger and Clark (2000) for bowhead calls, to automate call identification seemed attractive. The 4827 records from the *bluey* recording set presented an enormous and time consuming data set to search for blue whale calls. Two other sets of the *bluey* logger are also available for searching for blue whale calls, 2955 records from off Cape Leeuwin in 1998, and 5069 records from off Exmouth in 2000 (with confirmed blue whale calling in). Automatic identification would allow the accurate placement of components within a record, and thus allow calculation of each component level, a requirement for the acoustic censusing technique using a single hydrophone.

Spectrogram correlation techniques were thus developed using high SNR ratio components to set up kernels, or reference spectrogram signals containing the component structure to be searched for, and correlating these against measured spectrograms. The standard correlation technique multiplied the kernel against the test section then summed the result to give a single value for each time point tested. All calculations were carried out using intensity, not dB values. This technique was sensitive to the normalisation method applied to the test signal, with the best result obtained when the test signal energy was normalised to the total energy in the kernel. The kernel was slid along the test signal, allowing an appropriate overlap at each end (0.4 used). This was done at 1.22 Hz and 0.3 Hz spectrogram resolution. This method gave excellent discrimination for recordings with single components and little background interference. But the presence of a large number of overlapping components in some sequences (with up to nine different callers evident in some 90 s records of the *bluey* logger), the long duration of components (40 s for the type I component) and the presence of large numbers of the 20 Hz clicks (section 3.5), destroyed this techniques sensitivity. Thus the conventional cross correlation technique was modified in an attempt to give an '*all or nothing*' type recognition. The correlation technique developed is elaborated in greater detail, and involved:

- using the *bluey* logger data, with a spectrogram resolution for each 90 s block of 1.22 Hz;
- setting up a reference kernel (K a 2D array) from a high SNR component, or spectrogram section, encompassing only the component section of interest;
- converting the kernel to intensity (K_i) and modifying as required, generally by flattening the high level spikes;
- inverting K_i (multiply by minus one) and normalising by setting the minimum value to zero (nK_i);
- convert the test signal to intensity (T_I a 2D array);
- finding the mean background noise level ($\bar{x}$) and its standard deviation (a) from the test signal T_i at four frequency bands outside of the blue whale call envelope;
- from the test section T_i , beginning at the signal start and sliding along in one time increment steps, extracting n spectrogram sections with the frequency range and length in time of the kernel (T_{i_n})
- for each step in time, normalising the test signal segment by subtracting the mean noise intensity plus one standard deviation ($\bar{x} + a$), inverting this array (multiply by -1) and setting to zero all the positive values, to give nT_{i_n} ;
- subtracting the normalised test signal from the normalised kernel ($nK_i - nT_{i_n}$);
- and finding the minimum value of the resulting 2D array to give a measure of "*how far the kernel dropped into the test signal*" for each step in time, to give a correlation vector corresponding to the time overlay of template and test signal (which was adjusted so that the time value was that in the centre of the test section used).

The technique was akin to setting up the kernel and test signals as a *peg and socket* arrangement, and sliding the kernel signal along until it "*fell*" into a matching hole in the test signal. The resulting vector was then searched for discrete peaks above some threshold (found by trial and error and different for each component) and the central time of the peak use to give the first stage indication of the presence of a component. An example of the kernel and test sections of a correlation appropriately aligned, for a moderate signal to noise ratio signal is shown in Figure 37.

As a second check on the true presence of a component the presence of expected spectral peaks was determined. The returned time from the correlation technique was indexed into the original spectrogram and the spectral peaks found over discrete frequency ranges for each component. The frequency ranges used for the 1.22 Hz resolution spectrograms were 20-24 Hz for the type I component, 20-27 Hz and 68-76 Hz for the type II component, and 16.5-20 Hz for type III component (narrower ranges were used if the 0.3 Hz spectrograms were used). The fall within a given number of points either side of this peak was found and if it exceeded a specified value (4 dB for first spectral peak and 3 dB for second spectral peak) the correlation point was deemed correct.

This gave the presence of a component. To give the number of distinct calling animals within each 90 s block, the number of type II components was counted (since it was not possible for a single animal to produce more than one type II component in a 90 s block) and the number of type II components which fell within 32.5 s of the block start added to this (since a type III component followed around 22 s after a type II component and ran for approximately 23 s, thus a leading type III component indicated a different caller). Type I components which fell in the last 45 s of the block also would indicate a different caller, but were ignored in this version of the search technique as the correlation technique was not tuned for correct type I component identification.

An example plot for a poor correlation, showing the block spectrogram, resulting correlation vectors, and the component presence is shown on Figure 38. In this example the leading portion of the type I component has been falsely recognised as a type III component. This was only a problem for high SNR type I components. The type I recognition was not optimised and has falsely recognised a second type I component.

The technique was run across 4827 records of the *bluey* logger and cross checked against 500 records which were manually counted for the number of callers. The resulting errors of the number of callers manually counted minus the number of callers automatically recognised is shown by the distribution plot of Figure 39. The correct number of callers accounted for 35% of the sample, with the majority of the remaining blocks under-sampled. Reasons for the discrepancies were:

- the leading portion of the type I component being mistaken for a type II component - only an issue for the few high SNR type I components;
- very low component level or SNR - the most common error but not considered important in the acoustic censusing technique described below, since detection was limited on received level to those calls likely to be within the Rottnest trench region only, thus low SNR components were rejected from counting anyway;
- occasional mistake of type II for a particular sequence of close 20 Hz 'clicking' signal (section 3.5) - although this was rare and the algorithm was generally robust in rejecting the clicking signals;
- propagation effects causing pronounced variability in the received level throughout a component (ie. Figure 13) - mistakes here were worst for components with high leading and end sections and low middle sections;
- a particular combination of vessel tones being mistaken for a component - this was rare as it required the right mix of tones;
- propagation effects causing variability in the received level of the different spectral components - there were some blocks where components were rejected as the harmonics were lost due to different propagation of the different frequencies.

It is believed the correlation technique can be improved considerably by several adjustments, particularly by differences in the normalisation methods and varying the relative intensity of component harmonics, so that they play a greater role in the initial correlation.

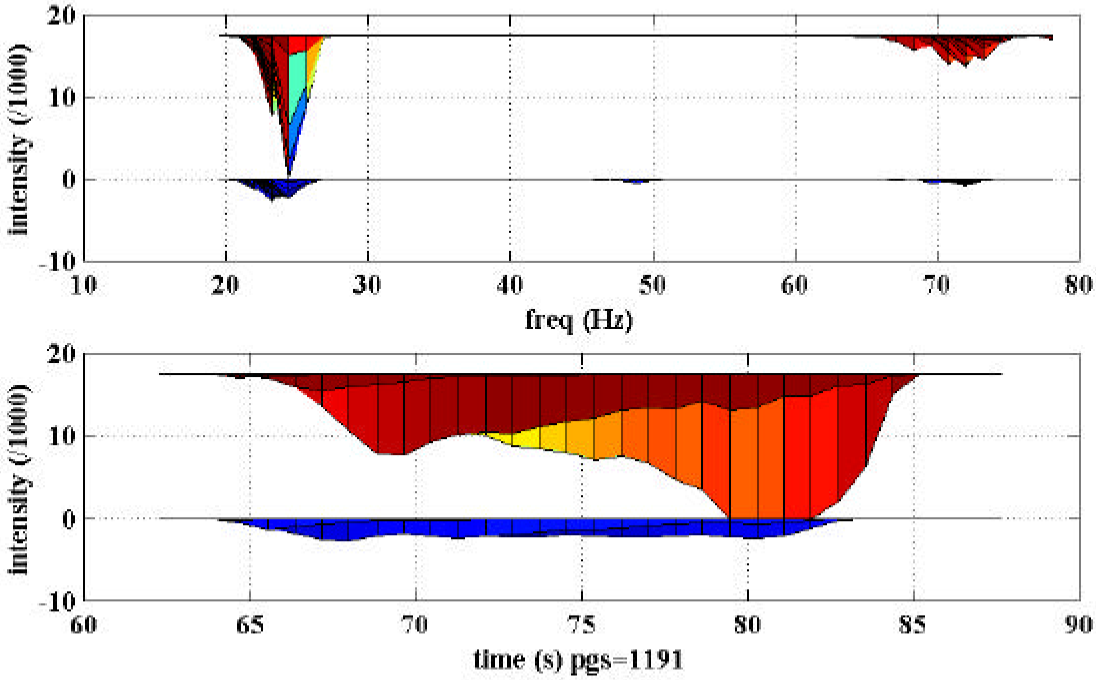

Figure 37: Arrangement of kernel (above zero each plot) and test section (below zero each plot) for correlation technique in block 10 from 62 s onwards, showing fit with frequency (top plot) and time (lower plot). The intensity units are arbitrary.

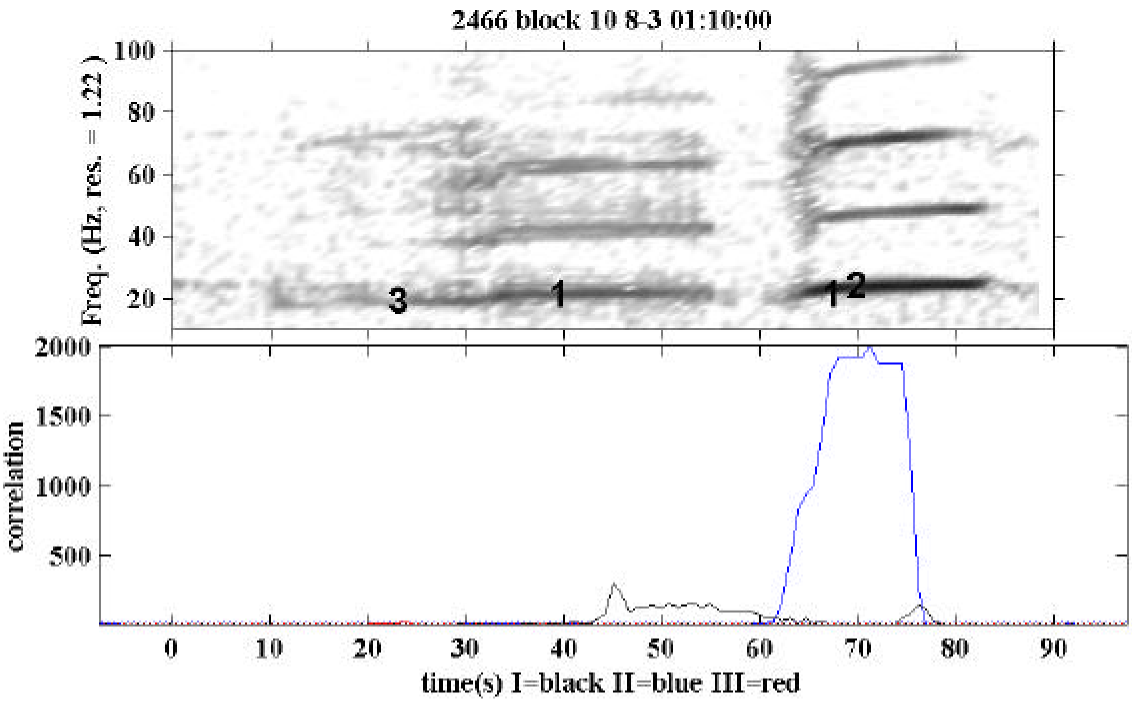

Figure 38: Spectrogram of block 10 showing a type I and type II component, with below the correlation vectors (large peak type II, smaller curve type I) and the presence of components shown by the numbering. Note that the type III identification was falsely scored due to the leading low frequency portion of the type I component, and a false type I score appears.

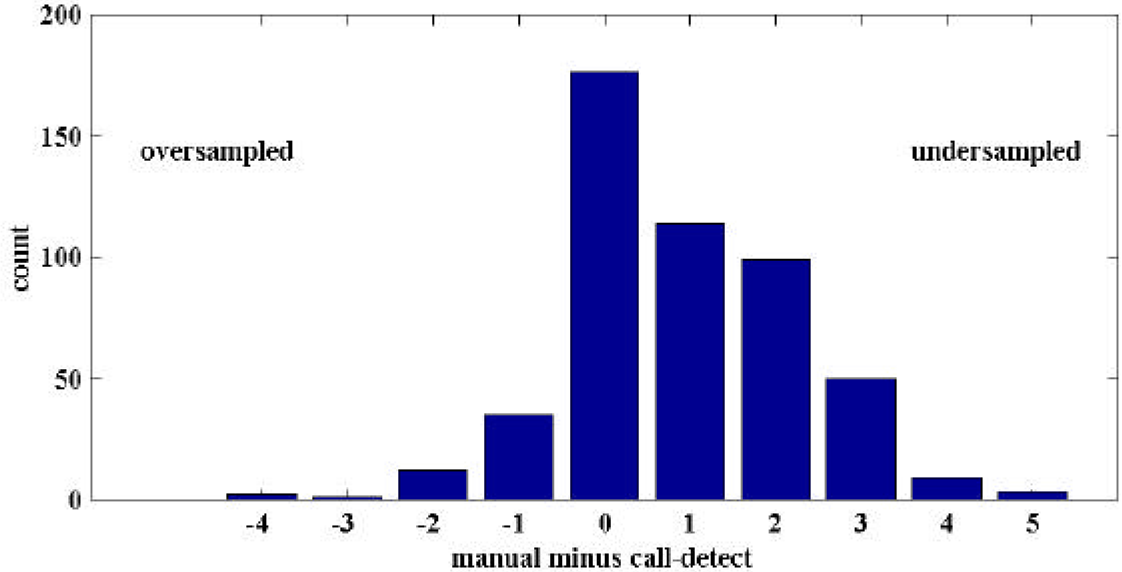

Figure 39: Error between manual count of number of callers minus automatic count of number of callers, for 501 blocks of the *bluey* logger (blocks 500 to 1000).

3.8) Blue whale calling through time:

The presence of calling blue whales throughout the study period from all recording sequences is summarised on Table 4. To correlate this with the sightings made from aerial surveys and boat based studies, the survey effort and blue whale sightings for the visual surveys are given on Table 5. The characteristic blue whale calls were first detected on the 13th of January (sample set 2460 is yet to be worked up) by the drifting gear. These calls were low level (< 96 dB re 1µPa msp) and estimated to be at > 40 km range. Thus they were most likely not in the Rottnest trench region. The first drifting set with calls from animals estimated to be in the Rottnest trench were those of set 2463 on the 29th January where animals within 40 km of the eastern head of the trench were recorded. The number of callers and the received level of the type II component for the 29th Jan drifting set 2463 are shown on Figure 40, from which it can be seen that mostly one, but occasionally two callers were heard and a large break in calling occurred. Blue whales were then sighted consistently by the boat based surveys and aerial surveys (seven sighted on 2nd Feb) throughout February, with the daytime drifting recordings picking up whales within (set 2468, 2469 27-28th Feb) and outside the trench region. The *bluey* logger consistently recorded near and distant blue whales from the day it was deployed (8th March) until the day it was recovered (10th April).

The *bluey* logger set was analysed manually for the number of calling blue whales for the first 998 records (or week 8-14th March). The incidence of vessel passage and the 20 Hz 'clicking' was noted. The level of all blue whale components which could be analysed (no overlapping components, competing shipping or 20 Hz clicking) was obtained, as was the maximum peak-peak level of the 20 Hz clicking for each block with the clicking present. The number of calling blue whales (averaged in 2 hour blocks or 12 points per average), presence of shipping, the maximum peak-peak level of the 20 Hz clicking and the level of the type II components which could be analysed, for this week are shown on Figure 41. The maximum number of calling animals in any given block was nine, although the mean was much less at 2.0 ± 0.10 (mean ± 95% confidence limits). The distribution of the number of callers measured is shown on Figure 42. The number of calling blue whales shows a definitive daily pattern with more calling at night than during the daytime. A power spectrum of the number of calling animals with time showed a strong peak at 24 hours. Using the data from this set then night time calling (over 20:00 - 04:00) was 2.2 ± 0.92 times (mean ± 95% confidence limits) greater than daytime calling (over 08:00 -

16:00) using combinations of mean callers/block for night/next-day and night/previous day. It can also be seen from Figure 41 that the 20 Hz clicking was prevalent, often at very high received levels (near to amplifier saturation) up to 153 dB re 1µPa peak-peak. Shipping noise was present in 27% of the samples of which 14% were qualitatively recorded as 'high' level and the remaining 64% at low or intermediate levels (based on visual comparison of spectrogram intensity only).

Table 4: Details of recordings made and presence of blue whale calling. Abbreviations or superscripts are: 1 - finish date given only for sets with repetitive sampling as opposed to a single drift sample (see Table 1); 2 - for sets 2459 and 2466 times are start time of first and last sample respectively; C, M, D - close, medium, distant, respectively.

Set #	**date start finish**[1]	**useable time start / stop**[2]	**blue whale calls**	**# blue whale callers**	**air-guns**	**Notes**
2456	10-Jan	09:20-10:58	N	0		ship passage at 3-4 n mile range
2459	10-Jan 12-Jan	12:08-09:56				
2460	13-Jan	09:56-13:15	**Y- D**	1-2		distant blue whale calling only, moderate flow noise
2461	18-Jan	09:17-13:26	N	0		high flow noise throughout
2462	28-Jan	08:38-12:49	**Y - D**	1	Y	distant blue whale calling only, faint air-gun signals
2463	29-Jan	09:21-13:25	**Y - C**	1-2	Y	1-2 blue whale callers, one relatively short range, several large breaks in calling, air-gun signals increase towards end of tape, believed calling from Rissos dolphins heard
2464	12-Feb	13:27-16:05	**Y - D**	1		Only few calls of single distant blue whale evident, much flow noise, distant air-gun signals
2465	14-Feb	08:26-11:55	**Y - D**	1	Y	Single blue whale fades in and out at maximum range, distant air guns sometimes evident, moderate flow noise
2467	17-Feb	08:23-09:00	**Y - D**	1-2	Y	Two blue whales at range, very faint air-gun signals
2468	27-Feb	09:12-12:38	**Y - M**	1-3	N	Whole section contaminated with nearby shipping noise, difficult to recognise blue whale calls although three evident at one point
2469	28-Feb	09:34-13:45	**Y - M**	1-4	Y - F	One to four separate blue whales, ship passage and high flow noise make much of record difficult to discern callers
2466	8-Mar 10-Apr	00:10 - 12:30	**Y - C/D**	1-9		Large amounts blue whale calling and 20 Hz 'clicks' over 5 weeks of deployment, some air-gun signals
2470	13-Mar	12:20-13:00	N	0	N	No blue whale calling, no air-gun signals

The automatic call counting technique (section 3.7) was then run over the 4827 records. The resulting count of the mean number of callers (averaged in six hour blocks with 95% error bars shown) for the entire deployment (8th March to 10th April) is shown on Figure 43 along with the sighting data for overlapping boat surveys. This analysis returned calling statistics for the 4827 x 90 s blocks over the 33 days of deployment of:

- minimum number of calling blue whales of zero / 90 s block
- maximum number of calling blue whales at eight / 90 s block
- mean number of callers per 90 s block of 1.02 ± 0.03 (95% confidence limits)
- mean number daytime callers per 90 s block of 0.74 ± 0.16
- mean number of night time callers per 90 s block of 1.06 ± 0.18

Again a strong day-night pattern in calling is evident, with the night time number of callers 2.2 ± 0.60 (mean ± 95% confidence limits) times greater than daytime calling (calculated as per the manual counts). This is identical to the manual count trend for the first weeks data.

Table 5: Details of sightings from aerial surveys and boat based observations over early 2000 (based on Bannister and Burton 2000 for aerial surveys and data of C. Jenner for boat based studies). Time and position only given where blue whale sightings made and data available. The total days search time (hours) is given in brackets. A dash in the blue whale count column represents none sighted.

Date	**time**	**method**	**position**	**number blue whales**
06 Jan		aerial survey (3:24)		-
11 Jan		boat (7:00)		-
13 Jan		boat (6:28)		-
18 Jan		boat (7:36)		-
21 Jan		boat (3:53)		-
28 Jan		boat (9:10)		-
29 Jan		boat (8:21)		-
30 Jan		boat (4:59)		-
02 Feb		aerial survey (336)		**7**
03 Feb	9:25 12:43	boat (10:25)	32.00 3.65 115.00 0.96 32.00 5.23 115.00 0.45	**2** **2**
06 Feb		boat (9:04)		-
07 Feb	13:35 15:33	boat (8:35)	31.00 57.28 115.00 00.00 32.00 0.64 114.00 59.56	**1** **2**
11 Feb		boat (6:03)		-
12 Feb		boat (6:04)		-
14 Feb	10:10	boat (6:45)	31.00 57.70 115.00 2.49	**2**
17 Feb		boat (10:21)		-
13 Feb		aerial survey (3:24)		**8**
24 Feb		boat (4:20)		-
27 Feb		boat (9:15)		-
28 Feb		boat (8:32)		-
29 Feb	12:37	boat (7:48)	32.00 4.99 114.00 58.62	**1**
06 Mar	11:31	boat (5:22)	32.00 5.56 115.00 1.41	**1**
07 Mar		boat (7:15)		-
08 Mar	11:00	boat (7:49)	32.00 3.36 115.00 2.47	**1**
09 Mar		boat (7:13)		-
13 Mar	13:04	boat (9:13)	31.00 59.69 115.00 5.11	**1**
14 Mar	13:38	boat (5:26)	31.00 57.31 115.00 3.12	**1**
20 Mar		boat (8:42)		-
21 Mar		boat (5:13)		-
24 Mar		boat (8:05)		-
29 Mar	10:37 13:51	boat (7:56)	32.00 3.35 115.00 2.97 32.00 2.96 115.00 3.00	**1** **1**
30 Mar	09:59	boat (8:19)	32.00 3.07 114.00 59.48	**1**
06 Apr	14:30	boat (6:56)	32 3.24 115 5.70	**1**
10 Apr		boat (9:01)		-

For comparison the number of calling blue whales per block was similarly analysed for a deployment of the *bluey* logger in 200 m of water west off North West Cape, Exmouth, over the 16th Oct to 20th Nov 2000, and is presented in Figure 44. The presence of calls was verified by checking spectrograms. Only the portion of calling over 10-14th Nov was estimated to be within 30 km, all other calling was at much longer range (extrapolating call transmission from off Rottnest).

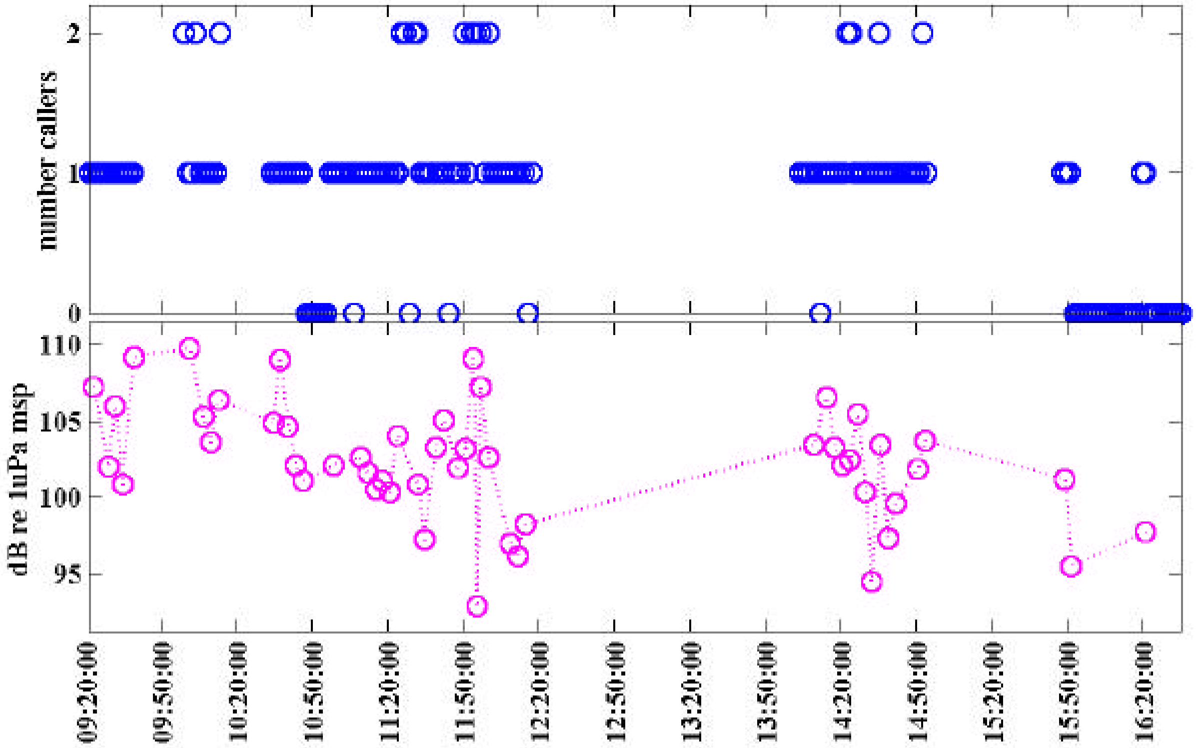

Figure 40: (**top**) Number of callers through time and (**bottom**) received mean squared pressure of type II component through time for recording set 2463 (29th Jan, drifting set).

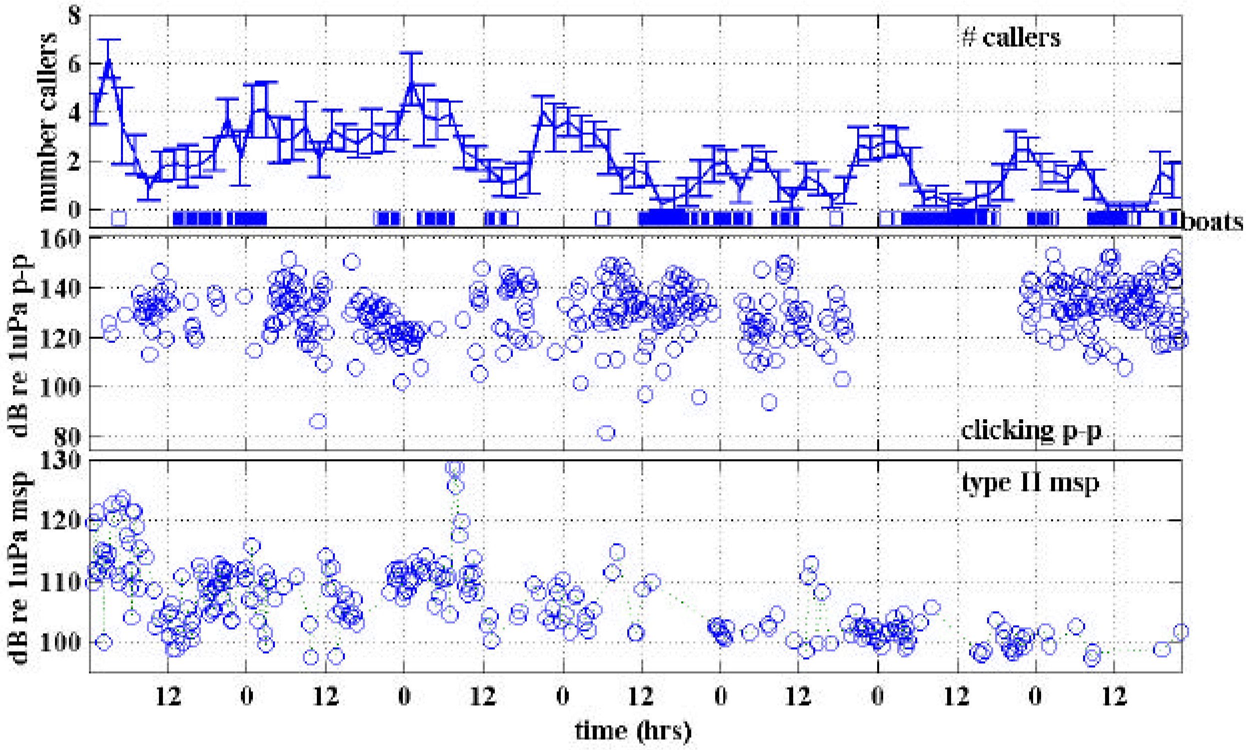

Figure 41: (**top**) For the *bluey* logger set over week 8-14th March, manual count of the number of blue whale callers (12 averages per 2 hour block with 95% confidence limit error bars) with presence of shipping noise (squares), (**middle**) where present, maximum peak-peak level of 20 Hz clicking in block, (**bottom**) received mean squared pressure of type II blue whale component

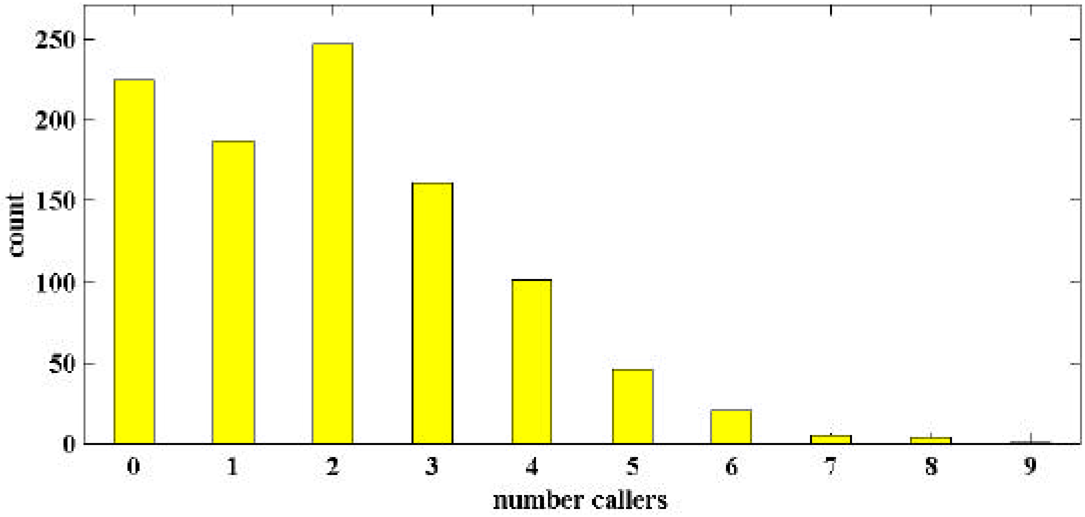

Figure 42: Distribution of the number of calling blue whales per block from 998 manually counted 90 s blocks of the *bluey* logger set.

The automatic search technique located each component within the block. This enabled the level of the call to be determined. For the bluey logger data set, this was done by:

- selecting a section of the waveform from 2 s before to 5 s after the identified component central point (adjusted appropriately if the selected times fell outside the actual times)
- calculating the power spectra of this section at a 0.61 Hz resolution using a Hanning window and no overlap (5 averages for a full seven second section);
- finding the spectral peak within the frequency bands 20-26 Hz or 16-19.5 Hz for the type II or type III component respectively;
- converting the spectral peak level over the selected frequency band to mean squared pressure using the empirical relationship given in section 3.1.3 (type III components were assumed to have the same relationship between spectral level and mean squared pressure as per Equation 1, and from 3.1.2 were assumed to have a 2 dB lower source level than the type II components).

By returning the spectral level over a narrow frequency band the chance of extraneous sources altering the component measured level was minimised. A problem with this analysis was that the received level of many blue whale components varied throughout the component, in several ways (ie. Figure 13). Hence measuring a small section of the component may give a slightly different received level as compared to measuring the entire component. But this error may be expected to be small, and when averaged over many samples of received signals, not significant.

The distribution of calculated type II component mean squared pressure values is displayed in Figure 45 along with an overlaid curve for the received level of an equal number of theoretical blue whale calls, spaced evenly at one km increments in a line from 280 km south to 280 km north with a propagation loss of 15 $\log_{10}$ (range). Assuming the region of the Rottnest trench to be defined as within 40 km of the *bluey* logger site, or ranging from Yanchep in the north to the southern end of Garden Island in the south, then the propagation calculations of the type II component from the bottomed *bluey* logger (ie. 95% probability of detection ranges Figure 26, Figure 27 and Figure 28) suggest that those signals above approximately 110 dB re 1µPa (mean squared pressure) were in the trench region. This assumes:

1. that most animals were located along the shelf edge, or along transects 1 (N), 4 (SE), 5 (S) and 6 (SW) and extrapolates the trend of the 95% probability curve for transect 1 beyond the transect length limitation;

2.   and the type II component call source level was 183 dB re 1μPa mean squared pressure
In reality the type II source level is likely to vary somewhat about this estimate.

Using these assumptions then the distribution of received type II levels (Figure 45) suggests that the majority of calling blue whales recorded by the *bluey* logger were from outside the trench region from ranges probably >> 50 km. Given the excellent propagation to the *bluey* logger site and other workers blue whale source level estimates, then this conclusion seems valid. The form of the distribution shown on Figure 45 for levels > 102.5 dB re 1μPa and its match with a theoretical distribution of evenly spaced sources along a line, suggests that the animals were distributed comparatively evenly along the coastline, that is they were not clumped at any specific site.

The drop in the numbers of received type II calls below the 102.5 dB re 1μPa bin would arise from the search technique not being able to discriminate the low SNR components, and due to natural variability in the ambient noise masking the lower level signals.

Using the predicted type II call propagation, the 183 dB re 1μPa source level estimate, a ≥ 110 dB re 1μPa received level cut off to discriminate calling blue whales within the trench region only (or within 40 km of the bluey logger site), and the *bluey* logger data set filtered to return only callers with received levels greater than this cut off, gave:

- the minimum number of calling blue whales within the trench at zero
- a maximum number of calling blue whales within the trench at five in a 90 s block
- within the trench an overall mean of 0.11 ± 0.1 (95% confidence limits) calling animals per block
- a day time mean number calling animals / 90 s block of 0.08 ± 0.04
- a night time mean number calling animals / 90 s block of 0.11 ± 0.03

These mean values are nine-ten times less than those returned for the full data set (not filtered on received level), indicating that only a small proportion of the blue whale tonal signals recorded by the *bluey* logger were within the Rottnest trench.

The mean value of calling animals per 90 s block may not give an indication of the total number of animals present in a region. Calling bouts may be short, possibly less than the sample increment (10 minutes) or less than the time span used to average samples (six hours in Figure 43 and Figure 44). The maximum number of calling animals per block should give a better indication of the total number of animals within a specified range of the receiver. Thus as an indicator of the minimum population size within a set radius:

- the results of the automatic search routine for the bluey logger data set were filtered to pass only those calls above a received level threshold, which indicated the animals were within the trench region (110 dB re 1μPa for within 40 km);
- and the daily maximum number of calling animals for blocks which fell between 20:00 hours to 04:00 hours found (since more calling occurred at night).

This estimate of the minimum population size within the trench region for the *bluey* logger deployment is shown on Figure 46. The proportion of the total local population of blue whales producing the tonal signals at any given time is not known. It is unlikely to comprise all the animals in a specified area, and may be as low as 10%, as found for humpback whales migrating past Stradbroke Island (data of D.H. Cato), in which case the numbers shown on Figure 46 would need to be multiplied by ten to give a population estimate, to in excess of 50%. The overall descriptive statistics of the maximum nightly numbers of calling animals within the Rottnest trench gave a range of 1-5 callers and a mean 2.24 ± 0.34 (± 95% confidence limits) callers. The aerial surveys sighted up to eight animals per flight in the Rottnest trench over the study period (Table 5). Given that the blue whales have long down times then the aerial surveys are unlikely to have sighted all the animals in the region. Thus the mean of the maximum number of calling animals per day of 2.24, will represent less than 28% of the total number of blue whales within the region (ie. 2.2/8) to give an upper bound to the proportion of blue whales within the Rottnest trench producing the tonal signals.

To give a display of the presence of blue whales through time, the power spectral density of each 90 s sample from the *bluey* logger (10 minute sample separation) was determined at a 1.22 Hz resolution using 219 averages per 90 s (Hanning window), and has been displayed with time on Figure 47 - Figure 51. The presence of blue whales is indicated by the banding at 18-25 Hz, while the 20 Hz clicking shows up as the intense narrow vertical stripes. It can be seen that the two call types dominate the sea noise spectra over this period. The *bluey* logger ran for almost five weeks. Although the degree of calling tapered slightly towards April, the sea noise spectra over the 18-80 Hz band was still dominated by blue whale calling and the 20 Hz clicking at the end of the sampling period, indicating how profuse the calling by blue whales and the 20 Hz clicking source was, and its significant impact on ambient sea noise levels in the region.

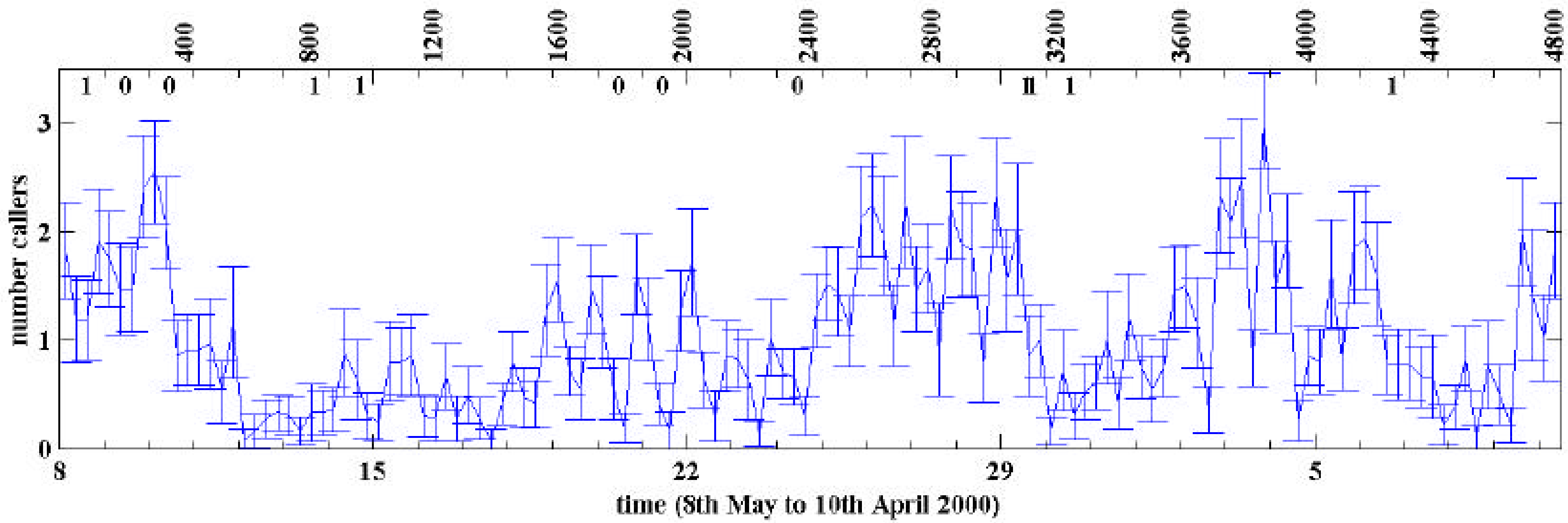

Figure 43: Number of callers averaged in six hour blocks from automatic call recognition, *bluey* logger site. Numbers on upper plot represent boat and aerial survey sightings. Upper scale is block number.

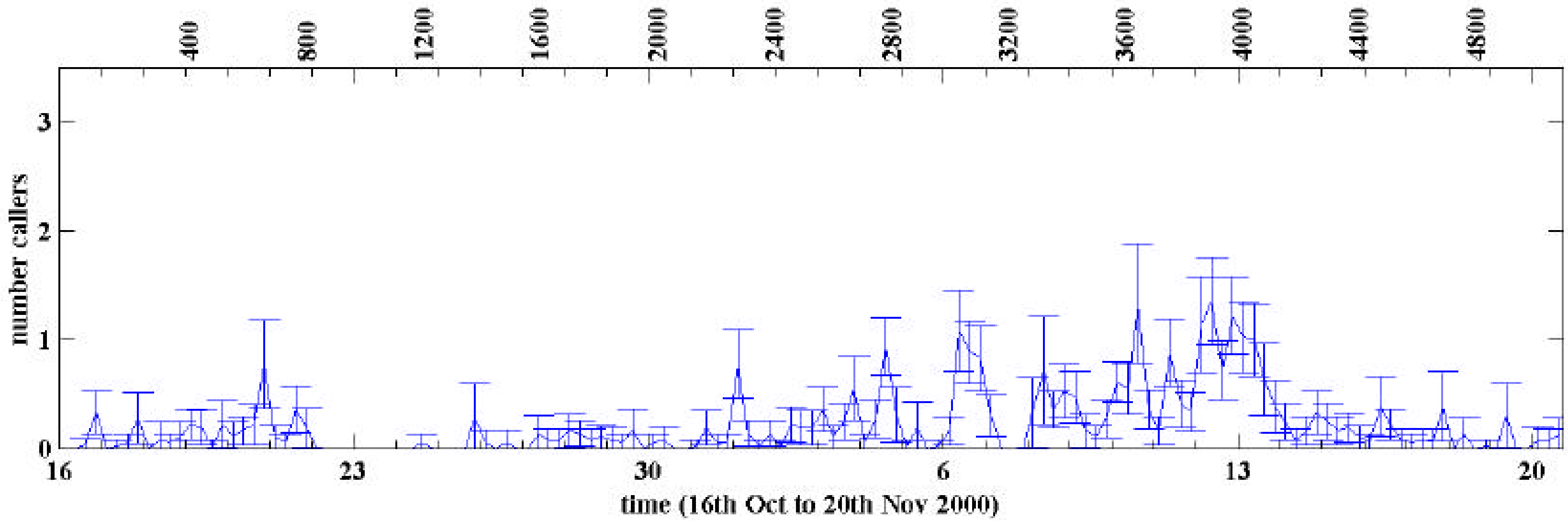

Figure 44: Automatic detection of number of calling blue whales, averaged in six hour blocks for 5069 records for a deployment off NW Cape, Exmouth.

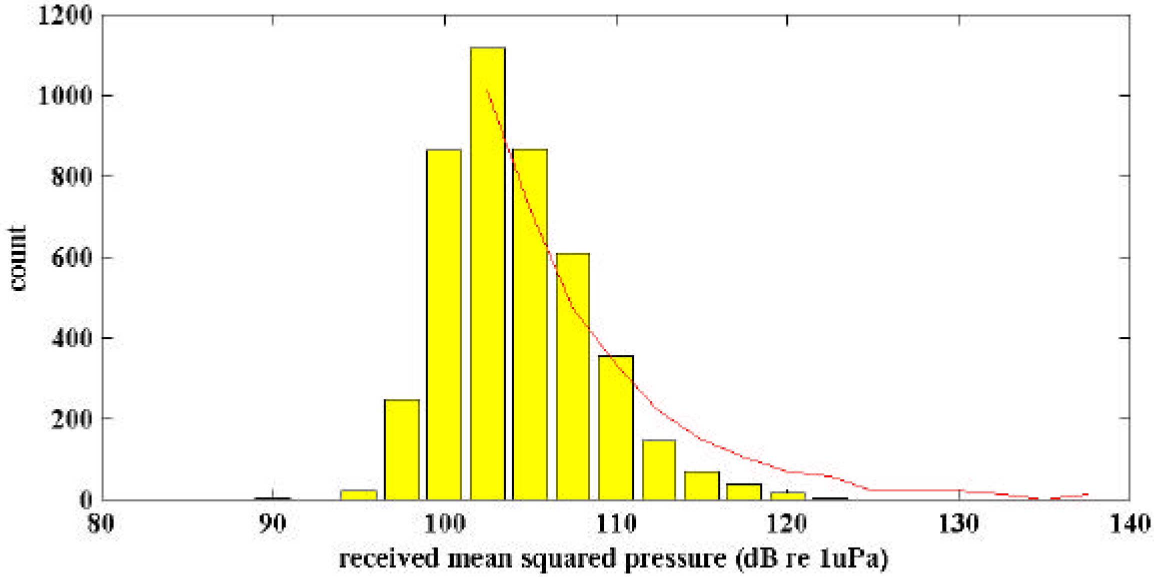

Figure 45: Distribution of the received level of 4363 type II calls (mean squared pressure), from the *bluey* logger data set. The curve is that from a theoretical distribution of sources spaced evenly apart in a line 280 km north-south, with loss 15 log (range).

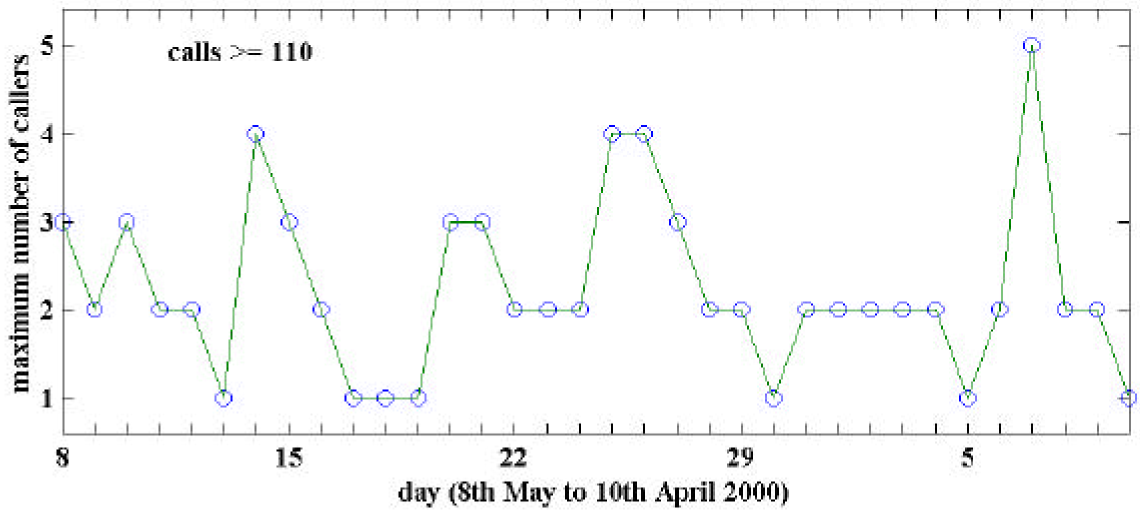

Figure 46: Estimate of minimum blue whale population size in the Rottnest trench from the *bluey* logger deployment.

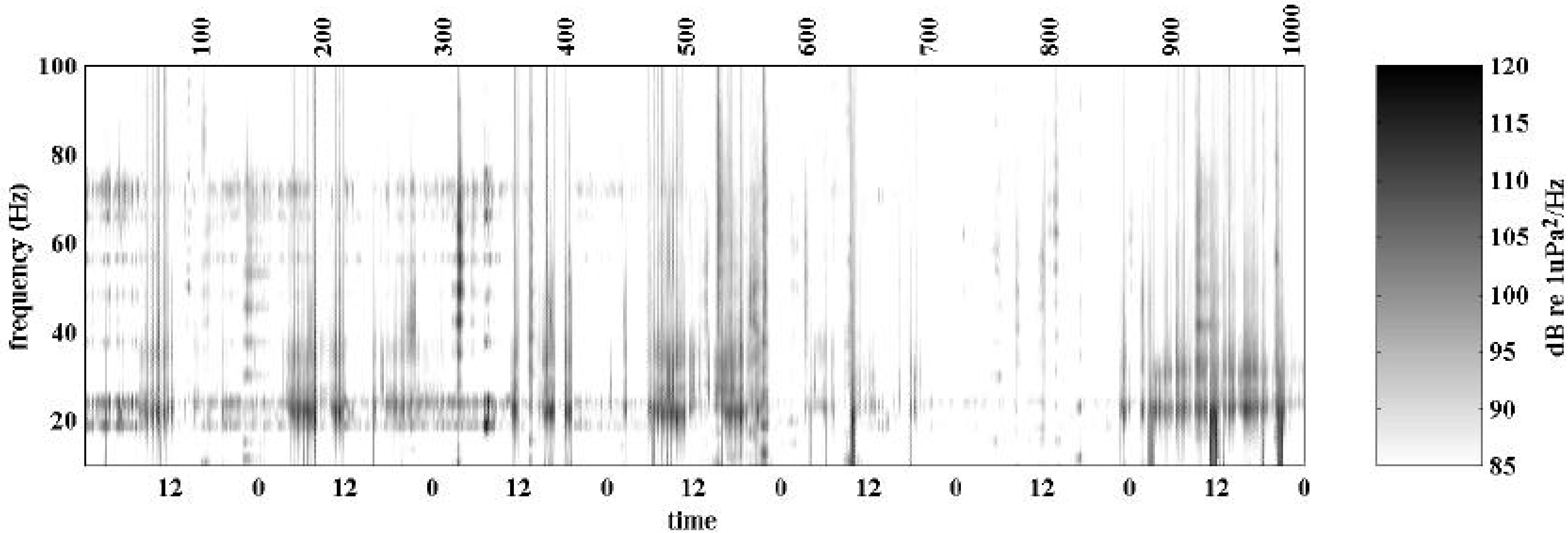

Figure 47: Time averaged spectra (1.22 Hz resolution, 219 averages each 90 s sample, 50% overlap) stacked in time, for week **00:10 8th March to 24:00 14th March** .

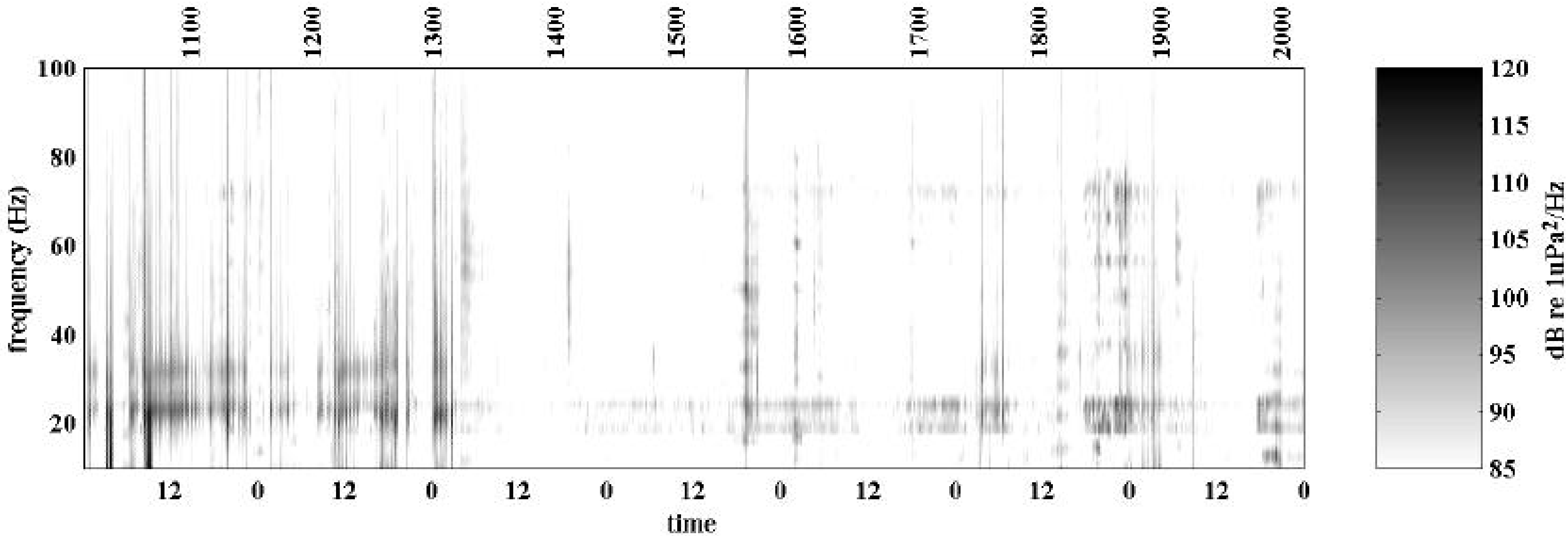

Figure 48: Time averaged spectra (1.22 Hz resolution, 219 averages each 90 s sample, 50% overlap) stacked in time, for week **00:10 15th March to 24:00 21st March** .

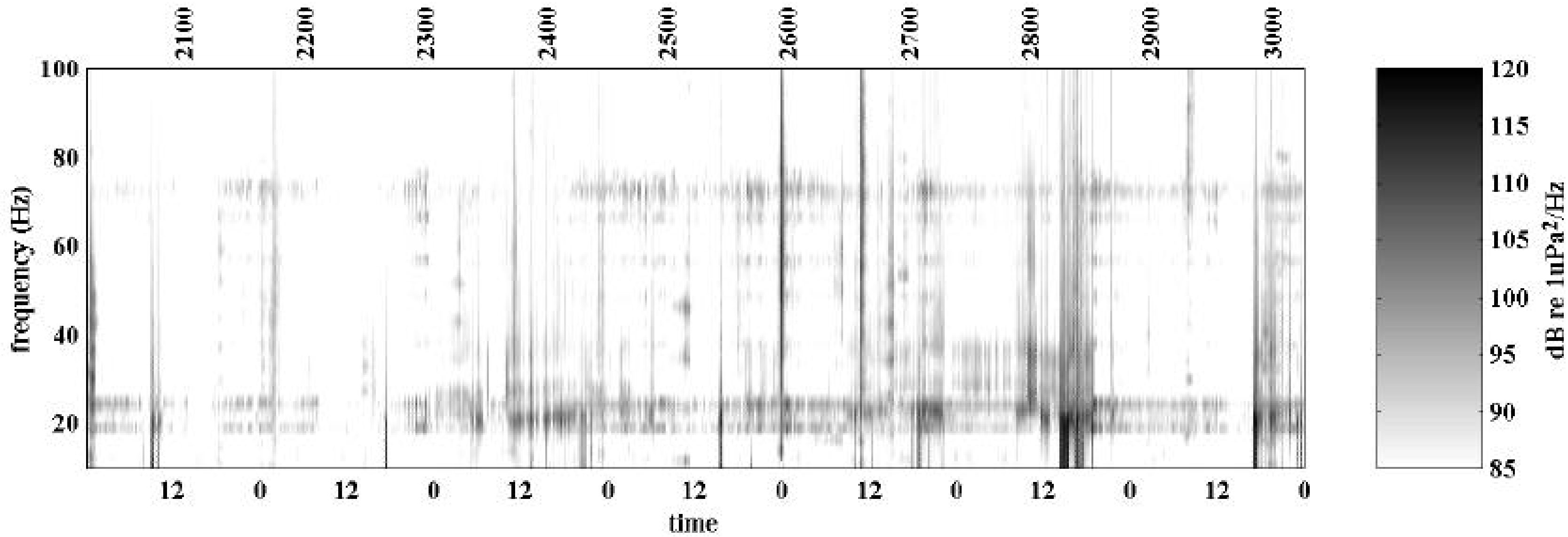

Figure 49: Time averaged spectra (1.22 Hz resolution, 219 averages each 90 s sample, 50% overlap) stacked in time for the week **00:10 22nd March to 24:00 28th March**.

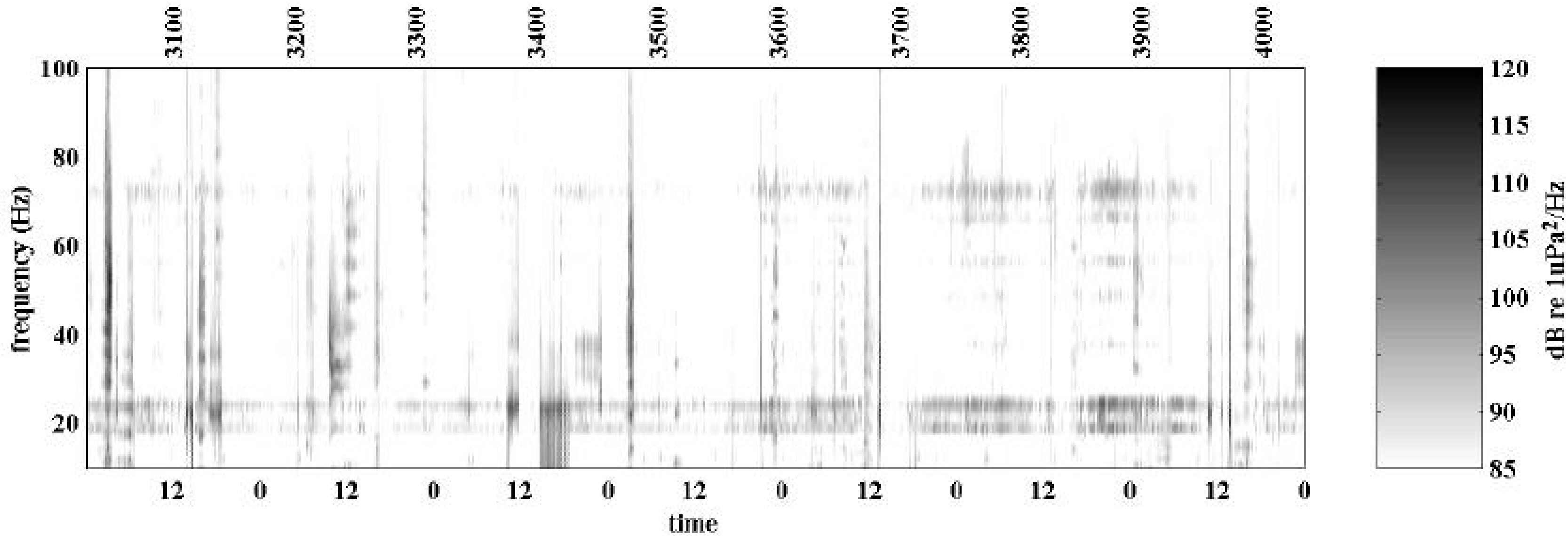

Figure 50: Time averaged spectra (1.22 Hz resolution, 219 averages each 90 s sample, 50% overlap) stacked in time for the week **00:10 29th March to 24:00 4th April**.

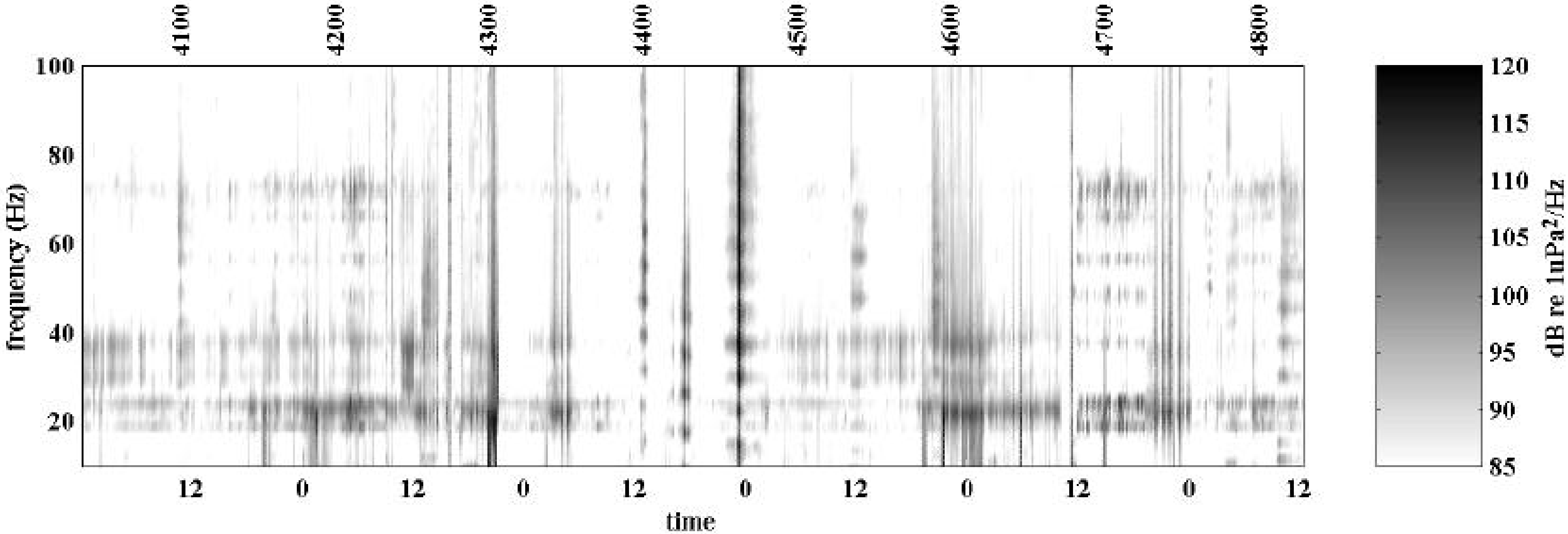

Figure 51: Time averaged spectra (1.22 Hz resolution, 219 averages each 90 s sample, 50% overlap) stacked in time, over the frequency range 10-100 Hz for six days of the fifth week of deployment of the *bluey* logger **(24:10 5th April to 12:20 10th April)**. Note that the logger was recovered immediately after this record.

4) Discussion

A series of three long tonal sounds (components I-III) repeated in a regular pattern, typical of blue whale calls and attributed to them here, plus a 20 Hz clicking signal of unknown origin, were found to predominate in sea noise records made over January to April 2000 in the Rottnest trench west of Perth. Time averaged sea noise spectra over the band 15-100 Hz were dominated by the two call types over this period. Up to nine calling blue whales were evident at a given time in a continual sequence of 4827 x 90 s records, each separated by 10 minutes and made over a 33.5 day period. The 20 Hz clicking signal was unlike any described calls, notably fin whale calls which are similar but always seem to involve a frequency sweep (ie. down-sweeps in Watkins 1981; Watkins et al 1987; or Thompson et al 1992). The 20 Hz clicking did not show any frequency sweep thus the origin of this call type is unknown. The persistent sightings of blue whales in the study area by aerial and boat surveys suggests the 20 Hz clicking call was possibly made by blue whales. Two other low frequency call types, again of unknown origin, were recorded, as were air-gun signals from a geophysical survey vessel some 280 km north, dolphin signals, and identifiable ship noise in 27% of samples.

The presence of multiple blue whale callers in samples was common, although when averaged over all samples from a deep water site with excellent long range propagation the mean number of callers at any given time (a 90 s block in analysis) was only slightly greater than one (1.02 ± 0.03 / 90 s block). Blue whale calling was consistently found to be greater at night as compared to during the daytime, by a factor of 2.2 ± 0.06. This has not been reported for blue whales before, but is consistent with studies of other baleen whale species. For example Watkins et al (1987) found a slightly greater number of fin whale calls at night as compared to day, as did McCauley et al (1996) for humpback whale songs.

On a seasonal scale blue whale calling blue has been shown to have seasonal trends (Stafford et al 1999 from the eastern tropical Pacific, McDonald and Fox 1999 from Oahu, Hawaii) as have 20 Hz sweeps from fin whales (Watkins, 1981; Watkins et al 1987, McDonald and Fox, 1999). The sampling made here was not of long enough duration to show any seasonal trends, although the arrival of blue whales in the trench several weeks after the beginning of the study period suggests that seasonal patterns would occur off Rottnest.

Each of the three blue whale call components was dominated by constant or slowly varying tones, over the range 18-26 Hz, although harmonics up to 100 Hz were evident in all components received at short range. A series of 65-66 Hz pulses were evident in all components, especially so in the third. These pulses seemed to occur independently of the 18-26 Hz tones and were possibly from a separate source within the animal. The multipath field of these pulses was used to localise several calling animals from within 6.2 km range, although identifying the appropriate sets of bounce paths was difficult.

A search routine was developed to automatically identify blue whale call components and this used to count the number of callers and return the received level of components. The search technique was based on a modified version of a spectrogram correlation technique. Problems were found with using conventional cross correlation techniques. These included the long length of signal components, (> 40 s for the type I), many overlapping components (up to nine callers / 90 s), components having similar frequency contents (eg. 19 Hz tone at beginning of type I and 19 Hz tone of type III), the presence of closely spaced 20 Hz clicking, and ship tones. The modified search algorithm used a spectrogram subtraction technique to provide a first identification, which was confirmed or rejected by the presence of the appropriate harmonics. The number of type II components per 90 s block and type III components in the first portion of each block then gave the total number of callers. From the location of identified components received levels of the type II and III components were calculated.

The transmission of blue whale calls towards a position along the shelf edge in 450 m water depth on the northern trench edge, and from a bottomed receiver (*bluey* logger site), was calculated to be excellent. Calculation of the range of calling blue whales from their received level to this site was carried out in this study, but it needs to be cautioned that this technique was fraught with problems. Such problems include a poorly known call component source level and probable variability in this source level (Watkins and Wartzok, 1985). The range of several calling animals was calculated from the mutlipath field of received signals, but propagation variability of the sharp tones which dominated the blue whale calls, was such that the transmission loss could routinely fluctuate 10-15 dB over horizontal scales of 100's of metres. This, and amplitude modulation throughout a component under the animal control, caused consistent observed fluctuations in the received level of a component throughout its 20-40 s duration. The transmission loss fluctuations or differences in propagation along different possible bathymetry paths from the receiver site, was such that small errors in range estimation compounded into a large range of possible source levels in the source level calculations. Neverless an estimate of the source level of the second component type was made, at 183 dB re 1μPa (mean squared or squared *rms* pressure). This component was estimated to be several dB higher in source level than the first and third component of the blue whale call, and resulted in the second component being that most easily observed in spectrograms of received signals from long range. This source level estimate is within the range of published source levels for blue whale calls, ranging from 169 dB re 1μPa (D'Spain et al 1995), 180 dB re 1μPa (Thode et al 2000), to 188 dB re 1μPa (Cummings and Thompson (1971).

Using the transmission loss estimations to the *bluey* logger site and the estimated component source level, it was estimated that calls within 10 dB of the prevailing ambient noise level (around 99-100 dB re 1μPa) had a 95% probability of being greater than 40 km from the receiver, with the lower signal to noise ratio calls possibly emanating from 100's of km north or south along the shelf edge from the site. Received components with received levels equal to or higher than 110 dB re 1μPa were estimated to have a 95% probability of emanating from within the Rottnest trench, which was defined as shelf edge waters 40 km north-south of the northern trench edge.

The distribution of received levels from 4363 type II components, calculated using the search algorithm applied to data from the *bluey* logger, was plotted (Figure 45). Received signals greater than the normal ambient level, for the hydrophone at this depth, (99-100 dB re 1μPa) displayed an exponential decay in distribution with an increasing received level, that is there were far more low level signals than high level signals. The curve of this distribution could be matched by using a theoretical distribution of blue whale calls evenly spaced along the shelf edge. This suggested that the blue whale calling was not concentrated at any particular geographical location, rather was spread comparatively evenly along a large stretch of the coastline. Using the transmission loss calculations and the call source level estimate and applying these as a filter to this data set, suggested that only around 10% of the total blue whale calling received at the *bluey* site emanated from animals within the Rottnest trench.

Two aerial surveys flown over the study period across the Rottnest trench in a large zig-zag pattern, returned sighting data of seven and eight blue whales respectively. The aerial survey technique did not cover 100% of the trench region where blue whales are now known to frequent. As in all aerial surveys for marine megafauna, the speed of the aircraft and the diving pattern of the animal concerned, transpire to bias the sighting data such that sightings represent only some proportion of the real population size over the area searched. This bias factor is currently not known for Western Australian blue whales. Thus the seven and eight sightings from two aerial surveys can be considered minimum population estimates. Using these values and the mean of the daily-maximum number of calling blue whales within the Rottnest trench, (measured at night, as per section 3.8) then blue whale calling from within the trench region will represent somewhere less than 28% of the total population in the area. Given the bias in aerial survey population estimates is likely to be high, with possibly up to less than 50% of animals sighted, then the numbers of blue whale calling (at night) in the Rottnest trench could represent somewhere between 14-28% of the total population in an area. Daytime numbers of calling animals will represent approximately half of these values since daytime calling was 45% (1/2.2) less prevalent than night time calling.

For blue whales within the Rottnest trench region, the low numbers of blue whales calling relative to the total population in the area, suggests that the tonal series of calls may have similar functions as for humpback whales, where only a small proportion of the population, mature males, produce the complex songs (Cato, 1991). Humpback whale songs are believed to be produced primarily in a reproductive context. For the tonal blue whale calls, the almost negligible absorption at the predominant 18-20 Hz frequencies (Fisher and Simmons, 1977), combined with a high source level, seem optimally designed for long range transmission. But as D'Spain et al (1995) and Thode et al (2000) point out, the calls are not produced at the optimum depth for long range transmission. The receiver depth will also play a major role in reception at long range, since a shallower receiver was found to have a much shorter reception range than a deep one. Neverless it is possible that the calls can be heard by other blue whales at ranges in the hundreds of kilometres, and hence may play some role in reproduction by bringing together widely dispersed animals. There may be alternate or multiple functions for such long range calling behaviour, including sharing information on patchily distributed prey.

The fact that blue whales seem to aggregate in the Rottnest trench has now been confirmed. Just why the animals aggregate their is not yet clear. The complex oceanographic conditions set up by the trench crossing the path of the southerly travelling Leeuwin current, and the strong offshore winds experienced in summers may result in localised upwellings around the trench. This would enhance plankton productivity and possibly result in the formation of dense macro-zooplankton aggregations, such as euphausiid krill swarms. Such swarms would maintain the attention of many species of large baleen whales.

The program detailed in this report has used passive acoustic techniques to monitor blue and other baleen whales in the Rottnest trench, Western Australia. The technique is relatively new and is being applied to a poorly studied whale population. Hence there is considerable scope for improvement in techniques and questions regarding the blue whale calling patterns, sound propagation and acoustic behaviour, and relating these to the general ecology of blue whales. A number of these issues, in no particular order, are:

- positive call identifications, which include biopsy sampling for true / pygmy blue whale discrimination;
- 3D tracking of animals using arrays to better describe calling behaviour (possible with 3+ bottom deployed hydrophones);
- accurate source level estimates;
- improvements in search algorithms to locate various call types in large data sets;
- verification of sound propagation characteristics;
- correlation of animal behaviours with acoustic behaviours;
- studies into the interaction of krill and blue whales and extrapolating small scale observations of krill distributions to large scale predictions of blue whale distributions

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