RADIATED UNDERWATER NOISE MEASURED FROM THE DRILLING RIG *OCEAN GENERAL,* RIG TENDERS *PACIFIC ARIKI* AND *PACIFIC FRONTIER,* FISHING VESSEL *REEF VENTURE* AND NATURAL SOURCES IN THE TIMOR SEA, NORTHERN AUSTRALIA

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Figure 1 Photograph of the exploratory drilling rig Ocean General with the rig tender Pacific Frontier standing by (looking from north, off aft port quarter).

ABSTRACT

Between the 21st and 23rd March 1998 measurements were made of the radiated underwater noise from the exploration drilling rig *Ocean General*, the rig tenders *Pacific Ariki* and *Pacific Frontier* maintaining position at the rig for supply purposes, the *Pacific Ariki* steaming at 11 knots and the fishing vessel *Reef Venture* steaming at 12 knots. Measurements were also taken of the local ambient noise with no vessel or rig noise input. The study region was 160 km NNW of the northern tip of Melville Island in the Timor Sea, in 110 m water depth 13 km inside the shelf edge 200 m depth contour.

Over the study period the *Ocean General* was involved in coring work, maintenance of the drill hole and active drilling, with the well head at 3,600-3,700 m. The rig was moored on eight anchors and had no active positioning systems. The major items of machinery aboard the rig were located on decks well above the waterline. The *Pacific Ariki* and *Pacific Frontier* were similar vessels, 64 m length, 5 m draught displacing around 2600 tonnes depending on load, with four main engines totalling 8000 Hp driving through two shafts with fully feathering propellers, and having through-hull, transverse bow-thrusters. The *Reef Venture* was 20 m length, displaced 20-30 tonnes and had a single main engine of 450 Hp.

Conditions were almost dead calm during the study period thus there was little masking of vessel signatures by wind or sea noise. A broadband ambient level of 90 dB re 1μPa was recorded, this is believed to be close to the lowest level possible in the region. Fish choruses were recorded from Shoals 8 km to the north and south of the *Ocean General* on all evenings sampled. It is believed the signature of these choruses was also evident from immediately astern the *Ocean General*. Dolphins were heard in many recordings from short and long range from the rig.

The noise produced by the drilling rig emanated from three sources. The quietest period was the rig working but not drilling with the tender on anchor. During this period the primary noise sources were from mechanical plant, discharged fluids, pumping systems and miscellaneous banging of gear on the rig. As the main machinery deck of the rig was well above the waterline the overall noise level was low, the near field corresponded roughly to the rig dimensions, and the highest broadband level encountered was 117 dB re 1μPa at 125 m from the wellhead. Various tones produced by machinery can be seen in the spectra of this noise. Under this operating condition and the calm sea conditions encountered, the rig noise was audible for 1-2 km.

The second noise source involved the rig actively drilling and the rig tender on anchor. The drill string produced dominant tones, notably in the 31 and 62 Hz 1/3 octaves. The drill string was considered to be a vertical line source some 3.8 km long comprising a steel tube (drill string) rotating in a steel (in water) or concrete (subsea) casing. Thus two sources were active, the rig itself and the drill string. A sharp near-far field transition was observed at around 400 m. While drilling and at ranges of less than 400 m from the wellhead the drill-rig noise dominated, so that measurements matched those of periods when the rig was not drilling. Beyond 400 m significant energy from the drill string tones became apparent resulting in an increase in the received noise level. For the rig drilling, the highest noise levels encountered were of the order 115-117 dB re 1μPa at 405 and 125 m respectively, with the rig audible out to 11 km.

The third noise source, which far exceeded the previous two, involved a rig tender standing by the rig for loading purposes. The tenders stood off the port or starboard side on a bow anchor, kept the main shafts spinning with the propellers feathered, and applied pitch to the propellers and activated the bow thrusters as required. Strong currents were experienced in the region, these caused the skippers to

almost continually apply bow and main shaft thrust to stop the vessel laying off. The use of the thrusters or main propellers under load produced very high levels of cavitation noise. This noise was broadband in nature, with the highest level measured at 137 dB re 1μPa at 405 m astern the rig, levels of 120 dB re 1μPa recorded at 3-4 km and the noise audible at up to 20 km.

The noise of the *Pacific Ariki* and the *Reef Venture* underway was audible out to about 10 and 5.5 km from each vessel respectively, with the 120 dB re 1μPa contour at 0.5-1 km for the *Pacific Ariki* and 250 m for the *Reef Venture*. Each vessel produced a complex mix of machinery and cavitation noise.

Vertically separated and drifting hydrophones, set over the study period, revealed that there were strong differential currents throughout the water column. Temperature, salinity and depth casts suggested that a deep body of colder water may have been creeping up the shelf whilst warmer water flowed over the top, setting in a general NW direction with a local tidal flow superimposed.

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DEMONSTRATION TAPE

Item

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1) INTRODUCTION

Over the period 20th-24th March 1998 the Centre for Marine Science and Technology conducted field work in the vicinity of the oil drilling rig, *Ocean General* located in the Timor Sea, to measure the radiated underwater noise of the drilling rig and its associated supply vessels. The program objectives for these measurements were:

1) Using calibrated systems, quantify underwater noise source-levels of active drill ship and selection of service vessels working permit NT/P48;

2) Measure reduction of drill ship noise with increasing range at several water depths;

3) Measure noise levels of drill ship at Evans Shoal and surrounding bank and un-named shoal approximately 5 nautical miles south of drilling operations;

4) Measure ambient sea-noise at time of sampling from nearby shoal with no rig-noise;

5) As best as possible describe sound propagation at the site;

6) Use noise levels of drill operations, sound propagation and influence of ambient sea-noise to predict noise levels of drilling operations experienced at increasing range from drill rig.

7) Use noise levels produced by drilling operations and available literature on effects of noise on fin-fish to predict possible effects of drilling noise on nearby fisheries operations.

8) Measure biological sea-noise at the site and determine if this is different than expected or possibly influenced by drilling operations noise.

The complete program of work also includes modelling the horizontal propagation of seismic-survey air-gun signals in the region of permit NT/P48. This modelling program is to be carried out separately to the underwater drill noise and vessel noise measurements.

The work described here has been carried out as an extension of the Centre for Marine Science and Technology's current APPEA/ERDC project which is studying the effects of seismic survey noise on marine animals.

This document presents an analysis of the Timor Sea underwater noise measurements and synthesises these results with respect to possible biological effects. For clarity in interpretation the discussion of the noise measurements is included with the results. The final discussion considers the biological implications of the noise produced by the *Ocean General* and rig-tender operations.

To clarify the types and comparative levels of noise described a demonstration tape is included with the report. Where applicable this tape is indexed into the report.

2) METHODS

2.1) Field work / site / environmental conditions

The exploration drilling rig *Ocean General* (*OG*) was moored with eight anchors 160 km (85 nautical mile) NNW of the northern tip of Melville Island in 110 m water depth. Vessel details are given in section 2.4. Co-ordinates of the well-head were: 10^o 2.1' S, 129^o 33.5' E. Water depths were relatively uniform in the vicinity of the rig with a general flat bottom. Evans Shoal lay eight km north of the rig and an un-named shoal referred to as Tasmania Shoal by the local fisherman, lay nine km to the south. The northern edge of the continental shelf (200 m depth contour) lay some 15 km north of the rig's position. Numerous shoals and reefs lay just inside the 200 m contour, extending west of the *OG*'s position.

Over the 21st to 24th March 1998 the vessel *Reef Venture* (*RV*) was chartered to conduct underwater noise measurements around the *OG*. Approximately 560 recordings ranging from 51 s to 4 hours were made in the vicinity of the *OG*. Recordings were made from a 4 m inflatable dinghy (*Nova*), from bottom moored autonomously operating packages (two of), a drifting package set to operate in free run mode, and a moored mid water package operating autonomously. Recordings were made at ranges of from 125 m to 22.5 km from the *OG*.

Locations of the general area, recording sites and CTD cast-positions are shown on Figure 2, Figure 3 and Figure 4 at decreasing scales. These figures are referred to the well head position (zero point) using the method described in section 2.3.2.

Full details of field activities made over the three days on site are listed in Appendix 1.

Weather over the study period was extremely calm. The highest winds experienced aboard the *RV* were less than 10 knots, with 'average' wind speeds of less than 5 knots. Sea conditions were thus calm throughout with a low swell.

The Australian Tide Tables (Anon, 1998) shows Evans Shoal as having diurnal tides, and lists tidal characteristics using Darwin harbour as a primary port. Using the simple tidal predictions given in Anon (1998) the predicted tidal regime over the study period for Evans Shoal is shown on Figure 5. A time of neap tides (predicted maximum tidal range of 1 m) was chosen for the field measurements so as to reduce the chance of encountering strong tidal flows. Flow induced turbulence around any suspended hydrophone and associated cable moored in a current produces pressure fluctuations at the hydrophone. This translates to artificially high measurements of noise, generally at frequencies below 100 Hz. By timing the field work to take place at neap tides it was hoped to largely avoid this artificial noise. As it transpired, over the study period a persistent and strong surface current setting mostly to the NW with sub-surface currents believed to be travelling at different rates and / or in different directions were experienced. Severe problems were experienced with flow / turbulent noise in some hydrophone sets, particularly drifting sets where two hydrophones vertically separated by 50 m were deployed. Differential flow across the 50 m of cable rendered the lower hydrophone recordings in these sets useless for sea-noise work at frequencies below about 150 Hz because of cable and hydrophone flutter. They did provide interesting information on the hydrographic regime of the area though. This is discussed in section 3.3.

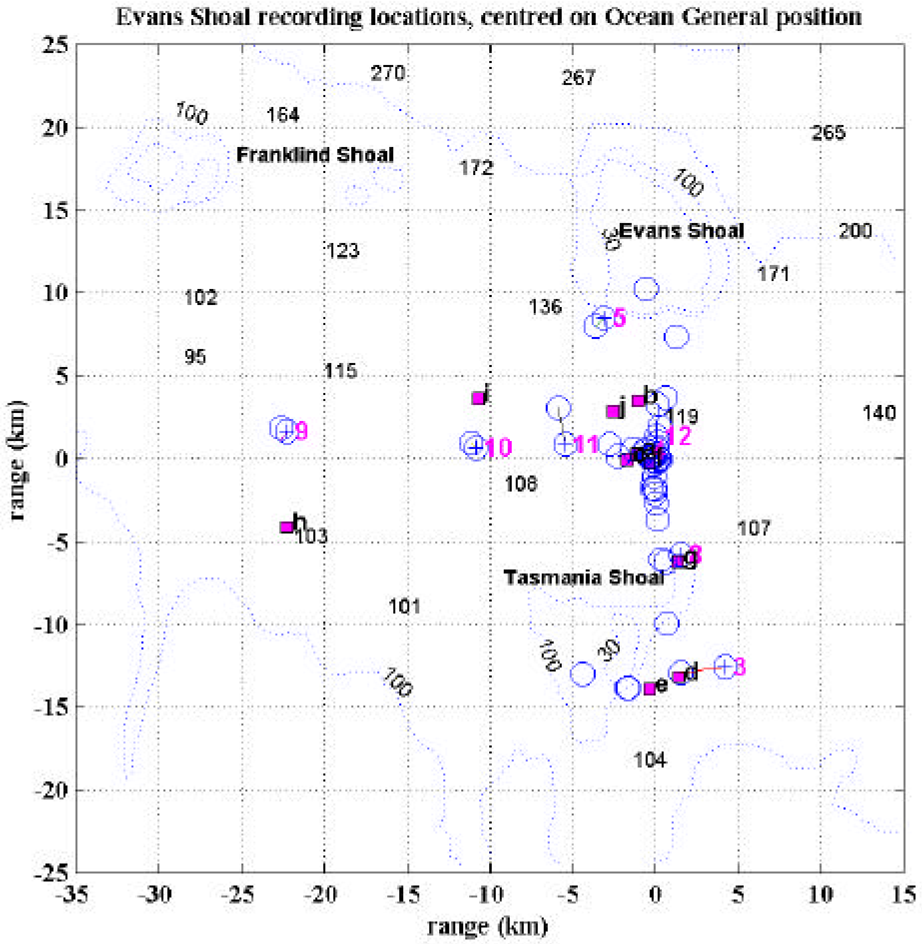

Figure 2: Location of Ocean General noise-study region (north up). This plot is centred on the wellhead location (10º 2.1' S, 129º 33.5' E), or approximately 160 km NNW of the NW tip of Melville Island, north of Darwin. Depth measurements are in m. Recording locations are shown by the open circles. For drifting sets the start location is shown with a cross, the drift shown by the solid line and each site numbered in bold. Locations of CTD casts are shown by the filled squares, with bold letters designating their sequence. The housing 1 location is at the southern end of the Tasmania Shoal 30 m contour. Tasmania Shoal is a local name, given by fisherman to the Shoal south of the Ocean General. Refer to chart AUS 310 for detailed site information.

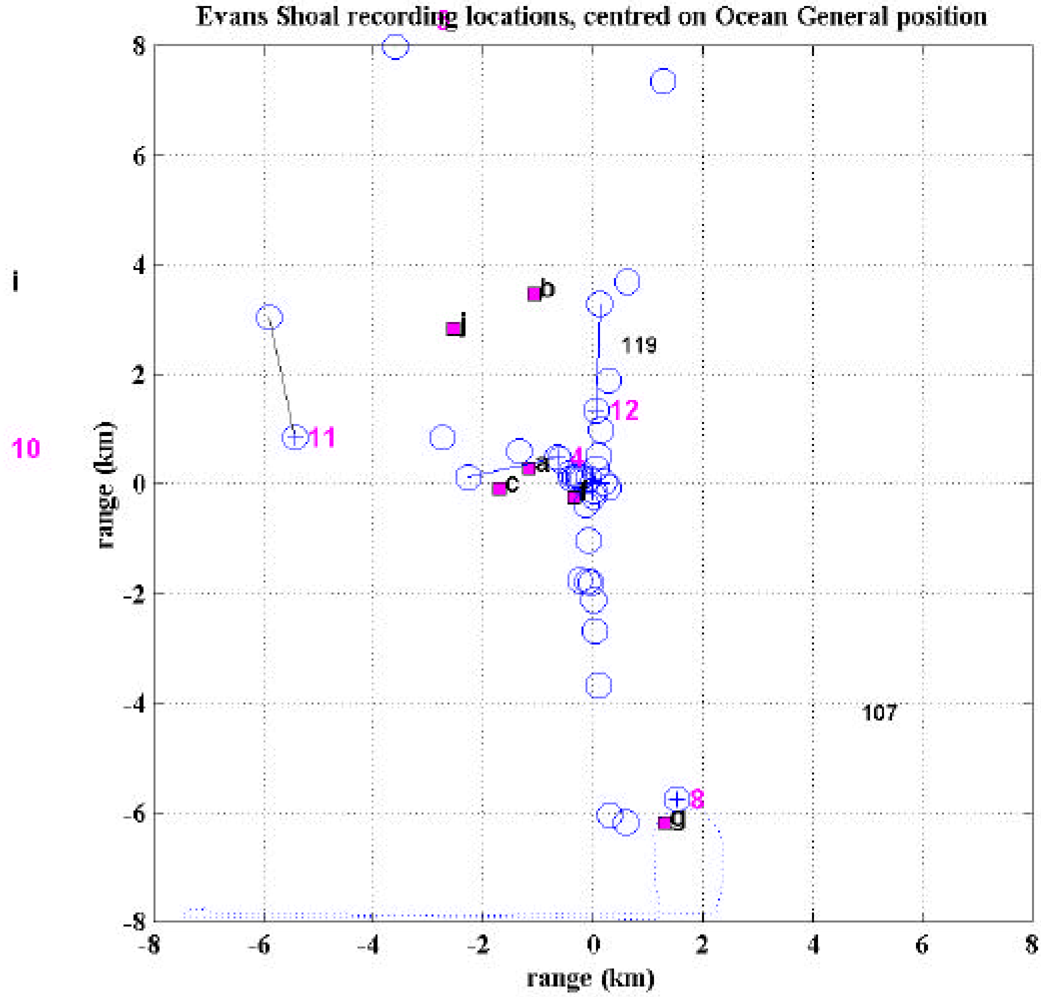

Figure 3: Location of recordings made within an eight km grid centred on Ocean General position (north up). The start of drifting housing sets are marked with a cross, the lines represent the drift track to recovery point. Housing 1a sets are numbered in bold. Set 8, on the N edge of Tasmania Shoal was moored with 60 s recordings every 15 minutes from 18:33 22nd to 08:47 23rd.

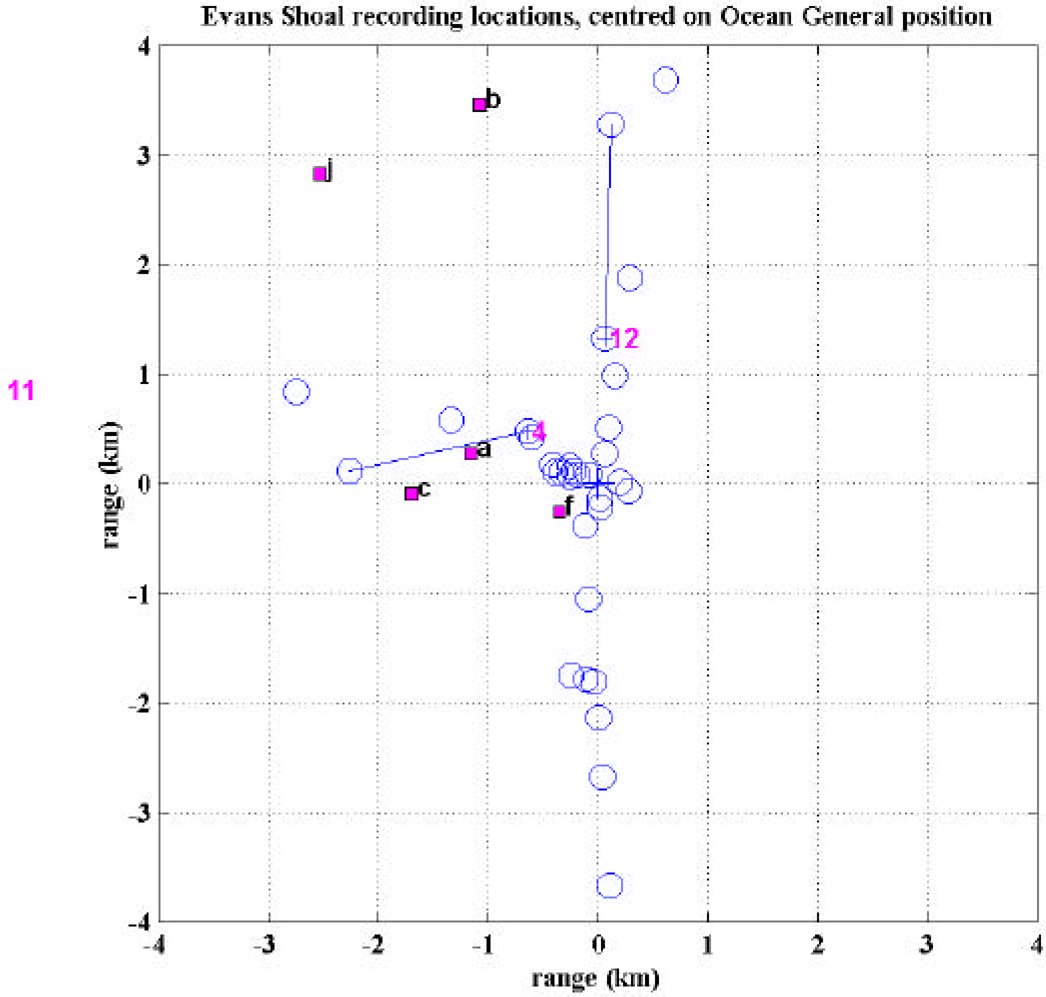

Figure 4: Location of recordings made within a four km grid centred on Ocean General position (north up). The OG was moored on heading 105º. Two successful drifting housing sets were made at short range to the OG. Two consecutive sets of housing two, recording 51 s samples every 10 minutes were made at 450 and 405 m astern (to the west of) the OG over 13:00 21st to 18:30 23rd. A S to N transect towards (from 10 km) and away (to 7.5 km) from the rig was made on the 22nd, and a transect approaching the OG from 22.5 km WNW, was made on the 23rd. Many recordings were made at short range to the OG from all aspects.

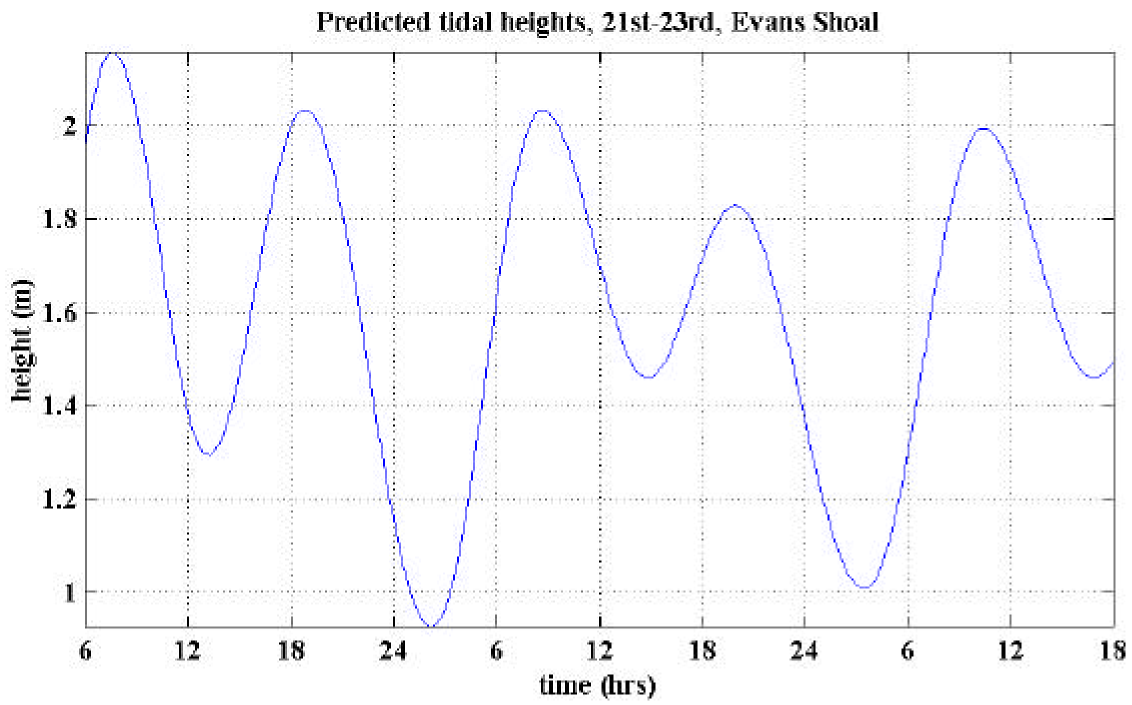

Figure 5: Predicted tidal movements on Evans Shoal based on Australian tide tables (Anon, 1998). It was hoped the comparatively low tidal range would coincide with low water movements over the study period. This was not the case, strong differential current flow was experienced throughout the water column.

2.2) Equipment

2.2.1) Acoustic equipment

All noise measurements were made in very low wind and sea conditions, but in the presence of persistent strong currents. Physical sea noise is very much determined by wind strength. Wind moving over the sea surface creates small wavelets and waves which generate air bubbles or bubble clouds in the surface waters. The implosion of these bubbles or the oscillation of individual bubbles or bubble clouds generates background sea-noise, the level of which is directly related to wind speed (Cato 1997). The persistent calm conditions over the measurement period meant that natural sea-noise levels were low. This created problems in many measurements with little rig or vessel noise input, as the sea-noise often fell below the system electronic noise. This was particularly noticeable at frequencies > 2 kHz in open water measurements. Threshold system noise varied depending on the equipment combinations used. The strong currents also caused problems in many recordings, producing flow or turbulent noise about the hydrophones (discussed further below). This resulted in contamination of the low frequency portion of the spectra (< 100 Hz) for many of the drifting records and selected recordings from the bottom mounted housing 1 on the southern edge of Tasmania Shoal.

Four sets of acoustic recording equipment were used in field measurements. Each comprised a calibrated hydrophone, pre-amplifier and digital tape-deck. Specific details of equipment used are given in table 2.1, while a brief description is:

Portable equipment - Comprised Clevite CH17 hydrophone deployed and monitored from the 4 m inflatable dinghy *Nova* (see 2.4). Always set with 30 m of cable out, with the cable spirally wrapped with fine cord to reduce flow induced turbulence. A drogue was deployed to help align the *Nova* drift with the prevailing current, again to reduce turbulence about the hydrophone and cable.

Housing 1 - comprised an underwater housing with attached Massa TR1025-C hydrophone. The housing was moored in 70 m of water at the southern edge of the shallow section of Tasmania Shoal, so as to be shielded from any noise produced by the *OG* and supply vessels working in its vicinity. The housing and hydrophone were set on the bottom. The unit operated on a timing cycle of a 3 minute recording every 45 minutes from 11:30 on the 21st to 19:30 on the 23rd. Unfortunately this housing was set with 250 m of 16 mm line with ~ 100 m of the line coiled in a bundle at the surface. The strong persistent currents experienced at the site combined with the drag of the bundled line produced large, persistent flutter in the mooring line and some movement of the housing. This produced artificial pressure fluctuations at the hydrophone, making many recordings below ~ 150 Hz of limited value.

Housing 2 - Comprising an underwater housing with an attached Brüel & Kjær hydrophone, operating on a timing cycle of a 51 s recording every 10 minutes. The hydrophone signal was split and recorded with different gains to separate channels of the tape deck. Two consecutive deployments were made at 420 m and 405 m astern of (or to the west of) the *OG* in 113 m of water. In both sets the housing and hydrophone lay on the bottom. A full 250 m coil of 16 mm line led to surface buoys and floats. No flow noise problems were experienced with either deployment.

Housing 1A - Comprised an underwater housing with two GEC-Marconi SH101-X hydrophones attached. This housing was normally drifted with the tape deck continuously recording. The housing was set at 30 m depth with 16 mm line attached to surface buoys and floats. One hydrophone was buoyed 5 m above the housing (25 m depth) with the deployment configuration such that the buoyed hydrophone did not foul the surface line, while the second hydrophone hung 45 m below the housing (75 m depth). A depth gauge recorded the maximum housing depth reached in each deployment. Each hydrophone recorded through individual pre-amplifiers, to separate channels of the tape deck. One overnight deployment was made with the housing and hydrophones set as above, but the surface floats attached to a mooring. In this set the unit operated on a timing cycle of a 60 s recording every 15 minutes. The shallow and deep hydrophones were the same in each set, but they were regularly swapped through the amplifier-tape-deck combination.

The drifting sets were made in the belief that the entire unit would drift with any prevailing current or tidal stream, so minimising flow noise. This was not the case. In all six successful drifting sets (in one set the tape deck failed), the bottom hydrophone recorded high levels of low frequency noise while the top hydrophone recorded much lower levels.

Equipment failure or some real effect were ruled out as possible causes of this noise. No equipment checks with any combinations of equipment before or after field trials revealed any faults, and swapping the hydrophone-amplifier-tape-channel combinations during field trials did not change the results. The levels of low frequency noise recorded by the bottom hydrophone of this housing were consistently high at all sites, far above measurements made at similar sites and times from shallower hydrophones (including the housing's 25 m hydrophone and separate recording packages), and greater than any recorded by the bottom mounted package immediately astern the *OG*. Although a downward refracting sound speed gradient was observed, it is inconceivable that the high levels of low frequency noise would not have been heard in the shallow recordings. Thus this low frequency noise is believed to be the result of the bottom hydrophone being dragged at a different rate and probable direction to the housing and top hydrophone. This would have set up strong fluttering of the bottom hydrophone cable, so producing high levels of turbulence about the hydrophone.

Time bases

All tape decks maintained and wrote to tape a time base. The time bases of a master watch and each tape deck were regularly checked against the displayed GPS time. Central Standard Time was maintained on all time-pieces. Deployment and recovery time and position of each hydrophone set was logged. Using the time bases written to the tapes and GPS or drilling logs, enabled calculations of ranges from drilling rig or vessel as appropriate, or correlations of measured noise with drilling activities.

Calibrations
All hydrophones were supplied with factory calibrations sheets for sensitivity. The sensitivity of the Brüel & Kjær 8104 hydrophone used in the housing 2 sets (immediately astern the *OG*) was calibrated with a Brüel & Kjær type 4223 hydrophone calibrator, and found to be within 0.9 dB of the factory calibration specifications at the pre-set tones of 250 and 320 Hz used by the unit. The sensitivity of the other hydrophones was then checked against the Brüel & Kjær hydrophone.

The frequency response of each hydrophone-pre-amplifier-tape deck combination was determined by characteristics of each component, specifically the pre-amplifier and hydrophone capacitance, the in built tape-deck roll off at low and high frequencies and the hydrophone response. To check the response of each combination in the field, white or pink noise of known level was recorded for each tape-deck-pre-amplifier combination before each set of recordings. White-noise is random noise of statistically equal intensity at all frequencies, while pink-noise is noise of decreasing intensity at increasing frequency such that 1/3 octave analysis (or analysis in steps of geometrically increasing bandwidths) gives equal measures across the frequency spectra. These calibrations were later compared with white and pink noise measurements made with the appropriate hydrophone in series with the pre-amplifier and tape deck combinations. Using the hydrophone in series will give a better description of the appropriate combination of equipment's low frequency roll-off. From the calibrations with the hydrophone in series, and the known sensitivity of each hydrophone, calibration curves for each set of equipment were derived. These are shown in Figure 6 for 1/3 octave measurements. By comparing these curves with calibration curves recorded during the field and as analysed, composite calibration curves were applied as appropriate to each analysis set.

2.2.2) GPS / CTD profiler / Echosounder logs

Position fixing was by: 1) aboard the *RV*, differential GPS system comprising Fugro differential unit using a Garmin 45 GPS and output to two laptop computers; 2) GPS positions manually read from the *RV* navigation system which comprised a Furuno GP 70 MkII GPS interfaced to a Furuno FR 8100-D 48 mile radar and a Furuno GD-188 plotter; 3) in *Nova* at > 350 m from the *OG*, a Garmin 38 hand held GPS; or 4) in *Nova* and at < 350 m from the *OG*, bearing from hand bearing compass and range from Bushnell laser range finding binoculars. Despite almost ideal conditions and a good sighting target (the *OG* legs, shipping containers or huts on deck), the Bushnell binoculars could only locate the *OG* at < 350 m. Laser range sightings off the *OG* were reduced to ranges from the wellhead using the *OG* deck plans. The *RV* differential GPS position was continuously logged to computer at a 2 s output rate. The Furuno and Garmin 38 readings were manually read off the GPS or radar unit.

A system for logging echosounder returns was installed in parallel with the ships Furuno 292 echosounder transducer. The 50 kHz transducer outgoing and returning pulses were continuously monitored by the EchoListener system (SonarData Tasmania Pty. Ltd.) and logged to laptop computer along with the *RV* differential GPS co-ordinates. Where required, water depths have been recovered from the stored echo sounder pings.

Temperature, salinity and depth profiles were made with a Marimatech (Denmark) HMS 1820 CTD profiler. This unit was calibrated at Curtin in early March.

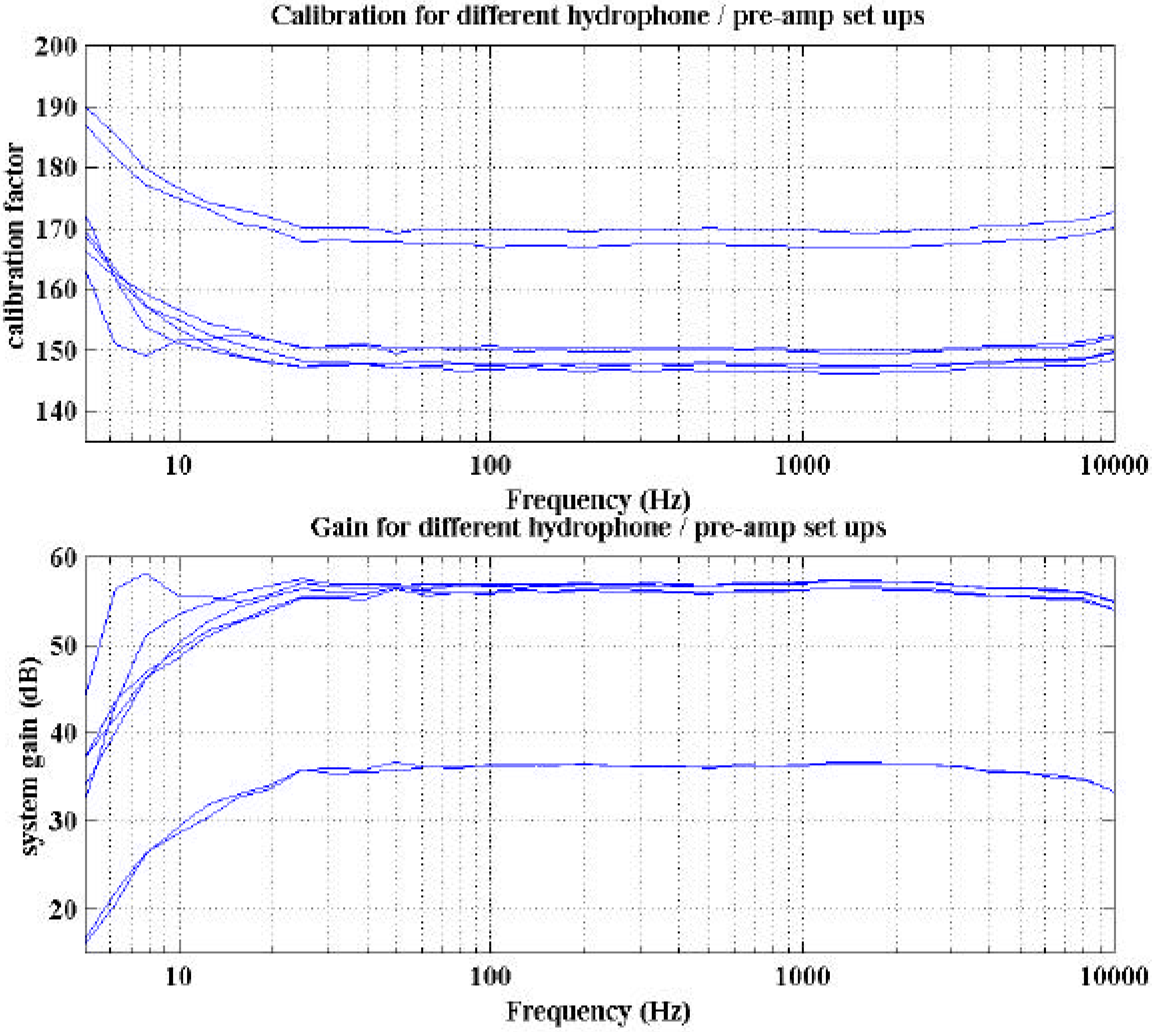

Figure 6: Hydrophone calibration curves (top) and system gain curves (bottom). Gain curves were derived from 1/3 octave analysis of pink noise recorded with the appropriate combination of hydrophone in series with pre-amplifier and tape-deck. Calibration curves are derived from this using the sensitivity of the hydrophone. Two pre-amplifier gain settings were used, differing by 19 dB hence the two sets of curves. Calibration curves used in analysis were based on comparing these curves with white or pink noise curves as analysed and recorded during field measurements.

Table 2.1: Specifications of acoustic equipment used.

Housing 1:	
timing	3 minutes every 45 minutes
hydrophone	Massa TR 1025-C, capacitance 0.038 μF, sensitivity -195 dB re 1 V/μPa
pre-amplifier	40 dB gain, RANRL PA6511-A, low noise, impedance 1 MΩ, linear response < 4 Hz - > 20 kHz
tape deck	Sony TCD D8, used in long play mode (32 kHz sample rate), 4 hour tapes, linear response 20 Hz - 14.5 kHz
system response	linear 20 Hz-14.5 kHz, recoverable 10 Hz - 14.5 kHz
deployment	anchored, always bottom mounted hydrophone
Housing 2	
timing	51 s every 8.5 minutes
hydrophone	Brüel & Kjær type 8104, capacitance .00845 μF, sensitivity -206.4 dB re 1 V/μPa
pre-amplifier	Channel 1 = 40 dB gain RANRL PA6511-A, low noise, input impedance 1 MΩ, linear frequency response < 4 Hz - > 20 kHz (serial # CPA7) Channel 2 = 20 dB gain, Curtin design, input impedance 470 kΩ, linear response 5 Hz - 22 kHz (serial # CPA5)
tape deck	Sony TCD D8, used in long play mode (32 kHz sample rate), 4 hour tapes, linear response 20 Hz - 14.5 kHz
system response	linear 20 Hz - 14.5 kHz (40 dB gain setting), recoverable 10 Hz - 14.5 kHz
deployment	anchored, always bottom mounted hydrophone
Housing 1A	
timing	continuous sample or 1 minute in 15 minutes
hydrophone	Channel 1 = GEC-Marconi SH101-X, capacitance 0.015 μF, sensitivity -203.5 dB re 1 V/μPa (serial # 082) Channel 2 = GEC-Marconi SH101-X, capacitance 0.015 μF, sensitivity -206 dB re 1 V/μPa (serial # 083)
pre-amplifier	1) 40 dB gain, purpose built, input impedance 10 MΩ, linear response 5 Hz - 22 kHz (serial # AIMS1) 2) 20 dB gain, Curtin design, input impedance 470 kΩ, linear response 23 Hz - 22 kHz (serial # CPA4)
tape deck	Sony TCD D8, used in long play mode (32 kHz sample rate), 4 hour tapes linear response 20 Hz-14.5 kHz
system response	linear 20 / 23 Hz - 14.5 kHz, recoverable 10 Hz - 14.5 kHz
deployment	drifting - housing at 30 m (measured each deployment by attached depth gauge), L channel (1) @ 25 m depth, right channel (2) @ 75 m depth; anchored - housing @ 30 m, hydrophones @ 25 m and 75 m as for drifting
Portable gear	
hydrophone	Clevite CH17, capacitance 0.0018 μF, sensitivity -204.7 dB re 1 V/μPa
pre-amplifiers	2 X 20/40 dB gain RANRL PA6511-A, input impedance 1 MΩ, linear response <4 Hz - > 20 kHz (1 = left channel, 2 = right channel)
tape deck	Sony TCD D8 or TCD D3, long play mode (32 kHz sample rate) 4 hour tapes, linear response 20 Hz - 14.5 kHz
system response	linear 20 Hz - 14.5 kHz, recoverable 10 Hz - 14.5 kHz
deployment	from Zodiac with drogue deployed; hydrophone depth 20-30 m

2.3) Analysis

2.3.1) Acoustic analysis

Analysis of recordings has been made using a Data Physics DP430 spectral analyser card installed in a 166 MHz Pentium computer. This system was calibrated in October 1997 at the factory and checked at Curtin shortly after delivery. Analysis has primarily comprised power spectra and 1/3 octave computations. The DP430 has a dedicated bank of 1/3 octave filters. Data capture, processing and storage was automated using the DP430 programming capability. All programs automatically tracked incoming signals and adjusted the

DP430 input settings to optimise the unit's dynamic range.

For long sequences of recordings (tens of minutes to hours), 5 s, 1/3 octave averages have been taken as fast as the PC would allow (every 6.4 s). For shorter samples such as those taken by housing 1 (three min samples) and housing 2 (51 s samples) 20 s 1/3 octave averages have been mostly used. In some housing 1 analysis, five or ten s averages were made, so as to avoid sections with housing movement.

The frequency content of signals is displayed either as narrow band spectra with units reduced to dB re $1\mu Pa^2/Hz$, or as 1/3 third octave spectra over the 1/3 octave bands of centre frequencies 10 Hz to 10 kHz (bandwidth of 9 Hz - 11.22 kHz). One-third octave analysis is most pertinent in studies of noise and its effects on animals since in all vertebrates which have been tested, 1/3 octave bands approximate the frequency span required to mask narrow band signals within that frequency band. To keep with the conventions used in physical sea noise studies and for comparison with narrow band spectral analysis, units within 1/3 octave bands are presented as dB re $1\mu Pa^2/Hz$. In other studies one-third octave levels may be presented as the total intensity within the 1/3 octave band (or in units of dB re $1\mu Pa$). To convert dB re $1\mu Pa^2/Hz$ to dB re $1\mu Pa$ add $10\log_{10}$[bandwidth]. The 1/3 octave centre frequencies, band limits and bandwidths as used by the DP430 spectral analyser are given in appendix 2.

In some time series measures the total signal intensity within a defined bandwidth has been presented (broadband levels). These values are calculated from the sum of the 1/3 octave intensities (dB re $1\mu Pa$ values converted to intensity) over the specified frequency band, converted back to dB re $1\mu Pa$. Bandwidths used were: 1) the system limits of lower frequency 9 Hz (set by the recording hardware) to 11.22 kHz (the upper limit of the analysers 1/3 octave analysis, 10 Hz to 10 kHz 1/3 octave bands); or 2) the 20 or 40 Hz to 10 kHz 1/3 octave frequency bands (to circumvent the excessive, low-frequency flow-noise in the drifting housing sets).

2.3.2) Position

All GPS latitude and longitude co-ordinates have been transferred to an x-y co-ordinate system using algorithms given by Vincenty (1975) for great circle range and bearing between two latitude and longitude co-ordinates (accurate to mm and thousandths of a degree). The zero point chosen was the well head co-ordinates for measures of the rig noise, or for vessel passbys the location of the recording hydrophone (which has been interpolated for drifting hydrophones).

2.4) Vessel specifications and activities

2.4.1) Ocean General

The *Ocean General* is an exploratory drilling rig operated by Diamond Offshore. The vessel comprised two large submerged tubular hulls, with a network of upright legs supporting several decks of superstructure. A photograph of the vessel with rig tender standing by is shown in

(at the documents beginning). The *OG* was moored using paired anchors off each quarter (eight anchors in total), with each anchor having nearly 1.5 km of chain. The vessel was moored on heading 105°. Three diesel generators were used to power the rig, these were located on the main deck well above the waterline, discharging exhaust and cooling water over the port side, again above the waterline. Most other major items of machinery were also located on the main deck level well above the vessel's waterline.

The drilling logs of the *OG* were made available for correlation with measured drilling noise.

2.4.2) Pacific Ariki & Pacific Frontier

The *Pacific Frontier* (*PF*) and *Pacific Ariki* (*PA*) were similar vessels and can be considered as representative of vessels widely used as 'rig tenders'. Through radio contact with the *Pacific Ariki* it was established that this vessel was: steel construction; 64 m in length; 5 m in draught; 2600 tonne displacement; had four main engines of 2000 HP each, coupled in pairs via gearboxes to two shafts with fully feathering propellers; and had through hull transverse bow thrusters.

The movements and activities of the rig tenders were noted in field logs when the *RV* or *Nova* was working in the *OG* vicinity or during a passby of the *Pacific Ariki* by a drifting hydrophone. During the passby the *PA* position and the drifting housing position were tracked using the *RV* navigation system (radar linked to GPS). Information on the movements of the rig tenders were also available in the sea-noise recordings of housing 2, as the movements and activities of the vessels were clearly evident in the recordings (section 3.2)

2.4.3) Reef Venture & Nova

The *Reef Venture* was a 20 m 'Westcoaster', a common vessel used in various configurations and lengths in offshore fishing operations around Australian waters. The vessel was: GRP sandwich foam construction; 20 m in length; 6.1 m beam; 2 m draught; and had a single V12 MAN 450 Hp (@ 1900 RPM) main engine coupled via a hydraulic gearbox to a single shaft with a four bladed fixed propeller. The *Nova*, a 4 m inflatable dinghy with 25 HP outboard motor, was launched and retrieved off the back deck of the *RV* as required. The *Nova* carried a full compliment of offshore safety gear plus spare radios and batteries, fuel and water.

3) RESULTS / DISCUSSION

3.1) Ambient noise

Natural levels of background noise at the site were recorded by hydrophones at long range from the oil rig or from the housing set on the southern side of Tasmania Shoal (housing 1). This housing was set in 70 m of water, on the leeward side of Tasmania Shoal from the *OG*, and thus would have received shielding of *OG* noise. Biological sea noise sources were evident in many recordings irrespective of position or distance from the *OG*.

3.1.1) Lowest ambient measured

Several curves of ambient noise with no audible rig or vessel noise input are shown on Figure 7, with a sample of this noise as item 1 on the demonstration tape. The top set of curves (3.1a A-E) show time averaged 1/3 octave curves (narrow band units), while the bottom set are narrow band spectral analysis (3.1b, curves F & G taken with 16 averages, 2.5 Hz resolution, 2.5 kHz span, Hanning window) with a composite open water, no-wind ambient curve. Details of the recording locations of curves A-G are given in table 3.1.

#	Location	Hyd. depth	time / date	Equipment	Drilling / tender movements
A	13.7 km S *OG*	25	08:50 21st	portable	not drilling / anchored
B	22.4 km W *OG*	25	10:48 23rd	housing 1a	drilling / on station
C	22.5 km W *OG*	25	11:33 23rd	housing 1a	drilling / on station
D	13.9 km SSW *OG*	70	12:03 22nd	housing 1	not drilling / anchored
E	13.9 km SSW *OG*	70	11:40 23rd	housing 1	drilling / moving about
F	13.9 km SSW *OG*	70	15:47 22nd	housing 1	drilling / on station
G	13.9 km SSW *OG*	70	17:18 22nd	housing 1	drilling / on station

Table 3.1: Details of the locations of ambient curves presented in Figure 7. The rig tender movements indicate wether the vessel was on anchor, moving about, or maintaining station off the rig for loading or unloading purposes (on station). No audible signatures, nor any spectral lines associated with the *OG* or rig tenders appear in the spectra.

Curves B & C, taken from 22 km west of the *OG* in open water reached the system electronic noise at frequencies > 2 kHz. Curves D & E taken from the back of Tasmania Shoal show similar trends to curves B & C between 100 Hz - 2 kHz, but above 2 kHz show increasing noise due to a snapping shrimp input. Snapping shrimp noise has greatest energy between 3-40 kHz, but will influence sea-noise up to 200 kHz (Cato and Bell, 1992). Curve A also shows snapping shrimp noise at > 2 kHz , and high flow noise at < 100 Hz. This hydrophone was drifted from *Nova* at 25 m depth in 90 m water over the edge of Tasmania Shoal.

Curves F & G (Figure 7) were taken from housing 1 off the back of Tasmania Shoal and are believed to show the lower levels of low frequency noise (< 50 Hz) encountered throughout the study. Most of the curves A-E in Figure 7) are believed to have a significant component of flow noise at frequencies below 50 Hz, with curves A & E showing the higher levels.

A composite curve (H) combining the low frequency portion of the bottomed hydrophone curves F & G (at < 200 Hz), all curves in the mid frequencies (200 Hz - 2 kHz) and extended at the same slope above 2 kHz (to remove shrimp noise) is shown on Figure 7. This is believed to be the lowest ambient noise level which would have occurred at the site over the period of measurement, correlating with environmental conditions of no wind and taken from open water regions with no snapping shrimp noise input. Small increases in wind speed and contributions from biological sources (snapping shrimp, fish, dolphins and possibly other sources) would greatly increase selected portions of this curve.

The lowest levels of ambient noise in an area, along with local sound propagation effects are crucial in determining the maximum range of audibility of any source. For long range predictions of noise audibility the curve H presented in Figure 7 has been used. When using recordings of vessel or rig noise and calculating received levels of noise, an ambient curve appropriate for the recording has been used. That is the ambient curve used in the following estimates of received rig or vessel noise, takes into account any low frequency flow noise, as heard in all drifting recordings. For analysis of vessel noise within 10 dB of the ambient noise level at a given frequency, the contribution of the ambient noise in the received signal needs to be taken into account. For these measurements the true vessel component of the signal at the specified frequency was calculated by subtracting the ambient intensity from the received signal intensity, and converting the value back to dB.

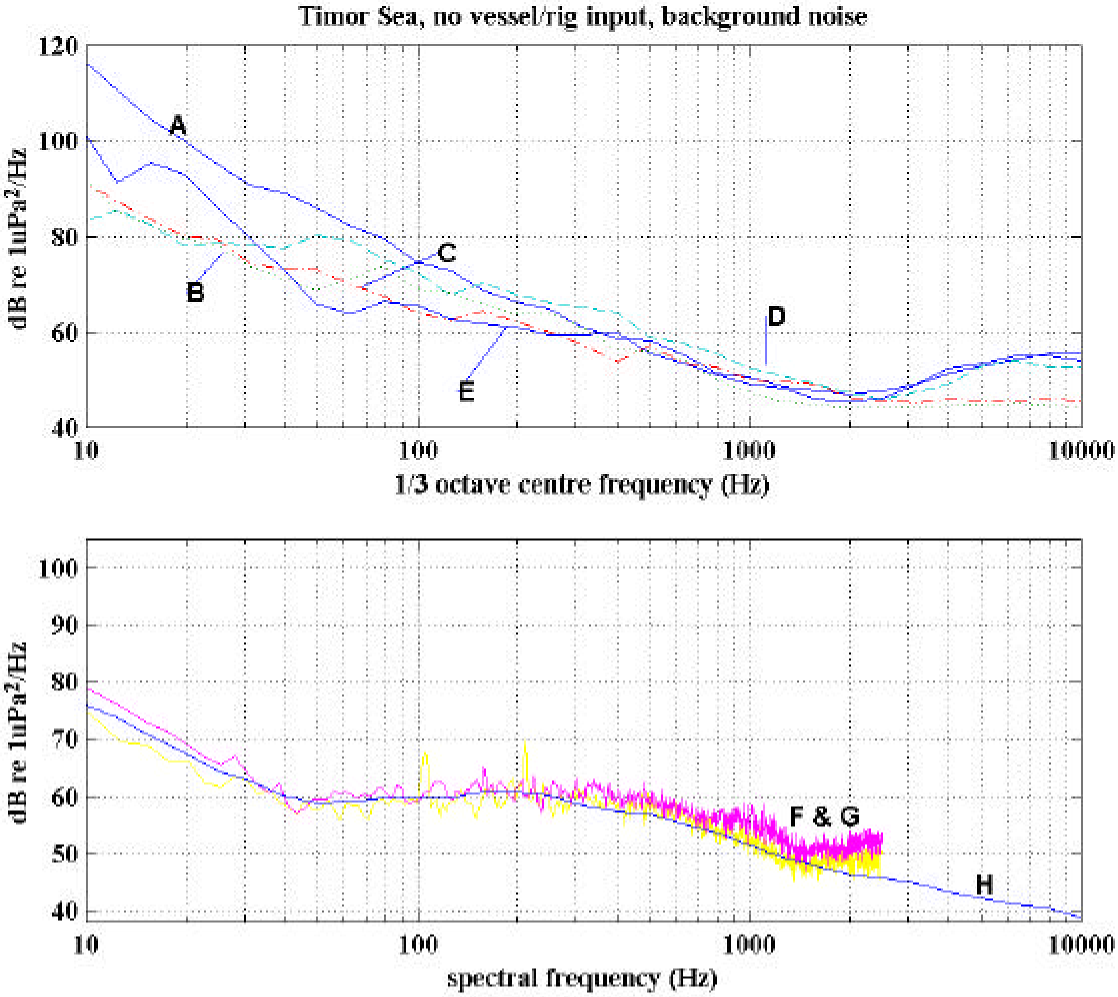

Figure 7: **(top)**: Ambient sea noise curves with no vessel noise based on 1/3 octave measurements (20 s averages). Curves are: A) - drifting hydrophone at 25 m depth 13 km S OG - shows artificially high level below ~ 60 Hz due to flow noise, shrimp input at > 2 kHz; B & C) - drifting hydrophone at 25 m depth 22.3 km W OG - high levels flow noise < 50 Hz, reach system electronic noise at 1 kHz; D & E) - bottomed hydrophone at S end Tasmania Shoal in 70 m water - have flow noise at < 50 Hz, D has slight fish noise, both have shrimp noise at > 2 kHz; **(bottom)**: F & G) - narrow band 0-2.5 kHz spectra (2.5 Hz bandwidth, Hanning window 40 averages) of ambient noise from S edge Tasmania Shoal with little flow noise (bottomed hydrophone). Also shown is a composite no-wind, no-biological input and no-vessel noise input, ambient sea noise curve for the study period (thickened curve H)

3.1.2) Biological sea-noise sources

Aside from snapping shrimp noise, which can be expected to be present over any complex bottom habitats, the presence of fish choruses was confirmed from all night time recordings. These included housing deployments from the southern side of Tasmania Shoal (housing 1, consistent over two evenings sampled), from the northern edge of Tasmania shoal (housing 1a moored, sampling 60 s every 15 min from 18:40 22nd to 08:46 23rd) and from the southern edge of Evans Shoal (housing 1a drifted 21:06-21:55 21st). In the housing 1 set on Tasmania Shoal much daytime fish calling can be also heard. Although not distinctly audible in the recordings there is some evidence that similar fish choruses, at low levels, were evident from the housing 2 set immediately astern the *OG* during evening periods when the rig tenders were anchored (the spectral signatures were masked by the vessel moving about). An example of this chorus is given on item 2 of the demonstration tape.

Evening fish choruses similar to these and described as a 'popping chorus', have been described in McCauley (1995, 1997) and in McCauley and Cato (1998). Depending on several factors, such choruses can cause up to 35 dB increases in night time sea-noise levels at the chorus spectral peak. McCauley (1997) found that although the choruses seem to be mostly associated with reef systems, they could often be active as far as 15 km from their believed parent reef. Nocturnally active planktivorous fishes working the night time plankton layer in shallow water depths were believed responsible for choruses.

Examples of the increase in sea noise caused by such choruses are shown on Figure 8a-c. Figure 8 (top) displays the 1000 Hz 1/3 octave from the housing 1 set with time over the three day set. This curve shows a regular increase in the 1000 Hz 1/3 octave level, coincident with the fish chorus. Figure 8 bottom-left and bottom-right, show the distinctive fish chorus spectral shape in 1/3 octave measurements from the northern edge of Tasmania Shoal and the southern edge of Evans Shoal. Figure 9 (top) shows the 800 Hz 1/3 octave spectral levels from the housing sets astern the *OG*, with selected spectra. A regular increase in this 1/3 octave appears between 22:00-23:00 on both evenings fully sampled (21st and 22nd). Some interference occurs around 23:00 on the 22nd from the *PF* moving around. It is believed these increases in the 500 Hz - 3 kHz frequency spectra, shown on Figure 9b-c curves 2 & 3, were due to distant fish choruses. They were not clearly audible above the background *OG* noise in recordings.Dolphin calling was also commonly heard in sea-noise records (item 3 demonstration tape). Dolphins were heard and seen at short and long ranges from the drilling *OG*.

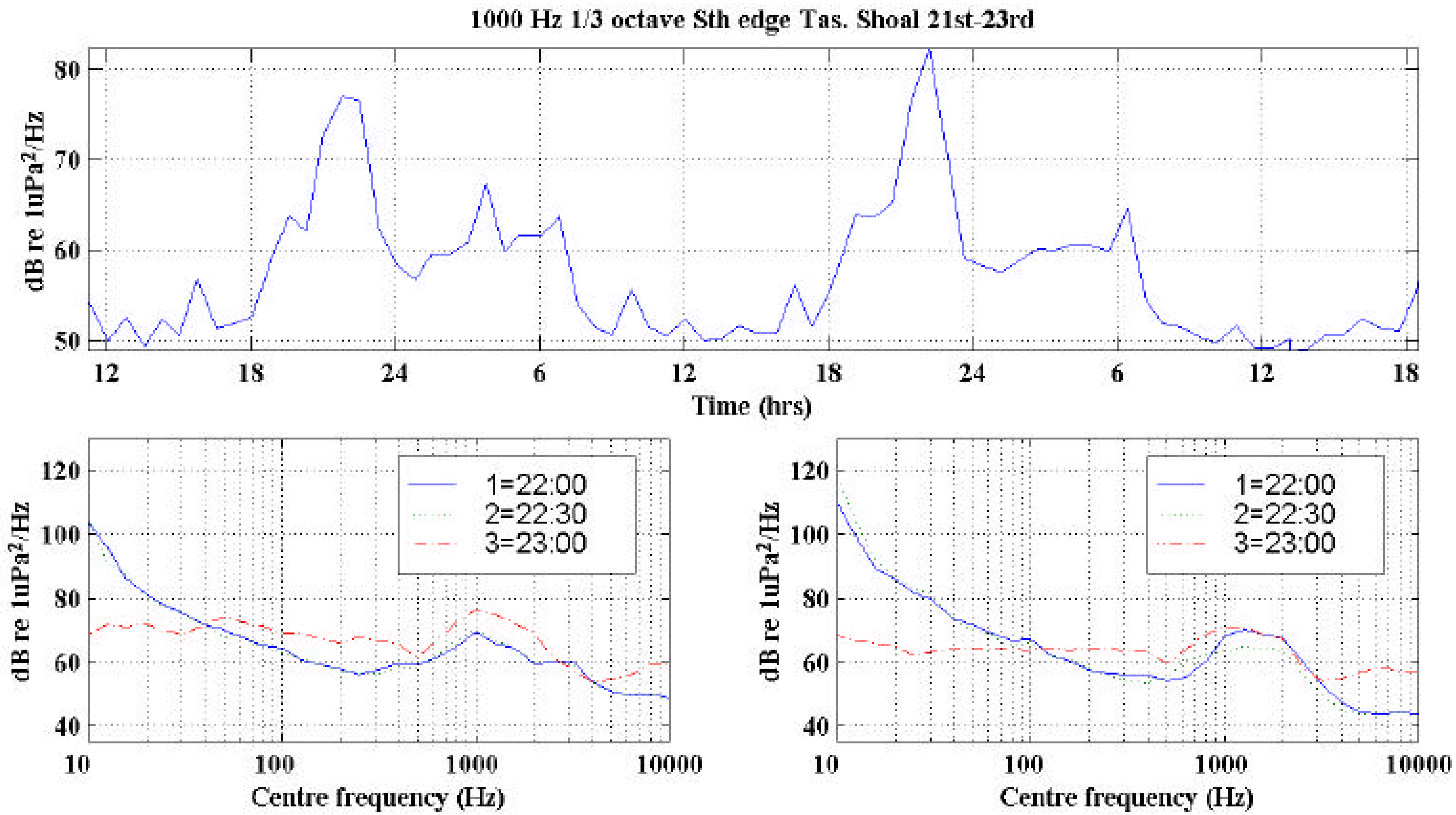

Figure 8: Biological sea noise spectra over study period (21st-23rd March). **Top** plot shows regular presence of nightly fish chorus off the S edge of Tasmania Shoal, as indicated by the 1000 Hz 1/3 octave spectral level with time (from the bottomed housing 2 records). This is the frequency of the chorus spectral peak (curves 3 bottom left & right). Similar choruses were heard from the S tip of Evans Shoal on the evening of 21st (**curves 1 & 2 bottom left**) and off the N tip of Tasmania Shoal on the evening of the 22nd (**curves 1 & 2 bottom right**). From the S edge of Evans Shoal and the N edge of Tasmania Shoal rig-tender operations could be clearly heard. Curves are labelled as 1-dotted; 2-dash-dot; and 3-solid. The curves 3 index into the top plot.

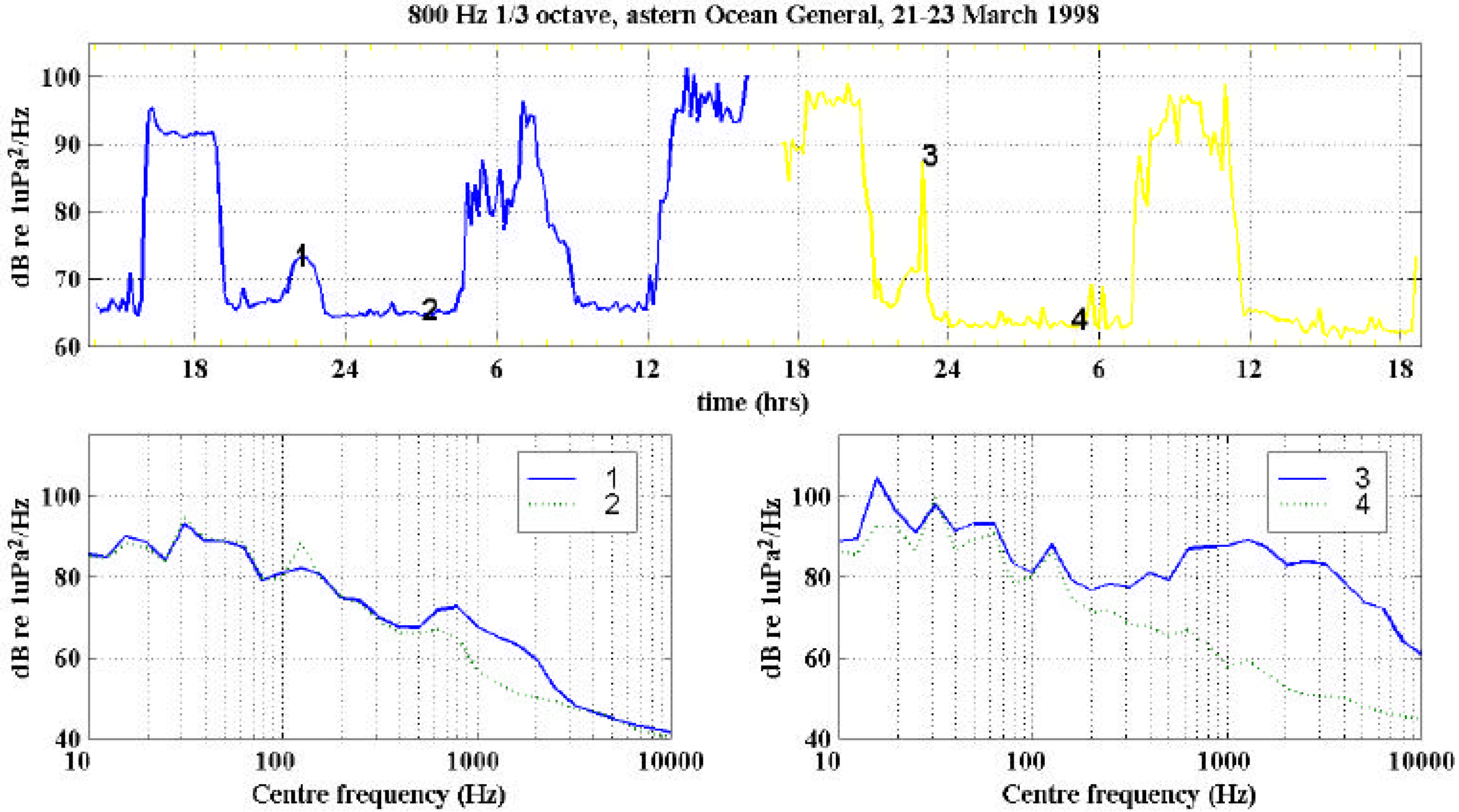

Figure 9: The 800 Hz 1/3 octave from immediately astern the Ocean General, showing small blips centred around 22:00-23:00 each evening. These were believed to be a distant fish chorus. One third octave spectra showing the spectral peak at 700-800 Hz and periods without the chorus are shown on the bottom plots (indexed into the top plot and labelled 1-4 uniformly). The small increase in level around 23:00 on the 22nd was due to tender cavitation noise.

*3.2) Rig (*Ocean General*) noise*

3.2.1) *Ocean General* and tender on station noise character

Changes in noise produced by the *OG* and rig tenders with time are presented in Figure 10 (top). This presents the total signal noise level (broadband) over the frequency span of the 1/3 octaves with centre frequencies 10 Hz - 10 kHz, or spanning 9 Hz - 11.22 kHz. Two consecutive housing sets were made, the first at 450 m astern the rig, the second at 405 m astern. To interpret the noise produced by the *OG* it is necessary to detail drilling activities aboard the *OG* and the movements of the rig tenders. These activities are given on table 3.2 from the *OG* drilling logs, from observations of tender movements or tender movements as recorded by the bottomed hydrophone immediately astern the *OG*, and through radio contact with the rig or tender.

Table 3.2: *Ocean General* drilling operations and rig tender movements over study period (07:30 21st to 19:00 23rd March). When not actively drilling the *OG* was involved in various tasks, most of which involved working the drill string or preparing the drill hole.

Date/Time	*OG* activities	Tender movts.
21st:		
00:00-24:00	no drilling	
to 15:00		*PA* anchored, @ 15:00 raise anchor
16:05		*PA* at rig on station
18:50		*PA* moves off, then anchors
22nd:		
03:46		*PF* passes S edge Tas. Shoal en-route *OG*, heard Hs1
05:00-10:00	3 hours drilling	
05:30-09:00		*PF* and *PA* moving about *OG*
08:30-09:30		*PA* passby hyd. E Tas. Shoal, *PA* steams Darwin
12:30-20:36		*PF* on station *OG*
21:01		*PF* on anchor
23rd:		
07:30-11:00		*PF* moves *OG*, on station
13:07		*PF* on anchor main engines shut down
13:00-24:00	11 hours drilling	

Not drilling noise, tender on anchor

Three states of noise were recorded from the *OG* and associated rig-tender operations. The first state was relatively quiet, and involved normal rig operations which did not involve drilling, with the rig tender on anchor. These operations included working the drill string in the hole, such as reaming work, but not active drilling. Examples of the noise produced during these periods are shown on Figure 10 (top) between: 14:00-16:00 on the 21st; 19:30 21st to 04:30 22nd; 09:30-12:00 22nd; and 21:00 22nd to 07:00 23rd (item 4, demonstration tape). The configuration of the *OG*, with the main machinery deck well above the waterline, probably contributed to the generally low noise output from the structure itself during no drilling periods.

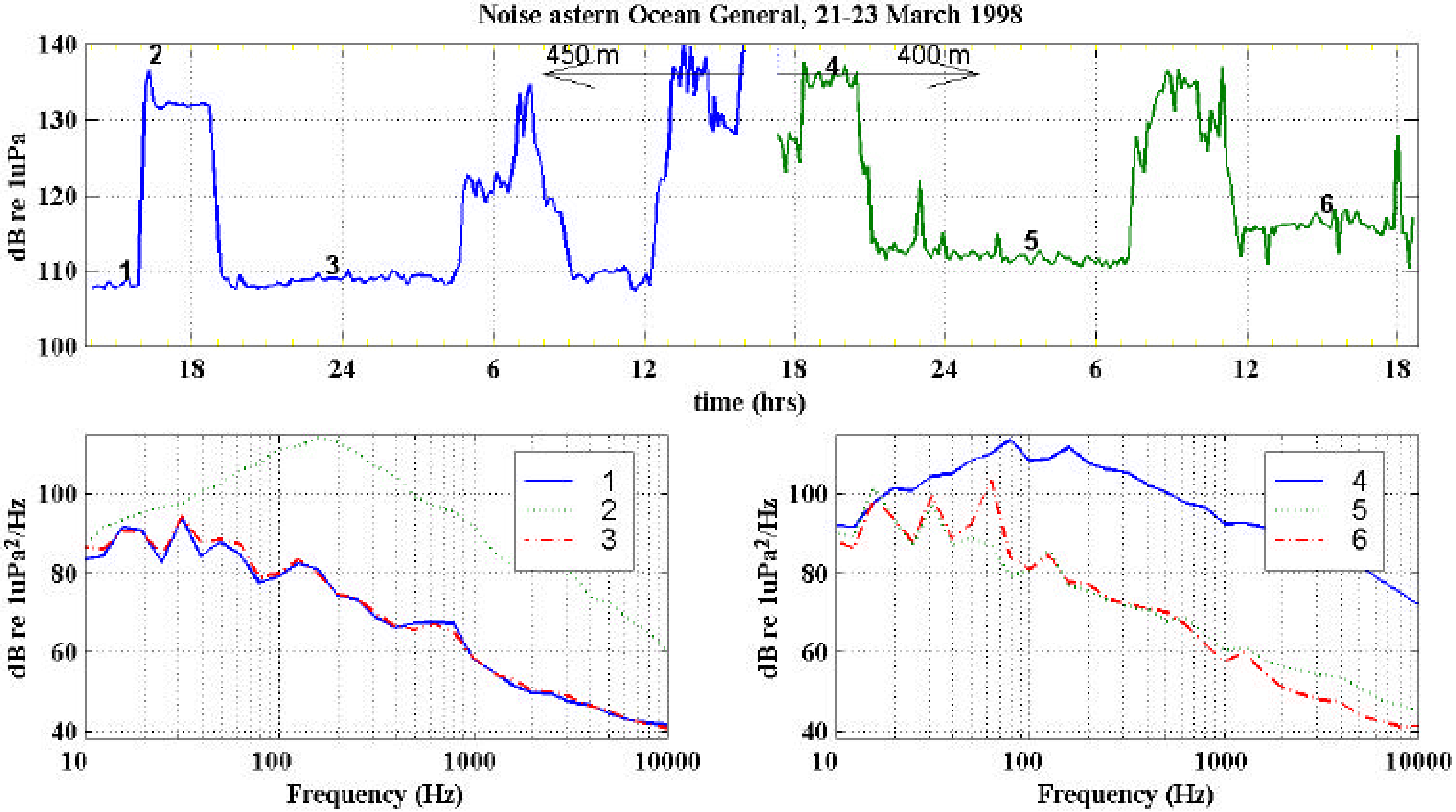

Figure 10: The broadband level recorded from a bottomed hydrophone directly astern the Ocean General (bandwidth 9 Hz - 11.22 kHz) over the study period. The housing was deployed consecutively at 450 and 405 m off the wellhead. Spectra (1/3 octave) for periods not drilling (curves 1, 3 & 5), drilling with tender at anchor (curve 6) and rig tender on station (curves 2 & 4) are shown below. The spectral curves 1-6 index into the top plot as indicated by the numbers.

Drilling noise, tender on anchor

The second noise state involved active drilling operations. An example of this noise is given as item 5 on the demonstration tape. Over the trials drilling occurred over two periods, 3 hours between 05:00-10:00 on the 22nd, and from 13:00-24:00 on the 23rd. On the 22nd drilling operations also coincided with tender movements (*PF*), and are obscured on Figure 10. On the 23rd the *PF* left position off the starboard side of the *OG* at 11:00 and was anchored with main engines shut down by 13:07. The increase in broadband noise of the *OG* during drilling operations as compared to periods not drilling can be seen by comparing sections of Figure 10 (top) between 22:00 22nd to 07:00 23rd with the period 13:00-17:30 23rd. An approximate 4 dB increase in broadband noise is evident. The spectral differences between drilling / not drilling operations are primarily associated with dominant tones and harmonics, presumably produced by the rotation of the drill string under tension in the drill casing. Figure 11 (top) displays for the housing 2 set immediately astern the *OG*, the 62 Hz 1/3 octave with time and several 1/3 octave spectra for periods of not drilling, rig tender on station and drilling. Tones at < 100 Hz are the primary differences between drilling / not-drilling 1/3 octave spectra. This is shown in greater detail in the narrow band spectra displayed on Figure 12 (top), which shows the increase in level of tones during the drilling periods. This predominance of tones during drilling periods combined with multipath phase interference effects and the widely distributed nature of the drill-string source, produced some peculiar differences in broadband sound levels within one km of the *OG*. These are discussed in section 3.2.2.

Tender on station

The third noise state, which produced considerably more noise energy than drilling operations, involved either of the rig tenders maintaining station off the *OG* for supply operations (example as item 6, demonstration tape).

The large sustained spikes in the broadband level curve with time on Figure 10 (top, 16:00-19:00 21st), all occurred when either the *PA* (on site until 08:00 22nd) or the *PF* (on site from 08:00 22nd) was maintaining station alongside the rig for loading purposes. When keeping station the tenders approached usually the starboard side, set a bow anchor then reversed back to the rig and laid out stern lines to the rig. To maintain their position and keep tension off the cables the tenders appeared to: keep their main-shafts turning with zero propeller pitch, applying pitch to the port or starboard shaft as required; and almost continually operated their transverse bow thrusters to keep the bow from laying-off. The constant tidal stream experienced over the study period (see section 3.4), which generally set fore and aft the rig, required the skippers to continually maintain some propeller and bow thrust. In the recordings the tenders' shaft can be heard spinning, pitch being applied to the propellers produced cavitation which can be clearly heard, and when activated the bow thrusters produced large bursts of cavitation noise which dominated recordings.

Cavitation noise is produced when pressure on the face, tips and hubs of propellers (main or bow thruster) is lowered by the propeller rotation and the forward motion of the propeller through the water, to the point where the water 'boils' and bubbles of water vapour form. These bubbles then drift with the water flow to regions of higher pressure whence they implode, releasing bursts of broadband sound (as well as light and physical energy which may damage propellers). Individual bubbles may coalesce to form larger bubble clouds, the oscillatory motion of these can also create noise. Vessel cavitation noise is distinct in recordings, producing a sharp crackling sound. The bow thrusters of the rig tenders produced particularly high levels of cavitation noise.

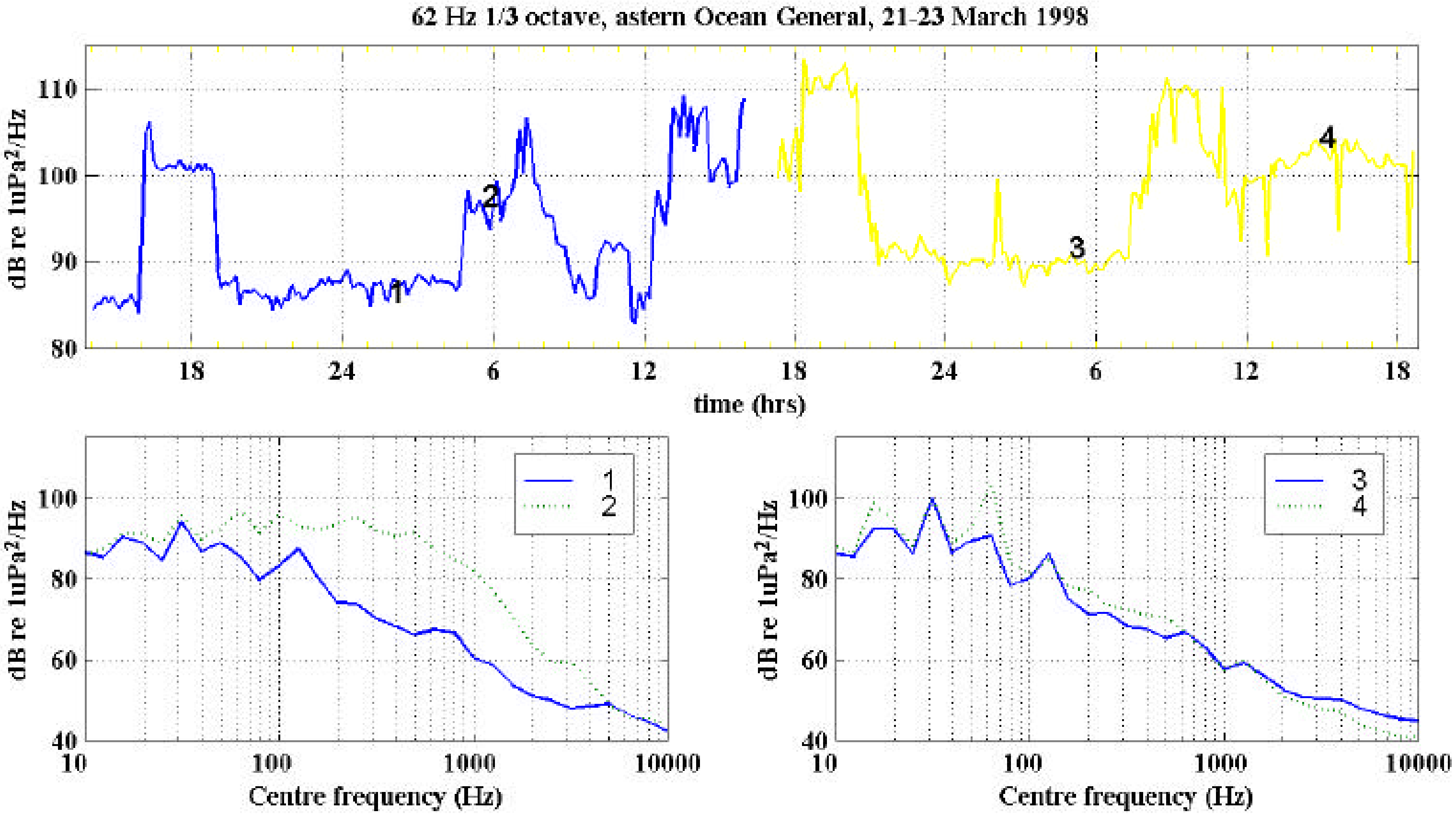

Figure 11: The 62 Hz 1/3 octave as recorded astern the Ocean General over the 21st-23rd March. A marked increase in the level of this 1/3 octave is evident when comparing not-drilling periods (24:00-0700 23rd) to drilling periods (13:00-18:00 23rd). Bursts of vessel noise are responsible for other periods with levels > 95 dB re 1μPa^2/Hz. Curves 1-4 in the bottom plots are of 1/3 octave spectra taken at the times labelled 1-6 on the top plot (52:38:10 and 62:09:53 hours are 04:38:10 and 14:09:53 on the 23rd).

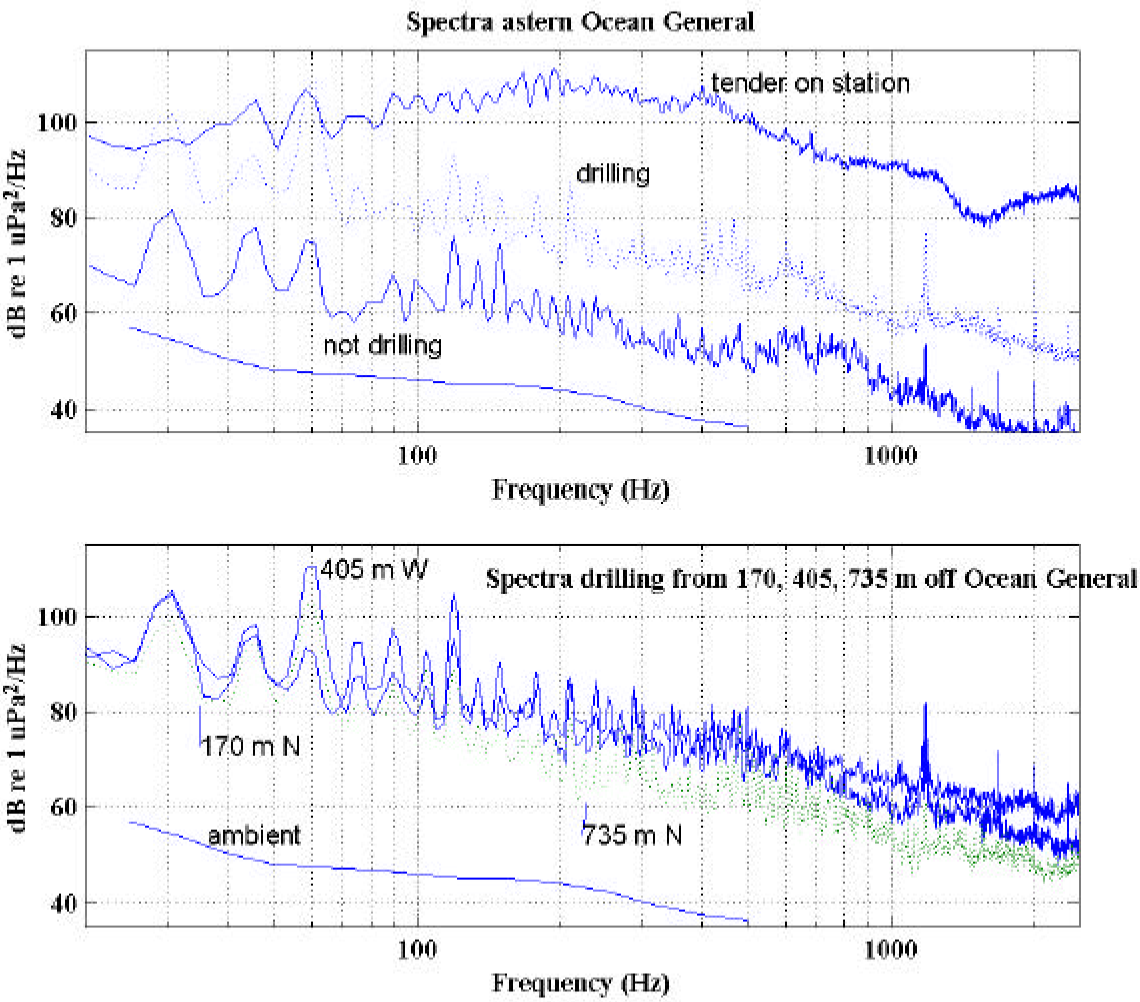

Figure 12: **(top)**: Narrow band spectra (20 Hz-2.5 kHz, 20 averages, Hanning window, 2.5 Hz resolution) of noise from: not drilling, tender anchored main engines shut down; drilling, tender anchored main engines shut down; tender on station noise; and ambient curve (lower thickened line). **(bottom)**: Narrow band spectra (20 Hz - 2.5 kHz, 20 averages, Hanning window, 2.5 Hz resolution) of period of continuous drilling with tender on anchor on the 23rd, showing measure from 735 m N with hydrophone at 25 m depth (14:35 hrs); measure from 405 m W from bottomed hydrophone (14:54 hrs); measure from 170 m N with hydrophone at 25 m depth (14:52 hrs); and ambient curve.

Narrow band spectra of the rig not drilling, drilling and the rig tender standing by are shown on Figure 12 (top) over the frequency range 20-2500 Hz. The broadband nature of the tender noise is apparent, as is the dominant tones produced during drilling, which are also apparent but not as high in level in the not drilling spectra. Several spectra of the rig drilling (tender at anchor) at increasing range are shown on Figure 12 (bottom). An anomaly occurs in the received broadband level with range due to the 60 Hz tone, this is discussed in section 3.2.2.

Underwater acoustic communications equipment

The noise analysis presented is confined to the bandwidth of analysis, nominally 10 Hz to 11.22 kHz, although the upper system limit was 14.5 kHz. Throughout all recordings at < 1 km of the *OG*, constant 'chirping' can be heard. This was due to the subsea communications packages used to interrogate the drill head control modules. These 'chirps' would have had most energy above the bandwidth of the equipment. For most fishes these chirps would have been of little consequence. With their excellent high frequency hearing the many dolphins in the area would have been well aware of them, and given their curiosity some interactions between dolphins and the 'chirping' equipment may have occurred.

3.2.2) Rig noise with range

To interpret the noise measurements with range requires some consideration of the appropriate noise source. During periods with the rig not drilling, no down hole work being carried out and the rig tender at anchor, the primary noise sources will emanate from the rig. Sources will include structure borne vibration, machinery noise, pumps, valves, the noise produced by discharged exhaust or fluids, flow noise produced internally by pumping fluids about the rig and miscellaneous banging of gear being moved about. As the main working decks were well above the waterline much of this noise would not transmit into the water. During this activity period the 'near field' of the source would approximate the dimensions of the rig, or roughly 100 m about the rig. In the 'near field' the noise level experienced will be dominated by the nearest source, beyond this or in the 'far field' the many spatially separated sources will add together in some fashion to produce a larger noise source than experienced in the 'near field'.

During drilling operations the rig-noise will still be present, perhaps enhanced by additional machinery bought into operation to operate the rotary head and drill string, but the additional source of the drill string rotating in the drill casing will be present. As indicated above this drill string rotation appeared to produce several dominant tones at frequencies < 100 Hz, which also dominated measurements of the broadband noise. During the study period the drill head depth was increased from 3,670 m below the seafloor at 00:00 on the 21st to 3,730 m at 24:00 on the 23rd. The water depth at the site was 110 m, so the drill string and casing was around 3,800 m long. Thus the source comprised the near surface rig and a 3,800 m tube, of which 3,700 m was below the seafloor, which had an internal steel pipe (drill-string) rotating in a steel (in water) or concrete (subsea) casing.

During periods with the rig tender on station the dominant noise source was cavitation produced by the tenders bow thrusters or main propellers. The vessel was 64 m long and given the thrust involved, the bubble plumes produced by the propellers would extend beyond this. Thus up to three noise sources were involved, rig-noise, tender-noise and the drill-string noise.

Broadband noise measurements made at various ranges from the *OG* during not-drilling-no-tender, drilling-no-tender and rig-tender on-station periods, are shown on Figure 13. This plot considers the broadband level over the 1/3 octave centre frequencies 40 Hz to 10 kHz (35 Hz to 11.22 kHz band limits), not the 10 Hz to 10 kHz centre frequencies shown in Figure 10. This was done as most of the measurements shown on Figure 13 were made from the *Nova* with a drifting hydrophone at 25 m depth, so had some component of flow noise below 40 Hz. The broadband measurements taken from the housing set immediately astern the *OG* over the 1/3 octave centre frequencies 40 Hz - 10 kHz were no less than 2 dB below comparable broadband measures taken over the 1/3 octave centre frequencies 10 Hz to 10 kHz. On Figure 13 measurements from the bottomed hydrophone astern the *OG* are presented as enlarged symbols and are calculated from the mean intensities of measurements made over the time during which the appropriate drifting measurements were taken, expressed as a dB value. Measurements from the 25 m depth hydrophone of the drifting housing (1a) are similarly calculated.

Several measures of the ambient noise are shown, with these giving a broadband ambient level over this frequency band of around 93 dB re 1μPa. The idealised ambient curve H shown in Figure 7 gives an ambient level of 89 dB re 1μPa over this frequency band. This level of ambient noise is believed to approach the absolute minimum possible at the site. Increases in the ambient level due to wind, will diminish the maximum ranges of audibility given below. Natural sea noise levels may reach to 110-115 dB re 1μPa in winds of force 5-7.

Not-drilling no-tender noise

The curve showing the not-drilling-no-tender measurements (crosses, lower left) gives the lowest noise levels. For this configuration the rig noise reaches ambient at between 1.5-2 km. The bottomed hydrophone astern the rig (enlarged cross) showed slightly higher noise level than predicted by extrapolating the 25 m depth hydrophone measurements. A downward refracting sound speed profile and coupling of the bottomed hydrophone to the bottom and thus the drill string may have slightly raised this level.

Extrapolating the curve back would give a broadband source level of the rig over the bandwidth (35 Hz to 11.22 kHz), at near 157-160 dB re 1μPa at one m.

Drilling noise with range

A series of measurements made from 11 km W of the rig and towards it when the rig was drilling (13:00-15:50 23rd) and the rig tender at anchor, is shown by the filled circles on Figure 13. Measurements from the drifting housing are labelled while the mean housing 2 measurements astern the rig over the correlating time are shown by the enlarged filled circle. All other measures shown by the filled circles were made from the *Nova*.

The *OG* drilling noise was barely audible in the 11 km measurement, which could be considered the audible limit of detection under the low wind conditions experienced. The rig-noise level increased steadily on approaching the *OG* to 405 m at the bottomed hydrophone site. The measured level then abruptly drops for the measurements < 400 m from the *OG* to similar values as for the rig-noise-not-drilling period (crosses). Although some time fluctuations in received noise can be expected, perhaps with changes in the drilling schedule, it is believed there is a real transition in the local sound field at 400-500 m from the wellhead. This is believed the result of a combination of: primarily the distributed nature of the drill string source; combined with a sound propagation phenomena where multipath arrivals of the tones produced during drilling arrive at a given point with different phases, causing the signal to wax and wane with range. The drill string can be considered as a 3.8 km long vertical line source. Near the wellhead the noise field will be dominated by the section of the drill string nearest the receiver. The noise from more distant parts of the drill string will suffer greater attenuation and absorption losses in the sediment and not contribute greatly to the received signal. On moving horizontally away from the source the contribution of the further sections of the drill-string becomes more significant, since more of the drill-string lies at similar ranges. At some range all sections of the source will add coherently to give the 'far field' signal of the drill string. Given that most of the drill string is buried and that the sediment acts as a low pass frequency filter, then predicting this 'far field' transition would be difficult. From Figure 13 the transition seems to lie about 400 m.

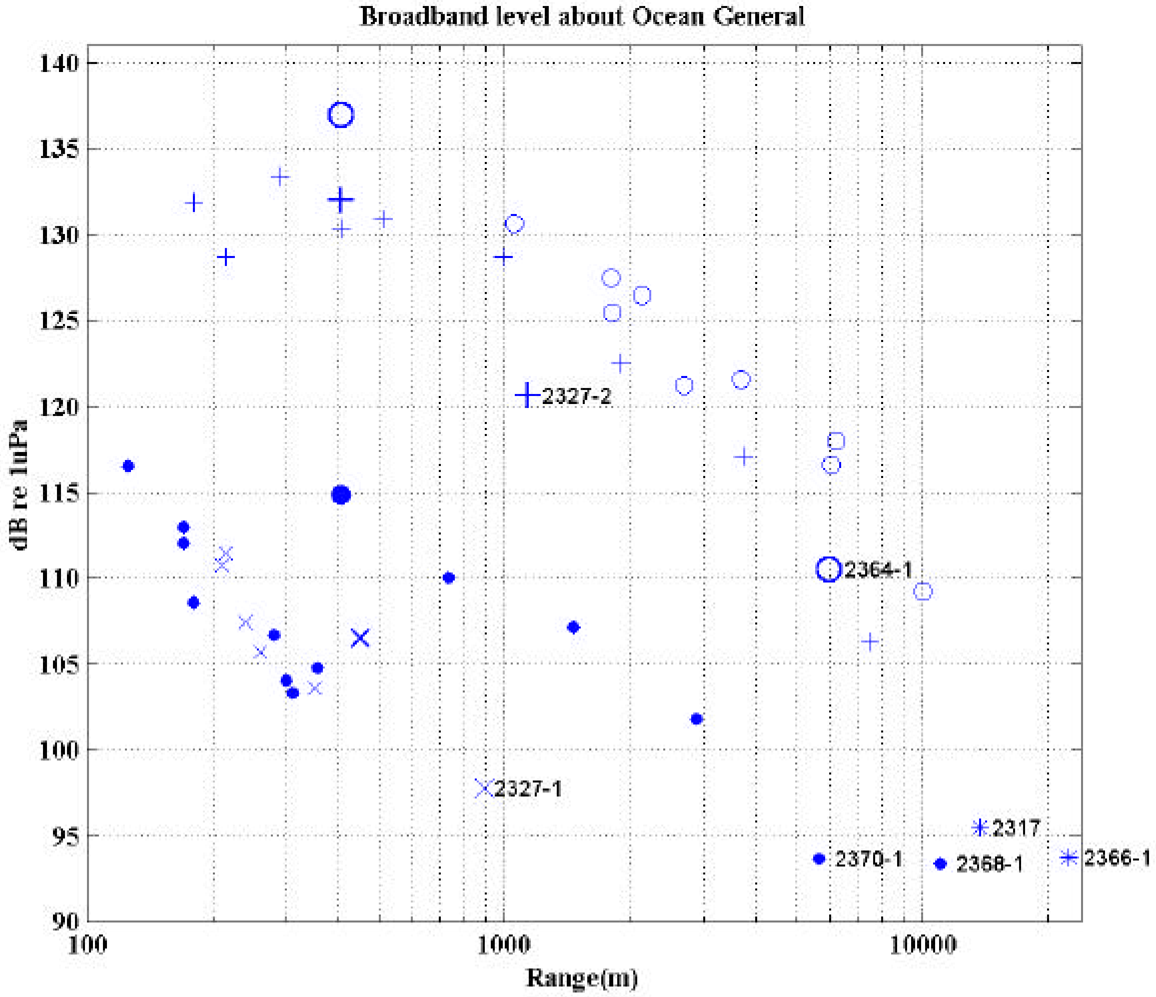

Figure 13: Broadband ambient noise levels made about the Ocean General (from 1/3 octave centre frequencies 40 Hz - 10 kHz). The recording sets are:
not-drilling no-tender - *crosses (x)*, *small* made from Nova 10:50-11:32 21st, *large-heavy* from housing 2 astern OG over 10:50-11:32 21st, **large-light** from housing 1a drifted over 15:30-15:48 21st;
drilling no-tender - *filled circles (*O*)*, *small-no-labels* from Nova 14:18-15:48 23rd, *large* from housing 2 14:18-15:48 23rd, *small-with-labels* from drifting housing 1a 2370-1 over 14:18-14:35 23rd, 2368-1 over 13:12-13:24 23rd;
tender on station - *open circles (o)*, *small* from Nova 13:09-14:22 22nd, *large-unlabelled* from housing 2 astern OG over 13:09-14:22 22nd, *large-labelled* 2364-1 from drifting housing 1a over 07:45-08:30 22nd
tender on station - *plus symbols (+)*, *small* from Nova 14:30-15:36 22nd, *large-unlabelled* from astern OG 14:30-15:36 22nd, *large-labelled* from drift nearby
ambient noise only - *asterisk (*)*, 2317 from Nova 08:30 21st, 2366-1 from drifting housing 1a 10:42-10:48 23rd.

A recording was made in the drifting *Nova* from 130 m north of the *OG* to 720 m NNE. This recording straddled the believed near-far field transition range. The section was subsequently analysed for 1/3 octave levels using 5 s averages every 6.33 s. One third octave spectra at 200, 300, 500 and 650 m range from the wellhead are shown on Figure 14a. Tones associated with drilling in the 31.25 and 62.5 Hz 1/3 octaves can be seen in the spectra. Below 20 Hz the signal is dominated by flow noise. Plots of the 31.25 and 62.5 Hz 1/3 octaves with range are shown on Figure 14b. At less than 400 m from the wellhead the 31.25 Hz 1/3 octave waxes and wanes, as would be expected from multipath interference on moving away from a point source with tonal character. For a tonal point source this pattern would normally continue outwards. But at 400 m the pattern changes, and although the general wax and wane trend is evident the signal tends to flatten with increasing range, indicating additional energy is being received. The 62.5 Hz 1/3 octave does not vary greatly over the 130-715 m range again indicating that as the range increased additional energy in the 62.5 Hz 1/3 octave from the drill string below the seafloor was becoming apparent in the received signal.

The spectra shown on Figure 3.6 (bottom) also show an increase in received energy for the 60 Hz drilling tone with increasing range out to 735 m from the wellhead. The spectra at 170 m has less energy at 60 Hz than the 405 m or 735 m spectra.

Rig tender on station noise

The noise produced by the rig tender holding station off the rig with increasing range is shown on Figure 13 by the open circles and the '+' symbols. Again measurements made during corresponding periods from the housing astern the *OG* are shown as the larger symbols while all others were from the *Nova*. The symbol at 22.5 km shown as '*' was made on the 23rd with the rig tender holding station at the *OG*. No vessel noise could be heard in this recording. Using this record and the general trend of the open circles curve, gives the expected maximum audible range of the tender-on-station noise as around 20 km under the low wind conditions experienced.

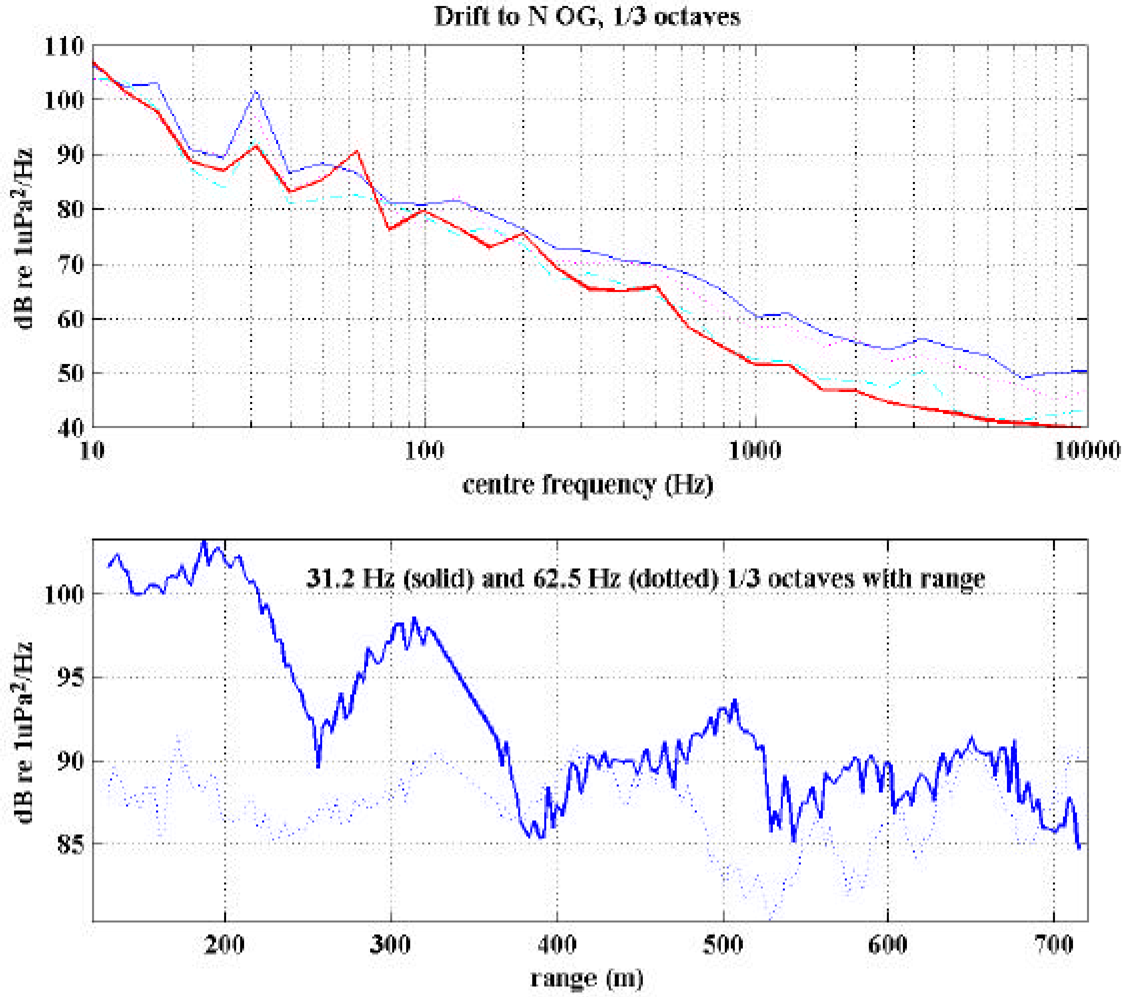

Figure 14: (**top**) Spectra (1/3 octave) taken from drifting *Nova* over period of drilling from ranges of 200 m (**solid thin line**), 300 m (**dotted**), 500 m (**dash-dot**) and 650 m (**solid thickened**) to the N of the OG showing differences in level particularly at centre frequencies 31.25 and 62.5 Hz (taken over 14:52-15:18 23rd); (**bottom**) 1/3 octave spectra for 31.25 and 62.5 Hz centre frequencies with increasing range from the *Ocean General* during period of drilling (over same period as top plot).

Considerable differences were measured in the levels of this noise with time. This would be expected given different vessels and as the tender skippers adjusted the amount of thrust required to maintain position according to the wind and tide state. This can be seen when comparing the tender noise measurements with range, or from the broadband measurements made astern the *OG* with time. For the measurements with range the open circles on Figure 13 were made approaching the *OG* from the south and astern the *OG* between 13:09-14:20 on the 22nd. Over this period the *PF* was maintaining itself off the *OG* starboard side. The measurements shown by the '+' symbols were made immediately after, between 14:30-15:37 on the 22nd. At 14:28 the *PF* moved away from the rig to the north side (port - where we were making recordings) and held its location keeping its shaft spinning and occasionally using main propeller thrust and bow thrusters. The two sets of curves can be seen to differ with the on-station curve showing the greatest levels at a given range. The point on Figure 13 shown by the '*', labelled '2327-2' was made with the *PA* on station on the 21st over 16:12-16:24 and again highlights the variability of this noise with time.

3.3) Vessel noise

3.3.1) Propagation

Sound propagation at the site was estimated by using the approach and departure noise from vessels as a noise source and measuring its loss with range in 1/3 octave steps using samples which were above the pertinent ambient noise. This loss is expressed as a simple logarithmic loss function, or as per the equation:

$$\text{Loss (dB)} = \beta \log_{10} (\text{ra}) \qquad \mathbf{1}$$

where β is the loss coefficient for the appropriate 1/3 octave and ra is the range in m.

Although a somewhat crude technique this is useful for vessel noise studies, in which the noise is statistical in nature with respect to level and less so with respect to frequency content. Cavitation and bubble noise produced around propellers and in wash will vary considerably over short time scales. Thus using 1/3 octaves with time averaged samples and the log-loss approach gives some averaging to the predicted values, with the actual level received at any range falling within some error bounds given by the time varying nature of the source.

Two sets of data have been used to describe this loss. The first is from the approach and departure of the *Pacific Ariki* towards a drifting hydrophone at 25 m depth (housing 1a) made E of Tasmania Shoal (drift 3, Figure 2) on the 22nd. The *PA* was asked to approach the housing (surface floats with radar reflector on pole) directly to 400-500 m, to then turn in an arc around the housing, and to depart with the housing directly astern. It was hoped to gain information on the sound propagation by using the direct approach and depart, and of the vessels noise beam pattern by using the period during a broad turn about the hydrophone. The vessels track normalised to the hydrophone drift is shown on the top plot of Figure 15, over the period analysed for propagation and beam pattern calculations. The *PA* travelled from the N (or top of plot) to S at a mean speed of 5.55 ± 0.164 ms^{-1} (± 95% confidence limits), or around 11 knots, with a minimum approach range of 400 m. The broadband received signal (20 Hz to 10 kHz 1/3 octave centre frequencies) is shown on the bottom plots with time and range. A section of the passage of the *Pacific Ariki* is given as item 7 on the demonstration tape.

The second pass was for the *Reef Venture*, 22.5 km W of the OG (set 9 Figure 2) with the drifting housing 1a and the hydrophone at 25 m depth. The section of the track used is shown on the top plot of Figure 16 with the corresponding broadband level (20 Hz to 10 kHz 1/3 octave centre frequencies) with time and range shown underneath. The *RV* travelled at 6.23 ± 0.117 ms^{-1} or around 12.5 knots, with minimum approach range 30 m and the vessel travelling from S (bottom) to N. A section of this passby is given as item 8 on the demonstration tape.

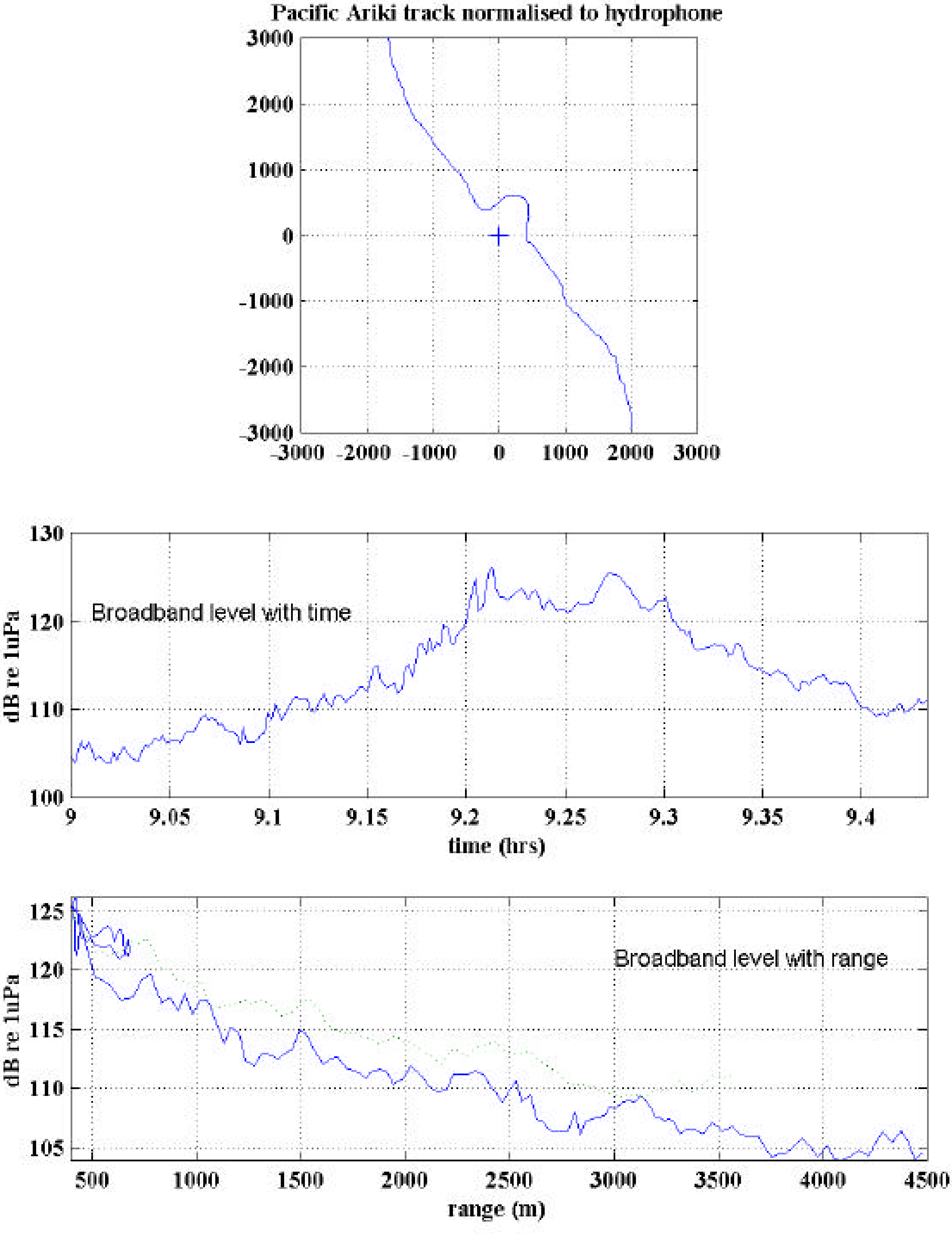

Figure 15: (top): Normalised track of Pacific Ariki used in describing sound propagation and the vessels beam pattern. The plot is referenced to the hydrophones location (13 km SSE of Ocean General location, set 3 Figure 2); (middle) broadband level with time over track (20 Hz - 10 kHz 1/3 octaves); (bottom) broadband level with range with towards (solid and away (dotted) legs differentiated. Closest approach was 400 m.

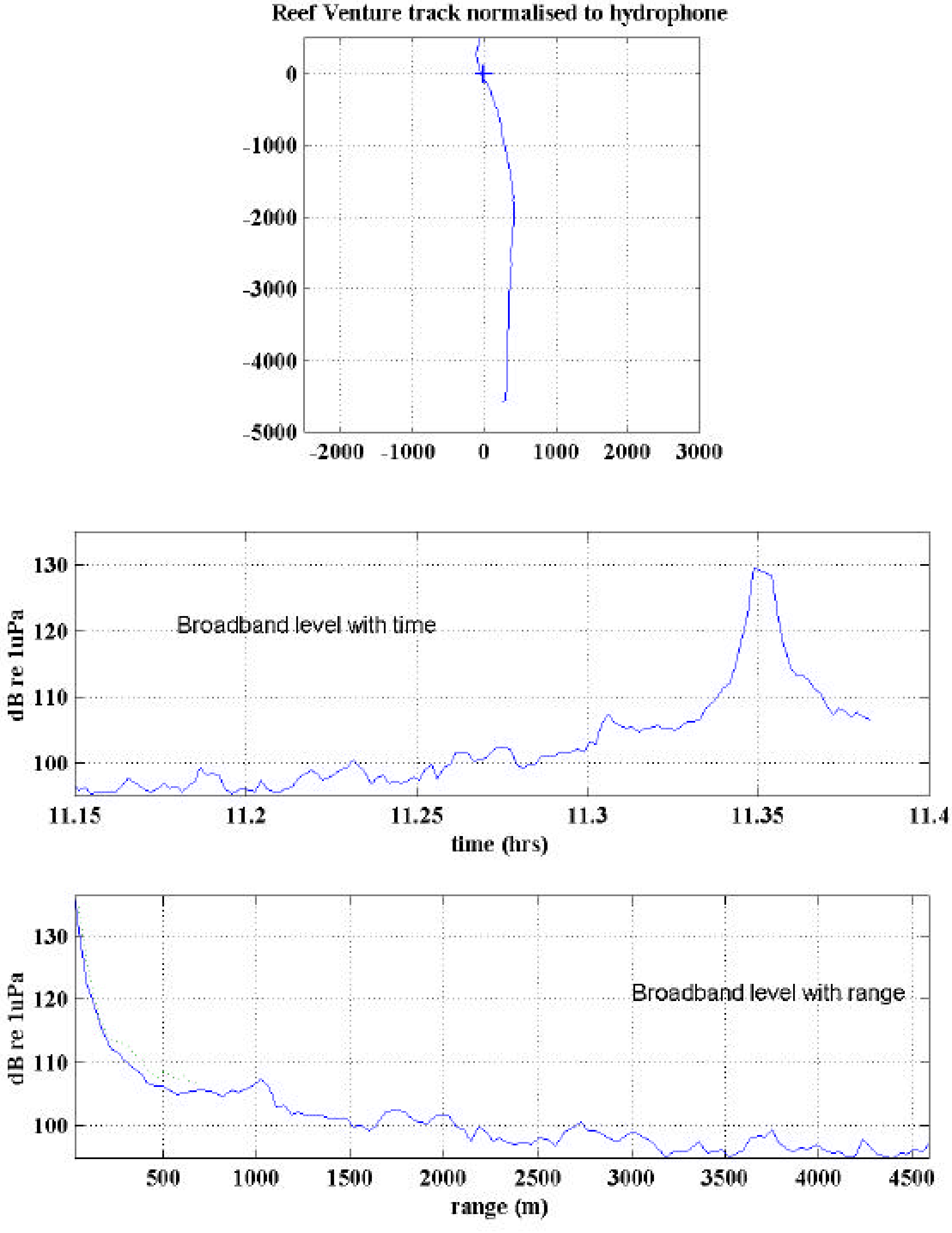

Figure 16: (top): Normalised track of Reef Venture used in describing sound propagation. The plot is referenced to the hydrophones location (22.5 km W of Ocean General location, set 9 Figure 2); (middle) broadband level with time over track (20 Hz - 10 kHz 1/3 octaves); (bottom) broadband level with range with towards (solid) and away (dotted) legs differentiated. Closest approach was 30 m.

For each pass the received signal was obtained in 5 s averaged 1/3 octaves from 10 Hz to 10 kHz, with a sample each 6.33 s. The program which collected the 1/3 octaves also wrote the sample start time to file. This was used to index into the GPS files to obtain vessel range from hydrophone for each sample. For both vessel's approach, 1/3 octaves from 25 Hz to 10 kHz were plotted with range. Approach was determined as samples where the angle of the hydrophone off the vessel's bow was less than 30^o. For the *PA*, a similar curve was plotted for the departure using only points greater than 150^o off the vessels bow (ie. hydrophone within 30^o of the stern). An ambient level appropriate for this 1/3 octave and recording was selected (using the entire tape's data, four hours for the *PA* pass, 1.75 hours for the *RV* pass). A cut off range was then determined, beyond which the appropriate 1/3 octave fell into the ambient noise. Samples for that 1/3 octave which fell below the threshold ambient noise or above the threshold range were removed from calculations. The resultant samples were then re-sized to remove any additive effect of the ambient noise and the log-loss equation 1 fitted to the data to give β, or the log-loss coefficient at the appropriate 1/3 octave centre frequency. For the *PA* pass the approach - departure coefficients were then averaged to give a mean value. An example of the curves for the 100 Hz 1/3 octave showing the full tape and the selected approach samples, the samples corrected for additive ambient noise, and the fitted curve are shown on Figure 17.

The resultant loss coefficients for each 1/3 octave are shown on
Figure 18 for the *PA* and *RV* data sets (asterisk and open circles respectively) and the mean value (+ symbols). Neither set of samples had sufficient energy below the 25 Hz 1/3 octave and above the hydrophone flow noise to give accurate measurements. The separate measures are consistent, showing a gradual worsening of propagation with increasing frequency, this increasing rapidly above 2 kHz.

3.3.2) *Pacific Ariki* and *Reef Venture* noise patterns

The sound fields or beam patterns of each vessel were then described using received levels from passbys, the frequency dependent log-loss propagation models derived above, and the lowest ambient noise levels likely to be experienced at the site.

For the *PA* passby and a set of recordings of the *RV* moving towards and away from a drifting hydrophone on the 21st (set 3 Figure 2) the beam patterns of the vessel were calculated. These were calculated using the received 1/3 octave levels with range. Those samples which were at less than the cut off range and greater than the threshold ambient level, as determined for the propagation measurements, were: adjusted for any additive ambient noise, reduced to source levels at one metre using the frequency dependant propagation model; then plotted with angle of hydrophone off the vessels bow (ie. no angle limits imposed). A second order polynomial was fitted with the angle-from-bow the independent variable and the received signal level the dependant. This described the vessels source level, in 1/3 octave steps, with aspect for those aspects available from the passby geometry.

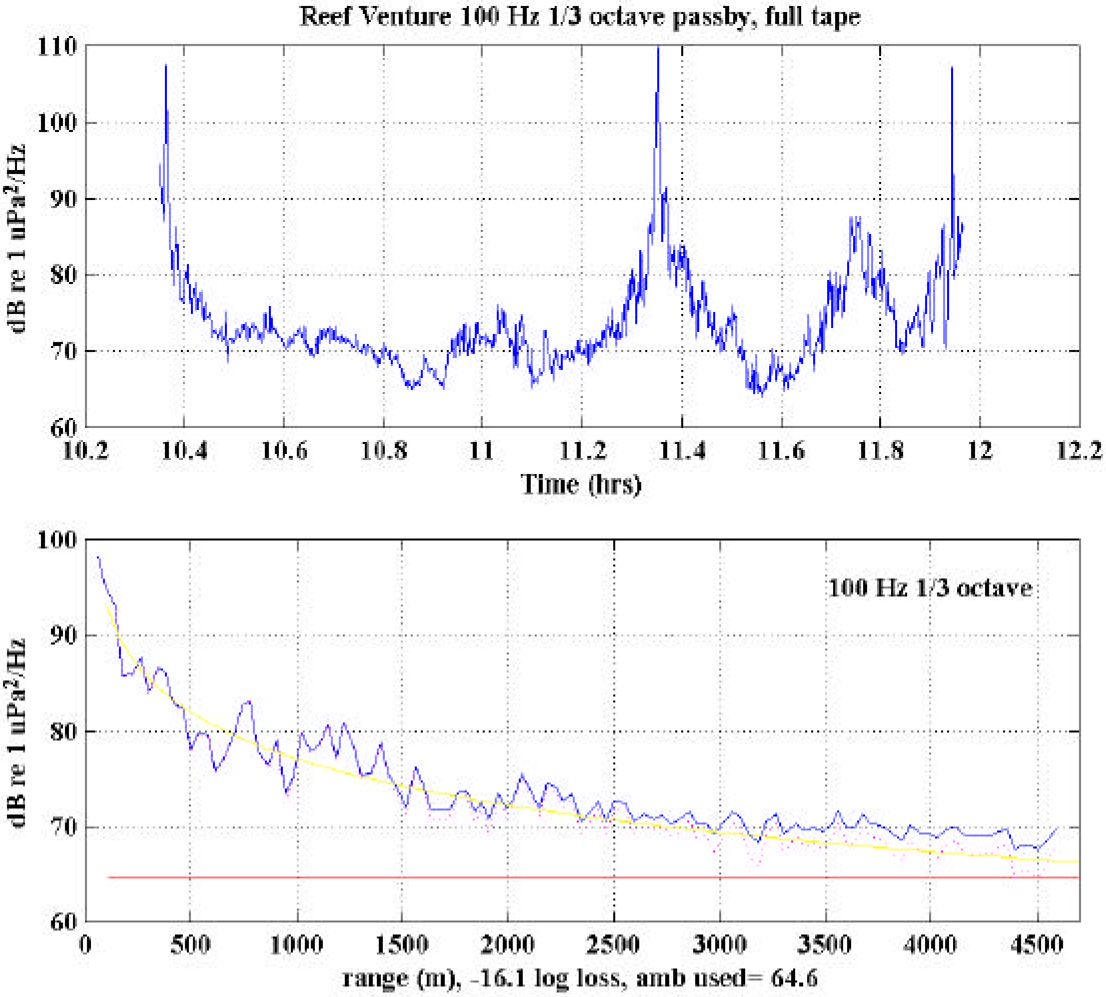

Figure 17: (top): Reef Venture 100 Hz 1/3 octave with time for entire tape from which propagation calculated. The departure of the RV after deployment can be seen to 10.5 hrs, two sets of approach-depart by the RV can be seen over 11.1-11.9 hrs and the approach for retrieval is apparent > 11.85 hrs. (bottom): Shown are the RV 100 Hz 1/3 octave approach leg as received (solid line, hydrophone within 30° of vessels bow), 100 Hz 1/3 octave approach values corrected for additive influence of ambient (dotted line), fitted logarithmic loss curve (thickened curve, from equation 1) and the ambient level used (65 dB re 1μPa^2/Hz). Only the section over 11:09-11:23 hrs (11.15-11.383) from the top curve was used in these calculations.

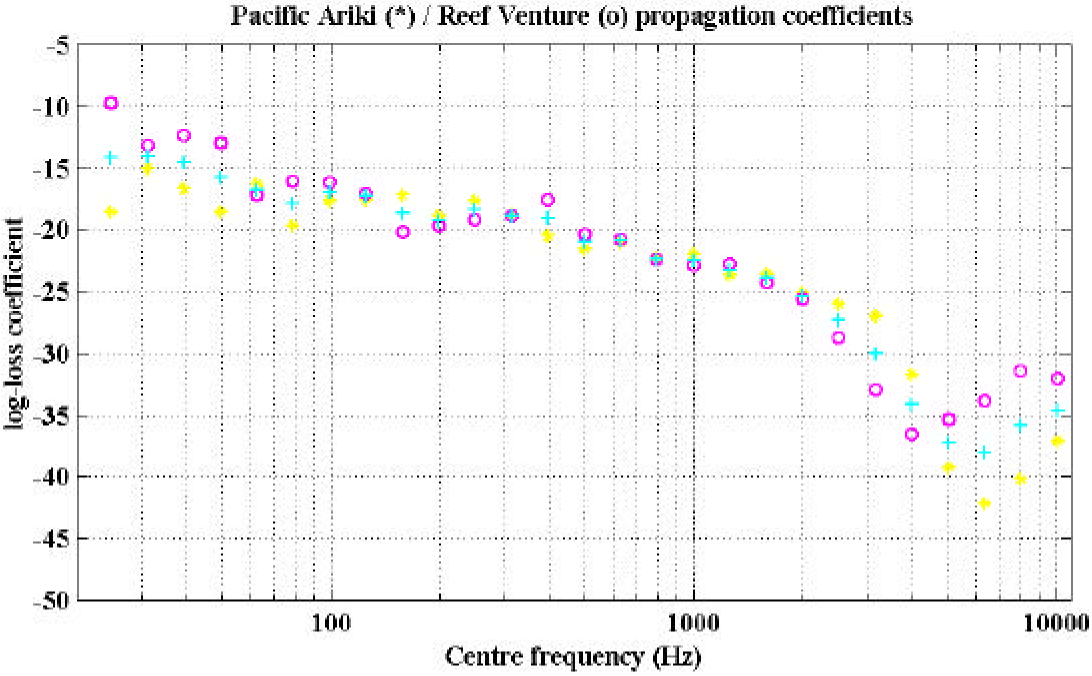

Figure 18: Mean logarithmic loss coefficients (+) for the loss of signal with range as derived empirically from equation 1, using the noise of Reef Venture (o) and Pacific Ariki (*) during approach and departures as the source. The loss increases significantly with increasing frequency as would be expected.

To plot the broadband level of each vessel as a beam pattern an x-y grid was established and from this the range and angle to the centre point calculated. Stepping through each 1/3 octave from 25 Hz to 10 kHz: the source level for each point in the grid was calculated from the appropriate 2nd order polynomial of angle-from the bow with received level; the propagation loss for each point at this 1/3 octave was calculated using the log-loss equation 1, and subtracted from the source level to give the received level at each point; the received level at each point was re-sized to include any additive effect of ambient noise (which re-sized points below the ambient noise to the ambient level); and the resultant array was converted to intensity. Each 1/3 octave intensity was then summed, and the result converted back to dB to give the broadband signal across the grid. Points which lay outside the geometry of the passby were then removed. This array was then plotted as broadband level with aspect as a contour plot.

Figure 19 (top) shows the beam patterns and calculated received broadband noise for each vessel underway (*PA* 11 knots, *RV* 12 knots) on a 20 x 20 km grid. The background ambient noise used was that shown on curve H, Figure 7 and can be considered as the lowest likely to be encountered at the site. This curve gave an ambient noise of 90 dB over the 1/3 octaves 25 Hz to 10 kHz. From Figure 19 it can be seen that the *PA* is still influencing the background noise at the extremities of the plot, although the contribution at these ranges is very small given the additive effect of the background noise (accounted for in the plot calculations). This agrees well with values of the *PA* noise measured during the passby. At 9.3 km the departing *PA* had reached a broadband level of 103 dB re 1μPa (bandwidth 25 Hz - 10 kHz 1/3 octave centre frequencies) where the recording ambient noise over this frequency range was estimated to be 100 dB re 1μPa (due to flow noise). In contrast the *RV* noise shown in Figure 19 for the vessel steaming at 12 knots, has reached well within 3 dB above the background noise an all aspects except directly ahead and astern (Figure 19 bottom plot). In recordings a tone produced by the approaching *RV* can be heard at 5.5 km, but the signal is not readily audible until 5.2 km. This agrees with the calculated broadband noise shown on Figure 19, where the signal would need to be at least 3 dB above the background to be audible.

Figure 19 shows that the *PA* radiated noise extends considerably further than the *RV* noise. This would be expected given the differences in the vessels, the *PA* is 2600 tonnes, 8000 Hp and 64 m long, the *RV*, around 20-30 tonnes, 450 Hp and 20 m long. Although the *PA* noise extends out to a long range compared to the *RV*, it must be pointed out that given the logarithmic nature of sound propagation in the sea high levels will only be experienced at short range to the vessel. The calculated broadband noise (25 Hz to 10 kHz 1/3 octaves) for the *PA* steaming at 11 knots and the *RV* steaming at 12 knots on a 5 x 5 km grid is shown on Figure 20. Again considerable differences are apparent in the noise levels about the vessels. High levels of noise could be considered to occur within the 120 dB contour, or within 0.5-1 km of the *PA* (depending on aspect) and within 250 m of the *RV*.

To compare the vessels frequency content, composite narrow band spectra are shown for each vessel at 520 m ahead the vessel (11, and 12.5 knot speeds *PA* and *RV* respectively), on Figure 21. Each curve displays many tonal components associated with machinery and the shaft rotation, as well as more broadband noise associated with cavitation in the higher frequencies. The *PA* curve exceeds the *RV* curve, with both curves well above the lowest ambient noise level.

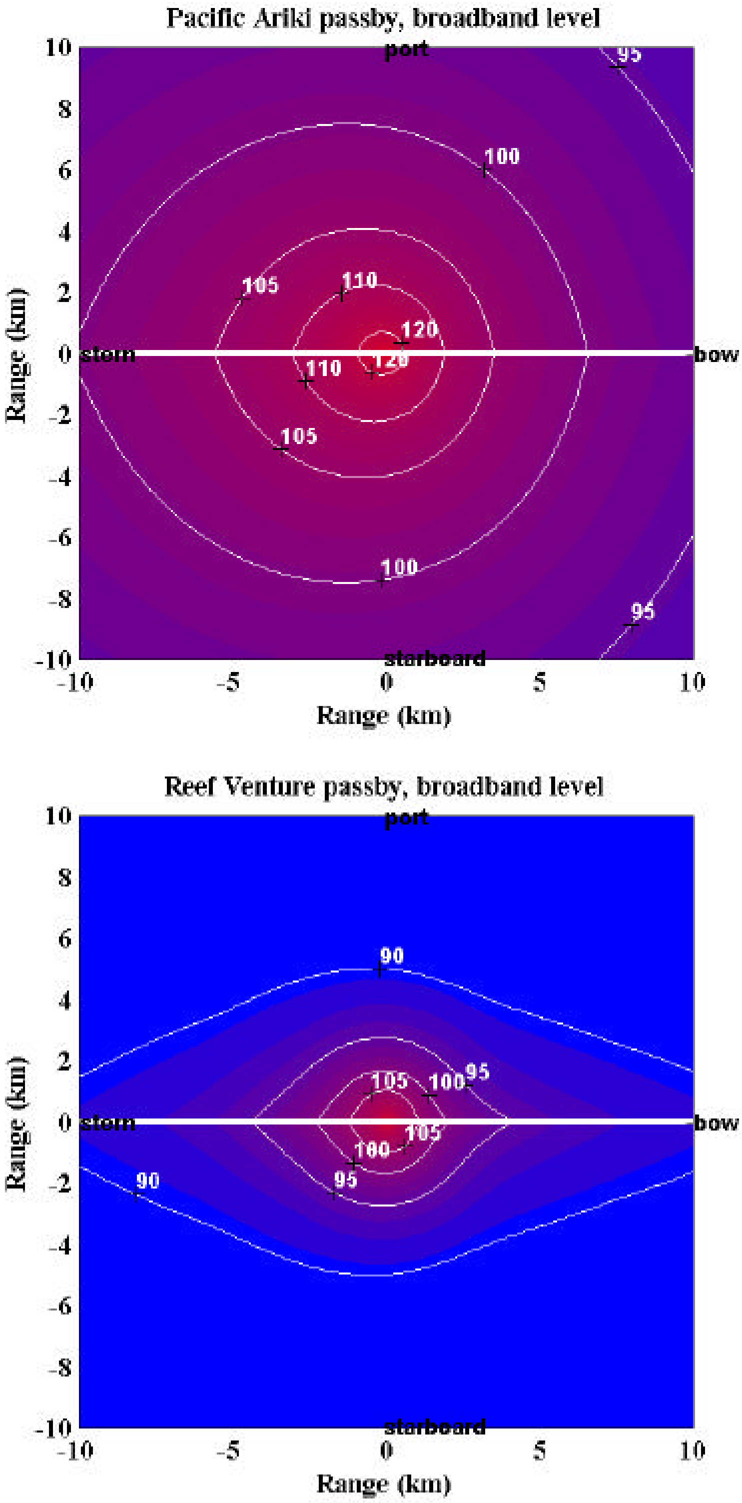

Figure 19: (top): Calculated beam pattern of the Pacific Ariki over a 20 x 20 km grid, presented as broadband sound levels (dB re 1μPa) over the 25 Hz to 10 kHz 1/3 octaves and referred to the lowest ambient noise curve H of Figure 7. The vessel is assumed to be at the plot centre steaming to the right at 11 knots. (bottom): Similarly calculated and presented beam pattern of the Reef Venture over a 20 x 20 km grid with the vessel travelling at 12 knots. Colours are coded so that 90 dB re 1μPa is pure blue and 180 dB re 1μPa pure red.

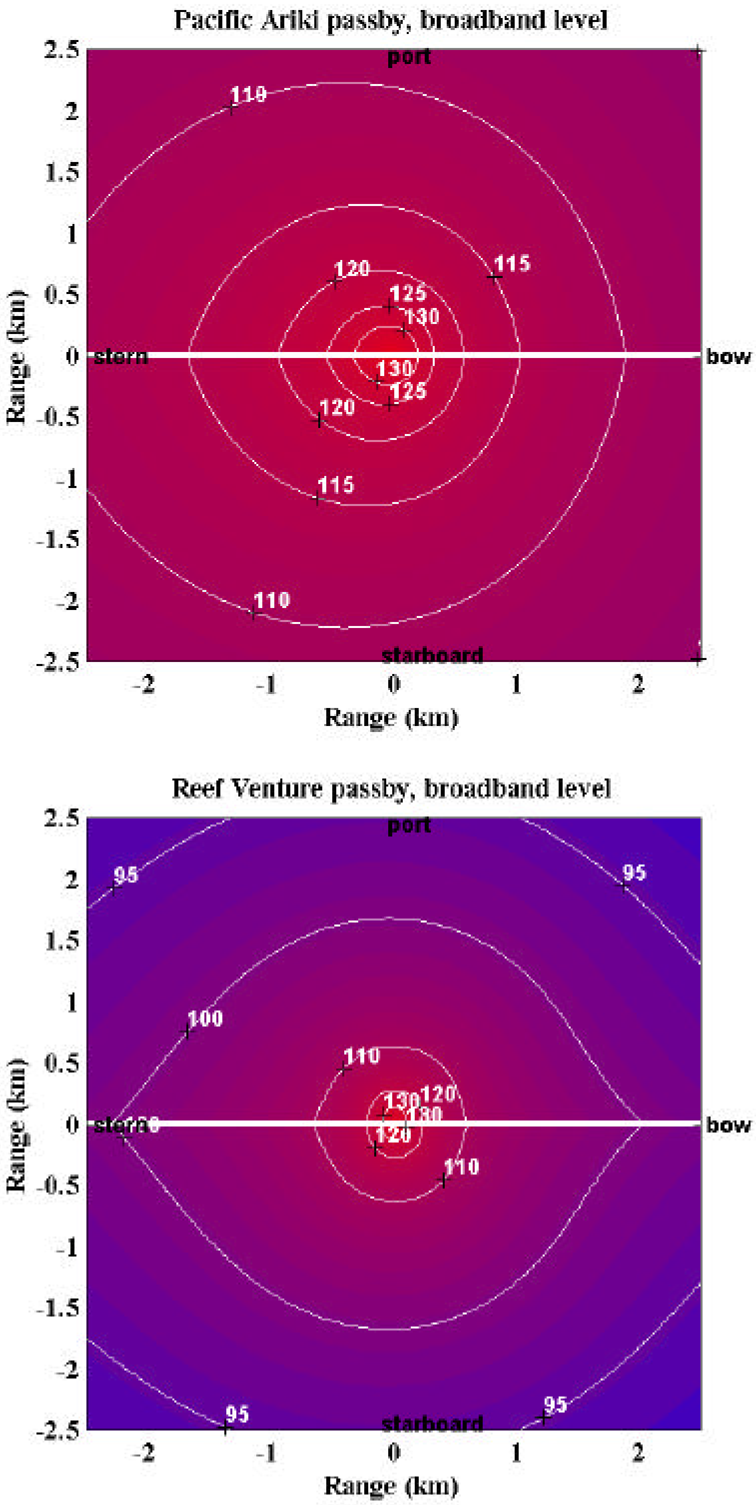

Figure 20: **(top)**: Calculated beam pattern of the Pacific Ariki over a 2.5 x 2.5 km grid, presented as broadband sound levels (dB re 1μPa) over the 25 Hz to 10 kHz 1/3 octaves and referred to the lowest ambient noise curve H of Figure 7. The vessel is assumed to be at the plot centre steaming to the right at 11 knots. **(bottom)**: Similarly calculated and presented beam pattern of the Reef Venture over a 2.5 x 2.5 km grid with the vessel travelling at 12 knots. Colours are coded so that 90 dB re 1μPa is pure blue and 180 dB re 1μPa pure red.

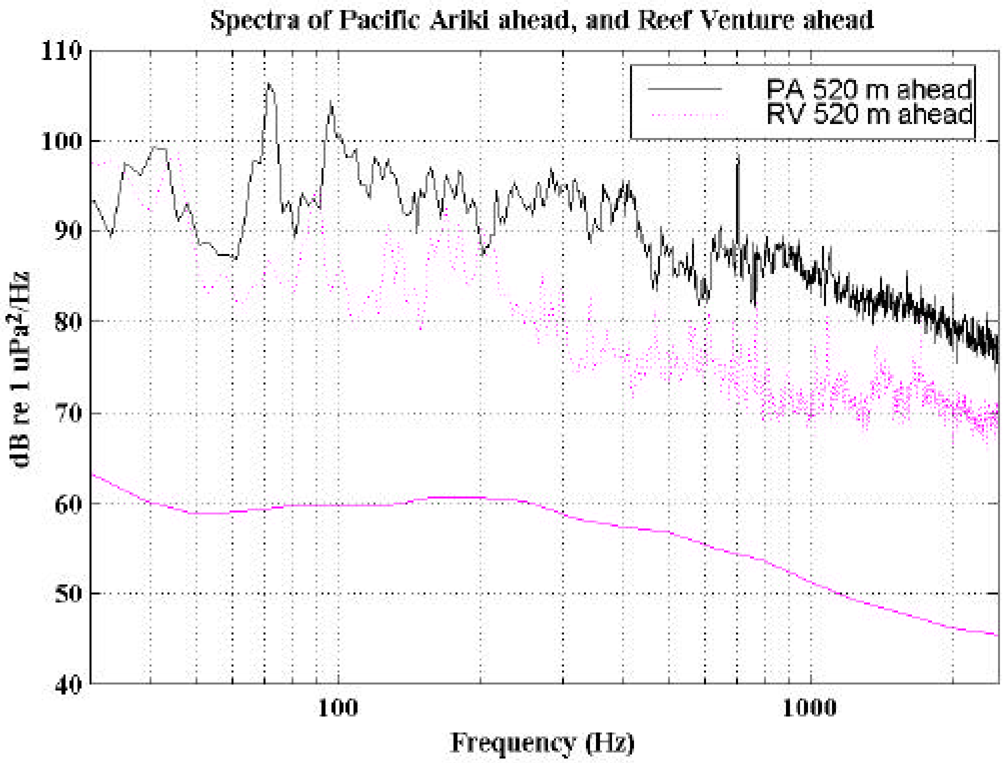

Figure 21: Spectra of the *Pacific Ariki* and *Reef Venture* as received from a hydrophone directly ahead the appropriate vessel at 520 m range and compared to the lowest ambient noise spectra (curve H Figure 7). Spectra used to obtain the plots were time averaged using a Hanning window, and 2.5 Hz resolution.

3.4) Hydrophone flow noise, CTD Casts and hydrographic regime

Ten temperature, salinity and depth profiles were made over the three days on site. These were initially taken so as to relate with sound propagation effects. The flow noise experienced in the vertically separated hydrophones of housing 1a (at 25 and 75 m depth), suggested that strong differential current flow existed in the area, with possibly surface layers travelling at a different rate and possibly direction than sub-surface layer. Drifting recordings made in zero wind and sea conditions from the *Nova* indicated that there was also a very shallow differential flow component. During such recordings and without a drogue deployed to align the *Nova* drift with that of sub-surface waters, the 30 m of hydrophone cable would often stream at a considerable angle.

Thus details of the CTD casts and the inferred hydrographic regime are presented below. The date, time, location and water depth of each site are given in table 3.3. Locations of each cast are given on Figures 2.1, 2.2 and 2.3. Profiles of temperature, salinity and computed sound speed (using the Medwin equation) are shown on Figures 3.16 and 3.17.

The ten temperature profiles were relatively consistent. In the top 5 m of water increasing surface temperatures were evident as the day progressed. Surface temperatures began at around 29^{o} C early in the day, increasing to reach as high as 30^{o} C by late afternoon. Below 5 m depth water temperature was less influenced by diurnal heating, showing a steady cooling with increasing depth to around 70 m. In this layer temperature dropped at 1^{o} C per 12-17 m of water (median drop of 1^{o} C per 14.4 m depth increase). Below 65-75 m and down to 100-110 m, all bar one cast displayed a stable temperature of between 23.5-24^{o} C. One cast (J on the 23rd at 17:30) showed a steadily decreasing temperature profile below 60 m. Where casts were made below 100 m they show a further cooling trend, with a near bottom temperature of 21^{o} C recorded at site B (21st, 15:55).

Table 3.3: Location and times of CTD casts:

Date	time	Latitude (S)	Longitude (E)	water depth (m)
210398	1402-1407	10 1.976	129 32.890	112
210398	1550-1600	10 0.247	129 32.932	114
210398	1905-1915	10 2.172	129 32.593	114
220398	0940-0950	10 9.269	129 34.273	107
220398	1120-1130	10 9.669	129 33.317	99
220398	1715-1725	10 2.262	129 33.332	113
220398	1920-1930	10 5.484	129 34.231	100
230398	1040-1050	10 4.362	129 21.355	103
230398	1305-1315	10 0.187	129 27.680	111
230398	1725-1735	10 0.591	129 32.139	114

The salinity profiles all showed a uniform body of deep water below 60 m, with salinity gradually decreasing towards the surface. This and the temperature casts supported the notion that at least two different bodies of water were present in the area, a colder, denser body below 60-70 m with a mixed layer above this which gradually increased in temperature and salinity on moving towards the surface. Interestingly when the mean temperature of the bottom water (over 80-95 m depth) is plotted with range from the 200 m shelf edge contour (Figure 24) the mean temperature increases on moving inwards from the shelf edge.

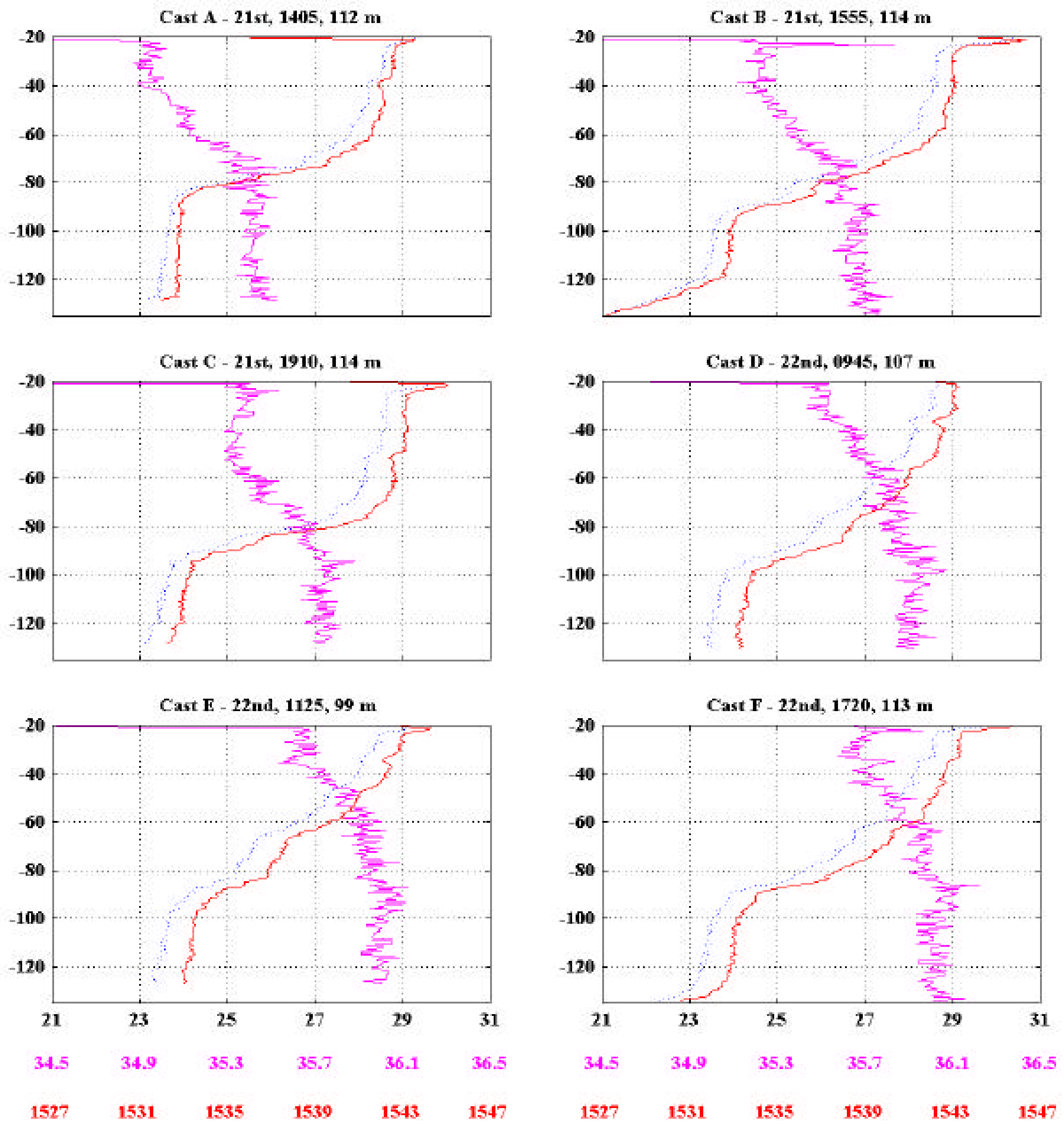

Figure 22: Temperature (dotted line), salinity (thin-solid line) and calculated sound speed profile (thickened-solid line) for CTD casts A-F (as per table 3.3). The appropriate horizontal scales are listed across the bottom (with sound speed in ms^{-1}) and depth (m) the vertical scale.

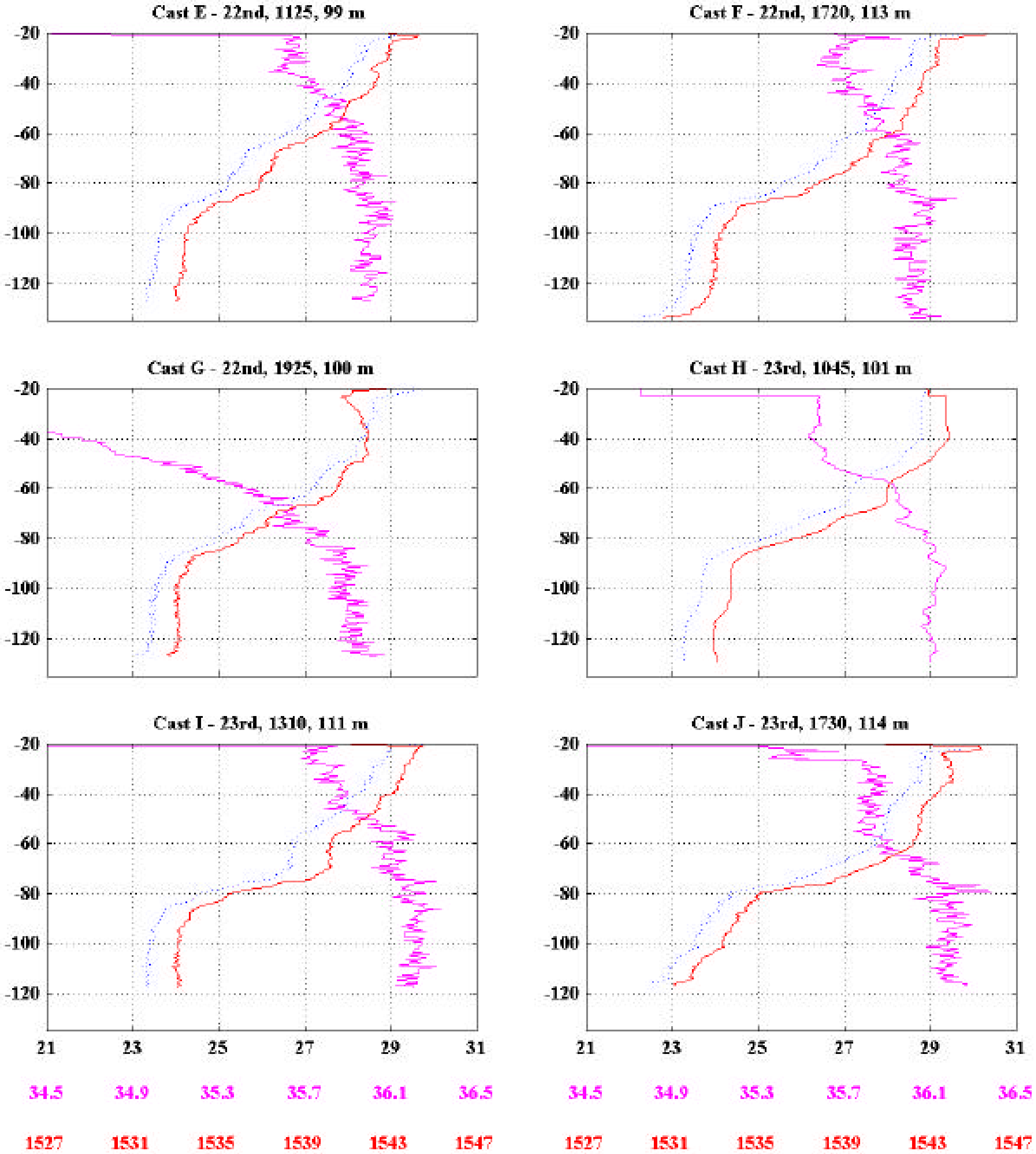

Figure 23: Temperature (dotted line), salinity (thin-solid line) and calculated sound speed profile (thickened-solid line) for CTD casts E-J (as per table 3.3). The appropriate horizontal scales are listed across the bottom (with sound speed in ms-1) and depth (m) the vertical scale.

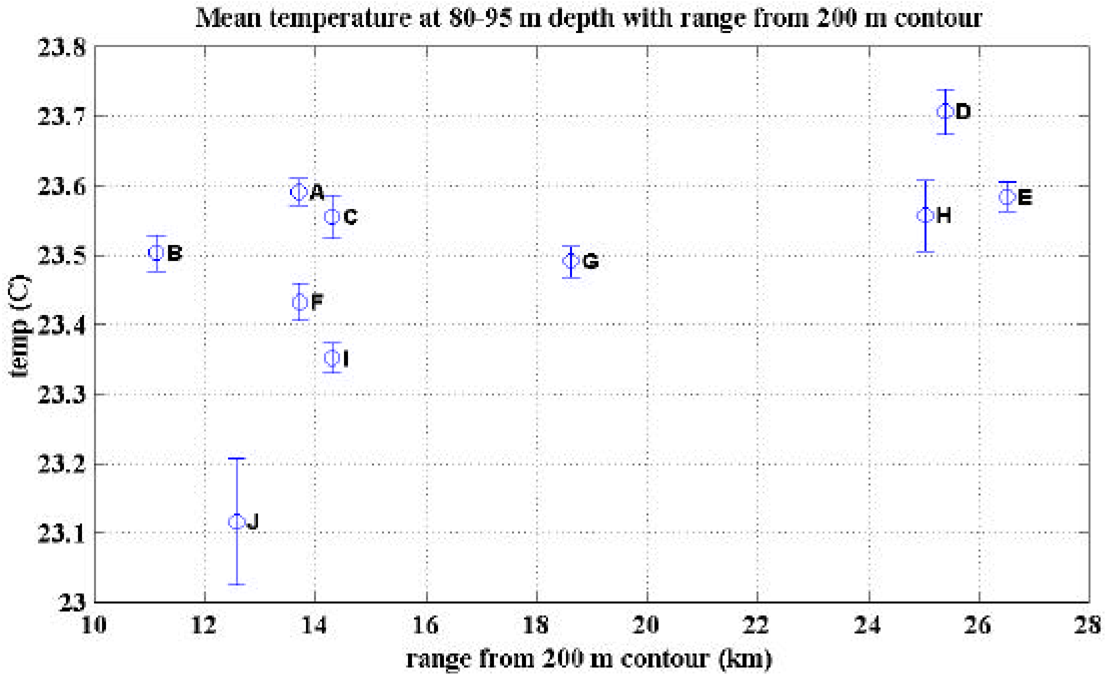

Figure 24: Mean bottom temperature over depth range 80-95 m with range from the shelf edge (200 m depth contour), with 95% confidence limit error bars. A gradual increase in bottom temperature can be seen on moving in from the shelf edge.

The consistent high levels of flow noise experienced by the housing 1 hydrophone at 75 m depth as compared to the hydrophone at 25 m depth could only have been achieved by it being dragged at a different rate and possibly direction to the housing, top hydrophone and surface gear which would have experienced the most drag. The seven sets of housing 1 drifted consistently between W to N, with drift rates and directions given in table 3.4.

Table 3.4: Drift rates and directions for the seven sets of housing 1. Numbering corresponds to that given on figures 2.1 to 2.3 and correlates to the order of analysis. The drift of set 12 is not shown on Figures 2.1-2.3 as the recording failed (believed due to the tape deck shutting down because of consistent overloading of the bottom hydrophone).

Set	date/time	drift direction (°)	drift rate (ms^{-1})
4	21st 15:20-1900	258	0.13
5	21st 21:06-21:51	227	0.25
3	22nd 08:35-12:21	263	0.20
9	23rd 10:20-11:56	218	0.12
10	23rd 12:54-13:32	322	0.17
11	23rd 13:58-16:30	348	0.24
12	23rd 16:58-18:58	0	0.27

The CTD casts suggest different bodies of water throughout the water column with a stable water mass below 60-70 m depth and a mixed layer above it. The increasing temperature of the deep water body as it moved up the shelf suggests that this may have been an intrusion of deep water from beyond the shelf edge which was creeping up-slope and gradually warming in the process. The hydrophone sets support the notion of differential flow between the deep (<60 m and shallow waters > 60 m).

The observations of a very shallow surface current from the *Nova* drifting hydrophone sets, suggest that further differential flow occurred in the shallow layer (< 60 m depth). The persistent W-N currents observed from the tracked housing 1 sets indicate that a persistent oceanic current flowed to the NW, which possibly had overlaid the local tidal flow.

4) GENERAL DISCUSSION

The production of underwater sound from the *Ocean General* operations has been covered by the above results and discussion. Briefly the rig-tender when maintaining station off the rig for loading operations, produced the highest levels of noise which under excellent listening conditions was audible out to 20 km (ie. Figure 13). The signal was dominated by cavitation noise produced by the vessels main propellers and bow thrusters, and so was broadband in nature. Comparatively high noise levels, arbitrarily defined by the broadband 120 dB re 1μPa level, extend out to around 3-5 km from the rig. Drilling and not-drilling operations when the rig tender was on anchor with main engines shut down, were considerably less noisy having a maximum audible range under ideal listening conditions of at best 11 km when drilling or 1-2 km when not drilling (Figure 13). With the rig tender on anchor the noise levels around the rig never exceeded 120 dB re 1μPa.

How these noise levels will impact on any nearby fin-fish populations is not clear based on an assessment of the literature. McCauley (1994) has reviewed the literature of noise effects on fin-fish, with respect to possible effects from offshore seismic surveys. Possible effects of high levels of man-made noise on nearby fin-fish populations could involve:

1) **Attraction** - There are documented studies of sharks being attracted (and repulsed) from specific types of noise (Myrberg et al 1976, 1978);

2) **Increases in stress levels** - Fish endocrine systems respond to stress with a series of hormonal induced changes which prime the fish to deal with potential threats (reviewed in Mazeaud et al, 1977). These stress responses are a normal facet of any animals life, although it is known that chronic stress creates physiological problems such as immune suppression;

3) **Disruption to any underwater acoustic cues** - Acoustic signals produced by a marine animal and used in a communicative sense with other animals, or which are physical in origin but convey environmental information, may be masked to some extent by continual intense noise;

4) **Changes in behaviour** - Levels of sound which are not sufficient to produce avoidance behaviour may elicit behavioural changes which can potentially disrupt normal activities;

5) **Localised avoidance** - It is known that fish will actively avoid certain types of sound, or leave an area in which intense sounds are being produced (Haymes and Patrick, 1986; Knudsen et al, 1992; Engås et al, 1993);

6) **Abandonment of a region** - It is possible that intense sound produced in an area over a long term (years) may cause abandonment of an area, although this effect is problematical and has never been conclusively shown to occur.

For each of these possible effects there will be a gradation of severity, which may not necessarily relate to what could be considered a serious environmental or commercial impact. For example an easily observable effect such as localised avoidance of a sound field, may have little or no significance to an animal from an environmental perspective. In contrast a more insidious but less obvious effect such as long term increased stress may potentially have more severe impacts.

To assess how the noise produced by the *Ocean General* operations would have influenced any nearby fin-fish populations, the nature of the sound produced and the hearing capabilities of the species concerned need to be considered. The highest levels of noise were broadband in nature and so would have encompassed the region of best hearing in fishes. This generally lies between 100-1000 Hz (Popper and Fay 1993), although some fish are known to have hearing at very high frequencies (tens of kHz, Mann et al, 1997) and at very low frequencies (< 20 Hz). Compounding any response are habituation to a noise source from which no back up threatening stimuli are received. Habituation can produce a very pronounced decrease in observed responses from fishes, with the author and colleague (Jane Fewtrell) observing an almost exponential decrease in behavioural response to nearby air-gun shots from juvenile striped trumpeter over a time scale of 10 minutes.

Studies into the effects of noise on fin-fish fall into several types:

1) **Physiological responses** - These have been mostly carried out in relation to aquaculture. Fish kept in noisy artificial environments, which until recently has been most aquaculture environments which use holding tanks, can be expected to suffer stress and possibly physiological damage which may retard growth. The noise produced in a mariculture environment involves fish which are constrained and exposed to the signal constantly. This differs from the situation of the *Ocean General* noise in that any nearby fin-fish are not constrained and the highest levels produced by the tender maintaining position has a duty cycle of less than 40% (calculated from Figure 10).

2) **Startle responses and avoidance** - Several laboratory based studies have been carried out on the startle responses of fish (eg. Blaxter and Hoss, 1981). Studies of avoidance behaviour have been carried out primarily with the intention of designing noise making equipment to keep fish away from critical areas, such as hydro-electric turbine, or cooling water inlets. These studies focus on using sounds of specialised nature, such as high level tone bursts (Blaxter and Hoss, 1981), impulsive signals (Haymes and Patrick 1986) or high frequency sources (Nestler et al, 1992), and so are not immediately relevant to the more continual broadband sound produced during the noisiest operations of the *Ocean General*.

3) **Response to vessel noise** - A considerable body of literature exists on the response of mostly commercial north Atlantic fish species, to the approach of vessels and to fishing gear (reviewed in Olsen, 1990). This work has focused on the reactions of fish to approaching trawl gear with an emphasis on improving fish catches, and with respect to determining changes in fish echo-sounder target-strength resulting from orientation changes bought on by behavioural responses to the vessel noise. Changes in target strength greatly alter echo-acoustic fish biomass estimates. It is clear that the fish which have been studied do avoid the approaching vessels to some degree, usually by swimming downwards or horizontally away from the vessels path. Such effects weaken with depth, with fish below 200 m seeming to show only small behavioural reactions. The studies have also shown that disruption is only temporary, and that fish resumed their schooling patterns and position in the water column within a few hours.
   A problem with these studies has been that none have provided accurate measurements or estimates of the noise field experienced by the observed fish during the appropriate vessel's approach. This type of noise differs from that produced by the *Ocean General* in that it increases over time, dramatically so at the range over which effects were seen. In vertebrate noise effects studies, it has been shown that sounds which increase rapidly produce a greater behavioural response than sounds of similar intensity but which increase less rapidly (eg. McCauley et al, 1996 for humpback whales). This is believed to be as the rapidly increasing sound, signals a rapidly approaching threat. For the most part, the *Ocean General* noise was of a continual nature.

4) **Response to high-level impulsive noise** - These studies have mostly looked at the response of fin-fish to impulsive noise sources used in offshore seismic survey work. Published works include Engås et al 1993, Pearson et al 1992, and Skalski et al, 1992. The author is currently running a

project on these types of effects. The intense but very short (mostly < 50 ms) pulses used in seismic surveys are nothing like the noise produced by the *Ocean General* and so the studies are not immediately relevant.

Given all of the above it will be difficult to accurately asses the effect of the *Ocean General* noise on any nearby fin-fish populations. Mitigating factors include: the low noise levels produced at times other than when the rig tender was maintaining station off the rig for supply operations; the low duty cycle of the periods of high noise levels (< 40%) and the lack of any threatening stimuli other than the noise, which will allow rapid habituation.

It is probable that during periods when the *Ocean General* was operating but the rig tender was on anchor, noise-effects were confined to behavioural changes within a few hundred metres of the rig. During periods when the rig-tender was maintaining station, behavioural changes may have occurred out to at least the 120 dB re 1μPa contour at 3-5 km, some avoidance may have occurred at shorter ranges and nearby fish would have been aware of the vessel at up to 20 km under ideal listening conditions.

The background noise could reach to 110 dB re 1μPa under force 5-7 conditions, at which the audible range of the rig with tender maintaining station would be reduced to approximately 10 km.

The recordings of fish choruses on the S edge of Evans Shoal, and the N edge of Tasmania Shoal indicated that these night-time planktivorous fishes were still active in areas insonified by the *Ocean General* noise. It is probable that partial masking of their calls would have occurred when a rig tender was maintaining station off the *Ocean General*. This noise would not have completely masked the fish signals (source levels of the call are in the order of 154-157 dB re 1μPa p-p at one metre, McCauley 1997), but may have reduced its audible range about a calling fish, to a similar range as experienced in force 5-7 sea conditions.

The recordings of probable choruses from immediately astern the *Ocean General* indicate that groups of these fishes may have been active near the rig. The slight drop in the chorus spectral peak from the recordings astern the rig as compared to choruses nearer shoals (800 Hz and 1000 1/3 octaves respectively) are in agreement with McCauley (1997). This frequency drop was speculated to be caused as larger fish could forage further away from their daytime resting place (shoals or reefs) than smaller fish. The swimbladder of larger fish produce lower frequency sounds than those of smaller fish, hence the lower chorus spectral peaks.

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APPENDIX 1:

Details of field activities over charter period.

19th March

14:00-18:30	load gear aboard *Reef Venture*, Darwin; prepare gear;

20th March

07:30-14:00	prepare gear; pick up satellite phone, sundry hardware
14:00-14:30	pre-sailing check of all safety gear;
14:30-17:00	depart Darwin, steam Tasmania Shoal; prepare gear;

21st March

07:30-08:30	arrive southern end Tasmania Shoal, deploy *Nova*, measure background sea noise;
09:11	deploy housing 1 (sample rate of 3 minutes every 45 minutes, bottom mounted hydrophone) in 70 m water at 10^{o} 9.622' S 129^{o} 32.618' on southern end Tasmania shoal (sheltered from rig noise) to measure background sea noise;
10:00-13:00	use *Nova* to measure noise of *Ocean General* from 150-500 m about rig, rig not drilling and relatively quiet;
13:37	deploy housing 2 (sample rate 51 s every 8.5 min, bottom mounted hydrophone) 460 m astern rig;
15:20	deploy housing 1A (continual sample, hydrophones at 25 & 75 m) in drifting mode with start position 500 m astern rig and drift to NW;
15:30-19:00	track housing 1A and *Pacific Ariki* which moves to and maintains station alongside *Ocean General*; record sea-noise from *Nova* on S end Evans Shoal; recover housing 1A;
21:06	deploy housing 1A drifting (25 & 75 m hydrophones, continual sample) south of Evans Shoal (9^{o} 57.54' S, 129^{o} 31.830' E), drifts NNW;
22:00-22:30	recover housing 1A, anchor on Evans Shoal;

22nd March

07:30-08:30	steam to position for *Pacific Ariki* passby;
08:35	deploy housing 1A drifting (25 & 75 m hydrophones, continual sample) 8 n mile SSW of *Ocean General* (10^{o} 8.946' S, 129^{o} 35.831' E), housing drifts due W;
08:45-09:40	track *Pacific Ariki* as it passes by housing 1A;
11:50-12:20	passbys of housing 1A by *Reef Venture*;
12:21	recover housing 1A; deploy *Nova*;
13:09-15:00	measure rig noise from 6 n mile to 150 m using *Nova*
16:25-17:00	recover housing 2 check, deploy @ 320 m astern rig
18:00-18:30	recover housing 1 check, deploy same position;
19:10	deploy housing 1A moored, north end Tasmania Shoal (10^{o} 5.255' S, 129^{o} 34.359' E) operating on 60 s sample every 15 minutes with hydrophones at 25 & 75 m;
20:00	anchored 3 n mile SE housing 1A position

23rd March

07:00-08:30	monitor movements of *Pacific Frontier* around rig;
09:00-12:00	recover housing 1A; steam to 12 n mile W *Ocean General*; deploy housing 1A drifting, continual sample (25 & 75 m hydrophones); measure background sea/rig noise; carry out passes of *Reef Venture* about housing 1A from 3 n mile off; recover housing 1A
12:50-13:30	deploy housing 1A 6 n mile W *Ocean General*, monitor rig noise; recover
14:00-16:40	deploy housing 1A 3 n mile W rig; deploy *Nova*, obtain measures of rig noise from 1.5, 0.75, 0.325 n mile with *Nova* then measure rig noise at 150 and 250 m off stern, port and bow of rig, strong N setting current experienced which ruled out making short range starboard measures; measure noise of *Pacific Frontier* at anchor with main engines shut down; recover *Nova*; recover housing 1A;
16:50-18:30	deploy housing 1A ~ 500 m NW rig; strong NNW drift; track
18:45	recover housing 2
19:00	recover housing 1A; steam to southern end Tasmania Shoal
20:15	recover housing 1; steam Darwin

24th March

11:00-16:00	arrive Darwin, berth at 11:30; pack; consign freight Perth

Appendix 2:

One third octave centre frequencies, bandwidths, and bandwidth corrections, as given by the DP430 spectral analyser and used in analysis.

Centre frequency (Hz)	band limits (Hz)	bandwidth correction (dB)
9.84	8.77-11.05	3.58
12.40	11.05-13.92	4.58
15.63	13.92-17.54	5.58
19.69	17.54-22.10	6.59
24.80	22.10-27.84	7.59
31.25	27.84-35.08	8.60
39.37	35.08-44.19	9.60
49.61	44.19-55.68	10.60
62.50	55.68-70.15	11.61
78.75	70.15-88.39	12.61
99.21	88.39-111.36	13.61
125.00	111.36-140.31	14.62
157.49	140.31-176.78	15.62
198.43	176.78-222.72	16.62
250.00	222.72-280.62	17.63
314.98	280.62-353.55	18.63
396.85	353.55-445.45	19.63
500.00	445.45-561.23	20.64
629.96	561.23-707.11	21.64
793.70	707.11-890.90	22.64
1000.00	890.90-1122.5	23.65
1259.92	1122.5-1414.2	24.65
1587.40	1414.2-1781.8	25.65
2000.00	1781.8-2244.9	26.66
2519.84	2244.9-2828.4	27.66
3174.80	2828.4-3563.6	28.66
4000.00	3563.6-4489.8	29.67
5039.68	4489.8-5656.9	30.67
6349.60	5656.9-7127.2	31.67
8000.00	7127.2-8979.7	32.68
10079.4	8979.7-11314	33.68