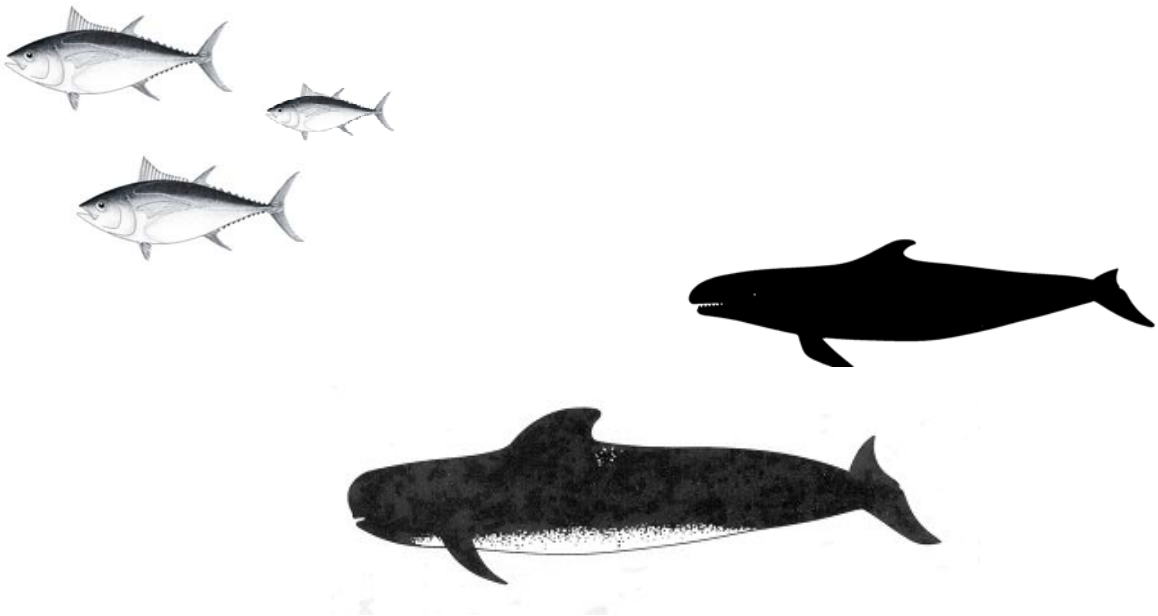
TESTING OF ACOUSTIC TRACKING SYSTEM FOR TOOTHED WHALES AROUND LONGLINE AND GILLNET FISHING GEAR, AND PRELIMINARY TRIALS OF DEPREDATION MITIGATION DEVICES FOR LONGLINE FISHERIES.

PROJECT REPORT (R02/0923)

Report to Eastern Tuna Management Advisory Committee, Southern and Western Tuna and Billfish Management Advisory Committee and Australian Fisheries Management Authority
September 2003



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TESTING OF ACOUSTIC TRACKING SYSTEM FOR TOOTHED WHALES AROUND LONGLINE AND GILLNET FISHING GEAR, AND PRELIMINARY TRIALS OF DEPREDATION MITIGATION DEVICES FOR LONGLINE FISHERIES.

SUMMARY

The prime objective of the current project was to demonstrate the potential of a MATLAB based tracking system to track toothed whales around longlines and gillnets. The ability of the system to track an acoustic source was demonstrated at extremely close range in a domestic swimming pool. A source was tracked in two dimensions at extremely close range under disadvantageous conditions for the system, where small measurement errors would generate major source location variation. Despite this, the source was located within centimetres of the known source. The array configuration relative to the array origin could also be determined by the acoustic pinger system associated with each hydrophone.

While the array was deployed underwater, it was capable of tracking the sonar emissions of nearby foraging insectivorous bats that have many acoustic and behavioural similarities to toothed whales including the use of high frequency short duration echolocation pulses and flexible, task dependent call repetition rates.

The system demonstrated its potential to track sound producing marine mammals in oceanic conditions where greater distances would nullify the constraints found, yet overcome, in the 9 m pool. Based on this small scale test, the full scale system proposed for the Coral Sea tuna longline fishery in Phase I is expected provide locations of toothed whales around longline fishing gear with sufficient resolution to statistically estimate distance between the whales and the gear, as the basis of an experimental evaluation of depredation mitigation methods.

The toothed whale primarily responsible for depredation in the northwestern Coral Sea has been determined to be the short-finned pilot whale (*Globicephala macrorhynchus*). Underwater photographs taken by fishing crews of toothed whales feeding on hooked fish were clear. The acoustic signature of depredating animals, and bite marks on fish, were comparable at least to pilot whales. Depredation from false killer whales, from identification of the bite marks at least, still occurs in some areas of the Coral Sea fishery.

Within the time frame of the known Japanese and domestic tuna handline and longline fisheries in the Coral Sea, short-finned pilot whales are considered to be recent comers relative to other species such as the false killer whale, although the short-finned pilot whales was present in the Coral Sea at the time of the development of the domestic tuna fishery.

Available gut content data for beached pilot whales of both short-finned and long-finned pilot whales in sub-temperate and temperate waters suggest that squid species are a major component of their diet. Krutzler (1952) proposed that short-finned pilot whales described as teuthophagous (*i.e.* squid eaters) were suction feeders. Werth (2000) described long-finned pilot whales as being close range suction feeders and described the process in detail. Squid were generally consumed mantle-first, and small fish head-first. If prey items were not sucked through to the stomach on the first attempt, the peg-like teeth and tongue were used to re-position the prey in preparation for another attempt.

With squid almost certainly the major component of pilot whale diet it would seem appropriate that east coast and southern and western tuna and billfish longline fisheries refrain from using squid as bait during periods when pilot whales were present in fishery areas.

Presentation of a natural food source as a bait would positively reinforce the depredation response.

The diurnal diving behaviour of short-finned pilot whales was recently studied by Baird *et al*. (2003). Deep diving behaviour observed off Hawaii, presumably for feeding, was reported during the day and night. Deepest dives (typically 600-800 m, maximum 27 minutes) were recorded during the day. Night-time dives were shallower (typically 300-500 m) that reflected a rise in the prey within the deep scattering layer. The rate of deep dives (>100 m) was four times greater at night.

Social activity occurred during long bouts of shallow (<100 m) diving during the day (Baird *et al*. 2003). It is unlikely that Coral Sea tuna longline operations would exceed the depth range of short-finned pilot whales and that these toothed whales would always be able to access longline hooked fish within Australian tropical tuna fisheries. It would not be feasible to expect that alternative gear setting arrangements could significantly reduce interactions on a time or depth basis. It is unfortunate that the social activities of short-finned pilot whales could well coincide with the same depth range as tuna hooked on longlines during daylight hours during the spring/summer fishery in Coral Sea waters.

This project commenced logistic trials with the Coral Sea tuna longline fishery to assess the feasibility of deployment and anticipated longevity of gillnet bycatch mitigation pingers primarily as they could be the basis for a future acoustic depredation mitigation device. While logistic improvements are required, some encouraging results for the devices, although totally unexpected, were observed by one industry vessel.

In November 2002, the South Pacific Regional Environment Program in Apia, Samoa hosted a toothed whale depredation workshop. The essential elements of the Plan of Action from the Workshop were that a series of Priorities be established for mitigation approaches. Of real concern to longline industry management was the apparent recognition by the Workshop of incidental toothed whale bycatch, although no data are available to confirm the extent of this. This has EPBC Act significance for Australian tuna longline fisheries. Depredation was not considered normal behaviour, rather opportunistic behaviour that should be reduced or prevented, as long as the methods were compatible with the conservation of toothed whales.

Developments of an acoustic strategy of AFMA, ECTUNAMAC and SWTBMAC to address the depredation problem were presented at the 8th Western Pacific Acoustic Conference in Melbourne, 7-9 April. The first ever bio-acoustic session at a Western Pacific Acoustic Conference provided an opportunity for an international audience to be acquainted with the problems of the fishery, with opportunities for further collaborative assistance with acoustic bycatch mitigation and tracking. WESPAC provided an opportunity to demonstrate that ETUNAMAC, SWTBFMAC and AFMA were approaching the problem in a methodical and ecologically sustainable manner.

The current project was to assess the effectiveness of possible acoustic and mechanical depredation mitigation devices. Discussions during the course of this project with defence scientists, mammal acousticians, behaviourists and physiologists have provided optimism for a wider range of depredation mitigation approaches than initially considered. The approaches include in no specific order;

- ‘stealth’ characteristics of fishing vessels, in particular acoustic disguise of their fishing operations involving specific fish finding equipment and machinery;
- acoustic modification / conditioning of toothed whale behaviour;
- chemical modification / conditioning of mammal behaviour;
- more appropriate species specific deterrent acoustic signals.

TESTING OF ACOUSTIC TRACKING SYSTEM FOR TOOTHED WHALES AROUND LONGLINE AND GILLNET FISHING GEAR, AND PRELIMINARY TRIALS OF DEPREDATION MITIGATION DEVICES FOR LONGLINE FISHERIES.

INTRODUCTION

The study was intended as a Phase II extension component of the initial study on the depredation effects of toothed whales funded by Australian Fisheries Management Authority (AFMA) and Eastern Tuna Management Advisory Committee (ETUNAMAC) (McPherson *et al.* 2002). This extension was to further assess the potential for depredation mitigation acoustic devices in Australian tropical tuna longline fisheries, and to continue development of methods for tracking toothed whales around longline gear as a means of achieving more appropriate experimental results to assess effectiveness. Analyses of acoustic source location methods concluded that the most appropriate tracking system for deployment from co-operating commercial vessels should be based on a 2 hard-wired hydrophone (ship-deployed) and 2 remote hydrophone (sonobuoy-deployed) system.

For the current extension, substantial yet temporary modifications were required to the optimal system partly developed in Phase I in order to demonstrate a lower resolution tracking ability suitable for demonstration purposes. The system was based on the construction of a 3 element temporary towed array with an aperture width of 50 m and a remote sonobuoy with an existing DAT recording system. It was proposed that this system would achieve approximate tracks of acoustic sources for demonstration purposes.

Up to 2000, false killer whales were thought primarily responsible for depredation events (Hisada 1973; McPherson 1991). McPherson *et al.* (2002) indicated that industry had recognised a species of pilot whale as being primarily responsible, presumably the tropical and warm temperate short-finned pilot whale *Globicephala macrorhynchus.* Other species of toothed whale in the area and capable of depredation events although not been implicated in regular depredation included killer whales (*Orcinus orca*),and sperm whales (*Physeter macrocephalus*), pygmy killer whales (*Feresia attenuata*), and melon headed whales (*Peponocephala electra*) (Nishida and Tanio 2001).

The Phase I study obtained acoustic data from the toothed whales in the Coral Sea including several echolocation runs directly toward hydrophones suspended behind baits. However no clear conclusions could be made concerning the taxonomic status of the toothed whales responsible for the depredation events and echolocation runs.

This extension was jointly funded between the two Australian Fisheries Management Authority Management Advisory Committees that currently experience major depredation losses on catch from toothed whales in tropical north eastern and northwestern Australian waters, namely the ETUNAMAC and Southern and Western Tuna and Billfish Management Advisory Committee (SWTBMAC) respectively.

OBJECTIVES

Five objectives were identified for this extension project.

1. Construction of a temporary, horizontal towed array, incorporating a pinger location system, a remote sonobuoy, and an FM radio control pinger activation system.
2. Test tracking of acoustic sources including pre-recorded mammal signals in shallow coastal waters and around longline gear.
3. Development of industry recommended prototype mechanical devices incorporated into existing commercial gear.
4. Procurement of 12 variable frequency sweep acoustic pingers (at $300 each) and distribution to commercial vessels for testing under specific conditions.

METHODS

Acoustic hardware and software

A single channel, low noise and variable gain (*i.e.* 10-50 dB) amplifier boost in addition to the 36 dB gain from the HITECH hydrophones was constructed by James Cook University Engineering Lab (Mr John Renehan) to increase the hydrophone signal to the audio-industry based RME HAMMERFALL sound card. Construction of a 6-track signal amplifier has commenced.

COOLEDIT PRO ver 2.0 (Syntrillium Software) was initially used as the multi-track acoustic software to save digital multi-track data from the 96 kHz analogue-to-digital sound card. Time-of-arrival-differences (TOAD's) between the tracks were completed manually (McPherson *et al*. 2002). However as COOLEDIT PRO could not save multi-channel (*i.e.* n>2) files in isolated tracks, the automated MATLAB cross correlation feature written for the system could not be used.

RAVEN v1.0 from Cornell University School of Ornithology permitted the saving of multi-track WAV files that could be read by the MATLAB cross-correlation feature. RAVEN was not available until after the field recording components of the project. ISHAMAEL (Mellinger 2001) was available to save multi-track WAV files for interrogation by MATLAB but could not be configured for the RMW sound card. ISHMAEL is configured for National Instruments data acquisition cards.

MATLAB v6.5 was used to develop a three dimensional tracking system.

Acoustic tracking

Fig 1 shows a MATLAB plot for the array configuration proposed to demonstrate the tracking system using synthetic data intended for this project extension (McPherson *et al*. 2002). Hydrophones were positioned in a line at 50 m spacing as a linear towed array. The hydrophone orientation originated at the origin with the second and third hydrophones aft of the origin and with negative *X* values as if the array was being towed towards the hydrophone in a sonobuoy 300 m forward and 200 m to the left (port) of the array. The sonobuoy is attached to the simulated net in green . The references to *X* and *Y* axes are arbitrary and are readily interchangeable.

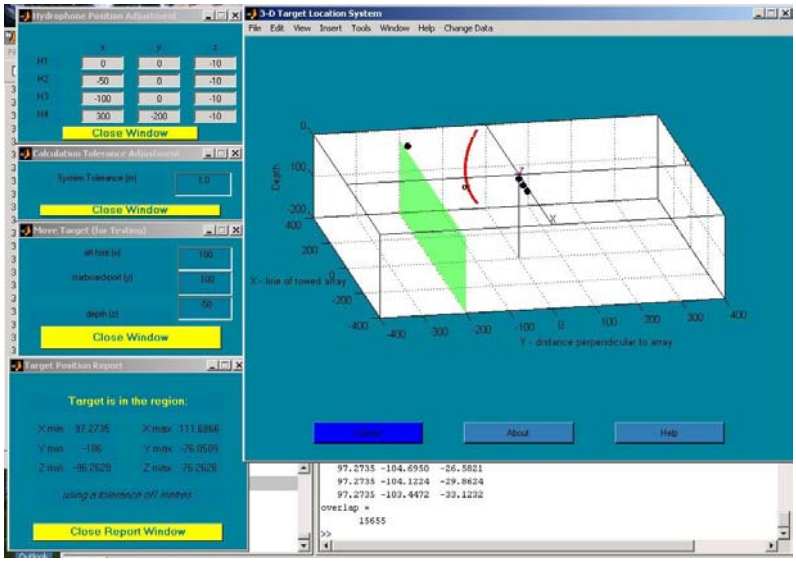

Fig. 1. Proposed MATLAB tracking array configuration for this project. 3D view of location of source relative to the area of fishing gear (▇) and origin of the towed array (100 m ahead on X axis, 100 m to port on Y axis, 50 m depth on Z axis) using linear towed array and single remote sonobuoy (• hydrophones at 10 m depth, ∝ acoustic source, • possible locations).

Logistic deployment trials of dolphin bycatch reduction device

To assess the logistic effect of bycatch pingers at least on commercial fishing gear, 12 AQUAmark 200 units were purchased from the UK at approximately $300 each. Each unit weighs 370 cm and is 14 cm by 5.6 cm with a single attachment point (Fig. 2) and features an immersion activation switch.

The pingers arrived in November 2002 and were immediately deployed on a Great Barrier Reef Tuna vessel. Total deployment on Coral Sea longline gear was 30 days. The fishing crew was asked to assess the most frequent and optimal setting rates of pingers in association with normal longline setting, and the robustness of the units in longline fishing situations.

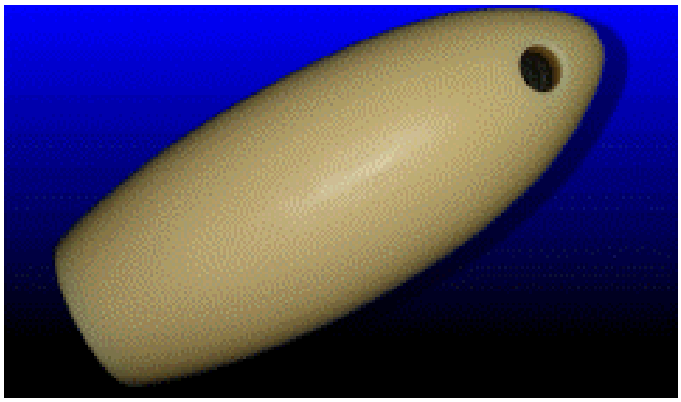

Fig. 2. AQUAmark 200 pinger used for logistic trials for depredation by catch mitigation trials. (dimensions 14 cm by 5.6 cm). (photo AQUA Tec)

RESULTS

Acoustic source tracking system

Towed array construction

To minimise costs the horizontal array cables were incorporated within flexible plastics for physical protection from the housing electrical industry. No permanent changes were made to the hydrophone cables in order that the towed array could be deconstructed for conversion back to the optimal configuration described in Phase I, specifically as the vertical array.

Three hydrophones were incorporated into the temporary array for preliminary tracking work (Fig. 1). The horizontal strength of the array was based on 12 mm diameter water ski float-rope that had a slightly buoyant capacity. The ski-rope and cables were bundled inside 12 mm plastic spiral-wrap that provided a horizontal rigidity. The cables and spiral wrap were then bound in two layers of overlapping 50 mm black duct tape. Present Naval and seismic systems use Kevlar sections for horizontal and vertical rigidity and are enclosed in PVC or dense rubber tubes filled with neutrally buoyant hydrocarbons and feature banks of vibration dampeners.

Hydrophone elements were not included within the spiral wrap therefore exposing them to the water for maximum signal detection. This also increased turbulence and subsequently 'self noise'. A pinger system for hydrophone location was incorporated. Undersea industrial grade cable connectors and joiners (at approximately $250 per pinger) were incorporated into the system.

The array was maintained at an average 5 m depth by a 4 kg torpedo-shaped lead weight paravane/downrigger. Cable from the vessel to the horizontal component of the array was surrounded in slotted black fluming to reduce cable strum. The horizontal configuration required was achieved by split fishing floats wrapped into the array at 2.5 m intervals and a small sea anchor at the distal end of the array. A schematic diagram of the array is given in Fig. 3.

The deployment performance of the array was tested from Great Barrier Reef Tuna vessels in shallow reef waters off Cairns where underwater diver observations of the gear were possible. The array performed as planned for forward motions of 0.5 to 3.0 kts to prevent catenary shape development caused by the horizontal cable sinking between floats. However the upper bound of the feasable towed speed is the standard idle speed for most tuna longline vessels making this system sub-optimal for deployment from Coral Sea tuna vessels.

During the project, more cost-effective towed arrays were offered for use by the project. However as the arrays were either military or seismic-based, the limited lower frequency acoustic bandwidth of the arrays were not considered suitable for the current application.

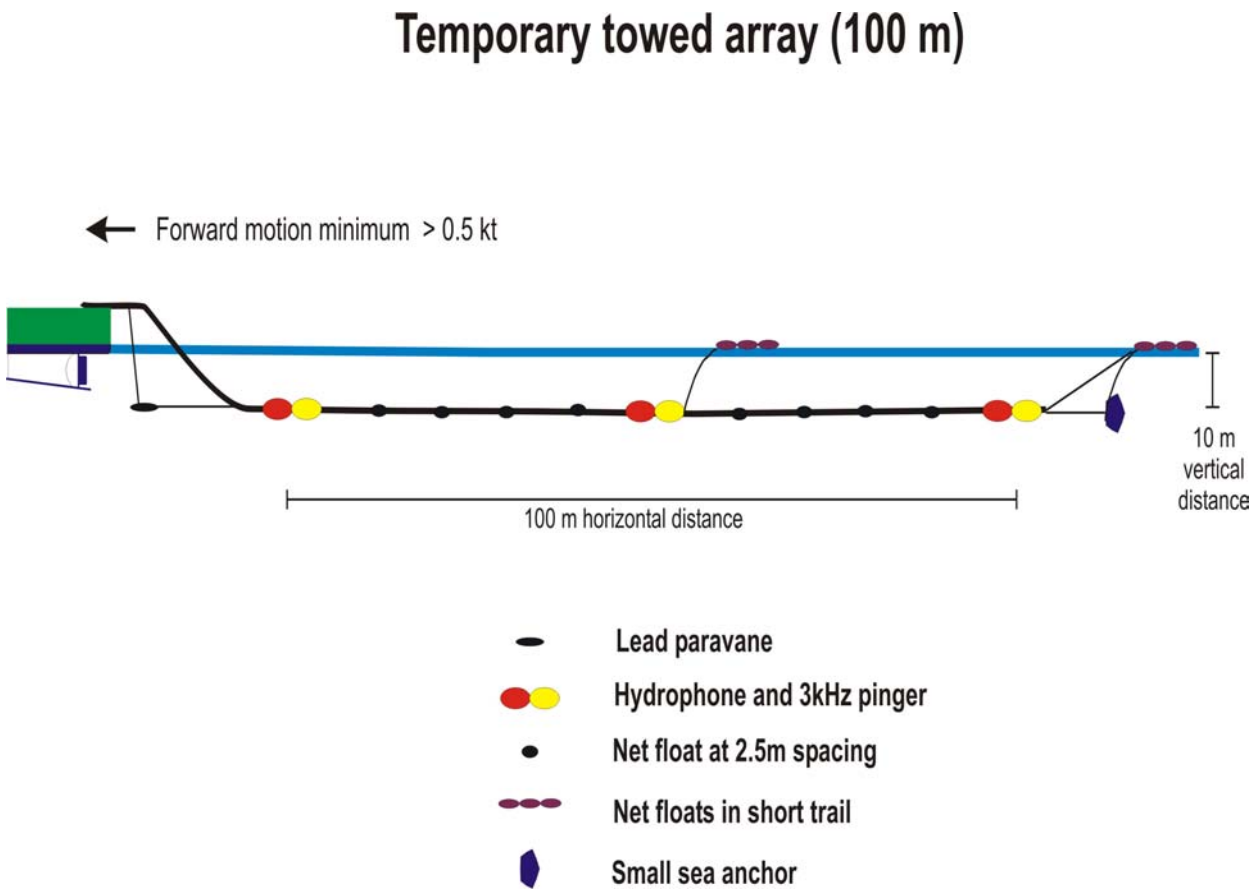

Fig. 3. Schematic diagram of temporary towed array. Hydrophones are 50 m apart, pingers feature a fundamental 3 kHz signal and mean depth of deployment is 5 m.

Acoustic controls

Control of the acoustic array is based on a 19" enclosure case that houses the laptop computer, the RME HAMMERFALL I/O sound card or proposed DAQcard, oscilloscope for signal calibration, pinger controls and appropriate cabling (Fig. 4). Battery (12V gel cell), rechargers and 240V power board are in the lower compartment.

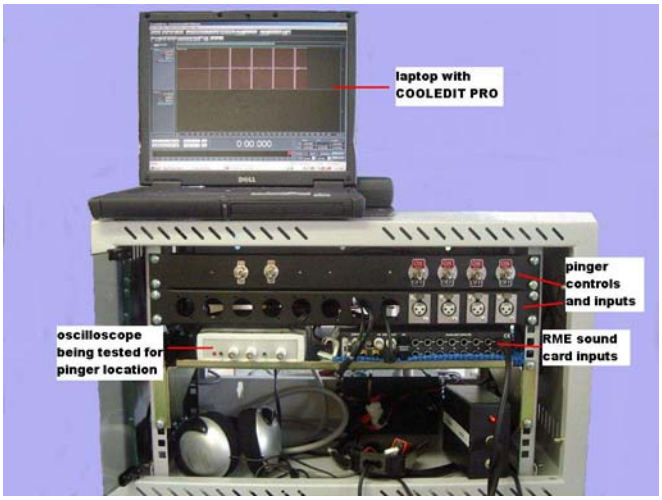

Fig. 4. Enclosure box for array control (laptop, sound card, oscilloscope and pinger controls)

Towed array tracking

Tracking of low amplitude acoustic sources such as the recorded source levels of toothed whales at 100-200 m range was not achieved from commercial tuna longline vessels by the temporary towed array partly due to an absence of animals on the days selected, and partly due to vessel 'self-noise'. Signal filtering could reduce much of this self noise with little loss of signals as most toothed whale signals are >1 kHz extending to >20 kHz.

Noise production occurs from the auxiliary, main engine, gearbox, water pump output splashing into the water, and hull movement through the water particularly near the stern of a vessel. Tracking with a shallow towed array at 5 m depth would be possible when drift conditions were >0.5 kt in the correct direction and all engines were turned off as 240V generation systems produce unacceptable levels of vessel noise. This would not be suitable for an operating vessel with catch aboard. Deeper deployed arrays incorporating remote sonobuoys would be less influenced by vessel noise.

Acoustic source within swimming pool

With deployment of the towed array from commercial vessels being considered sub-optimal the system was tested under confined small-scale experimental conditions where logistic problems were reduced. However accurate positioning problems were compounded by the need for extremely precise cross-correlation estimates for time of arrival differences between hydrophone pairs.

The array was deployed in a domestic swimming pool approximately 9 m by 4 m with depth ranging from 1 to 2 m. The hydrophone / pinger nodes were suspended from a floating wooden frame at set spacings at 0, 2.7 and 6.3 m and a constant depth of 0.5 m to simulate the

three element towed array. A single hydrophone 3.0 m perpendicular to the third hydrophone on the array was also at 0.5 m depth.

The array was deployed as a scaled-down length of 6.3 m comparable to the deployment shown in Fig. 1. The *X, Y*, and *Z* co-ordinates of the simulated towed array were (0.0, 0.0, -0.5); (-2.7, 0.0, -0.5) and (-6.3, 0.0, -0.5) respectively while the simulated sonobuoy co-ordinates were at (-6.3, 3.0, -0.5).

A LIEN (Cairns) acoustic alarm (McPherson *et al*. 1999) designed for humpback whale bycatch mitigation by QFS operating at only half power to simulate distant and potentially weak received mammal signals, was deployed from the wooden frame (*X, Y*, and *Z* co-ordinates of –2.70, 1.65, -0.50). The acoustic alarm generated a fundamental frequency of 3 kHz with a strong second harmonic frequency at 6 kHz (McPherson *et al*. 1999). The alarm simulated the low frequency variable output of the toothed whale signals described in McPherson *et al*. (2002) where the peak energy of an echolocation run directed toward a bait and hydrophone was between 3 and 4 kHz.

The 4 channel recordings of the alarm signals were digitally notch filtered to a centre frequency of the fundamental output of the alarm with a 400 Hz bandwidth. The six possible TOADs between the signals recorded by the four hydrophones (one per channel) were manually cross-correlated from COOLEDIT time series waveforms.

The project written automated MATLAB cross-correlation procedure for multi-channel .wav files was disabled for this operation as the COOLEDIT multi-track .wav files could not be interpreted as multi-track files by the MATLAB *wav-read* procedure. The incorporation of RAVEN multi-track software late in the project permitted the use of the automatic cross-correlation procedure on selected wav file segments.

The six combinations of hydrophone pair TOADs observed from the four hydrophones differed from the theoretical TOADs predicted by the system for <0.1 milliseconds corresponding to a distance of <15 cm in water at a speed of sound of 1,540 m/sec. The alarm was considered to be a point source, however as sound is produced from all outer surfaces of the 50 mm diameter and hydrophones recorded the signal from 360° around the source, errors of up to 5 cm were be anticipated.

The MATLAB system determined the location of the acoustic source within the pool. The three-dimensional system provided more solutions than required for the two-dimensional array and pinger that were all deployed at 0.5 m. The MATLAB screen with GUI inputs for hydrophone position adjustment, manual input of cross-correlated TOAD's, target position report giving maximum and minimum *X*, *Y* and *Z*-axis locations, tolerance adjustment, and all possible solutions for acoustic source location were plotted in Fig 5.

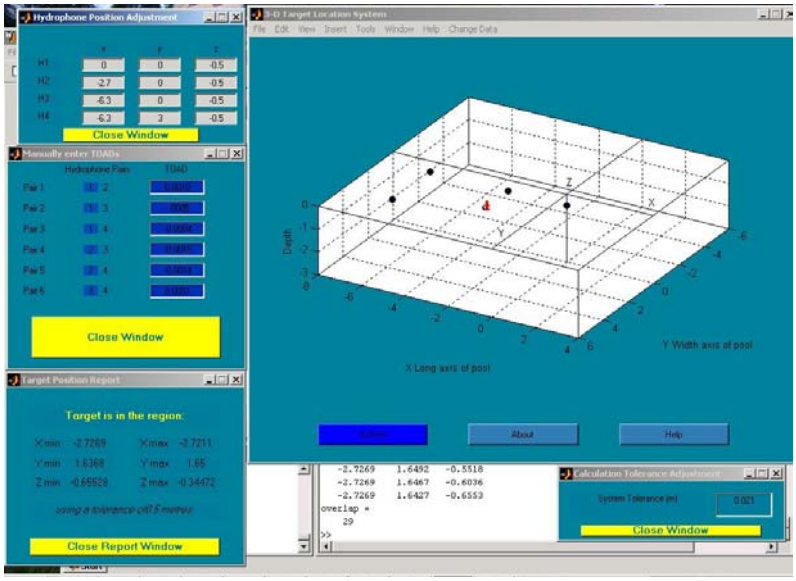

Fig. 5. MATLAB acoustic tracking system screen with input data screens and acoustic source solutions (●) in the swimming pool tracked by a 4-element array. The location of the acoustic source is given (∀).

The source location for plan and side views of the array with the approximate pool margins included are given in Fig 6. The *X*-axis is arbitrarily defined as the forward (positive) - aft (negative) axis that would normally define a ships heading. The *Y*-axis is to starboard (positive) and port (negative). The axes could readily be reversed to resemble a conventional number plane with X on the horizontal axis and Y on the vertical axis.

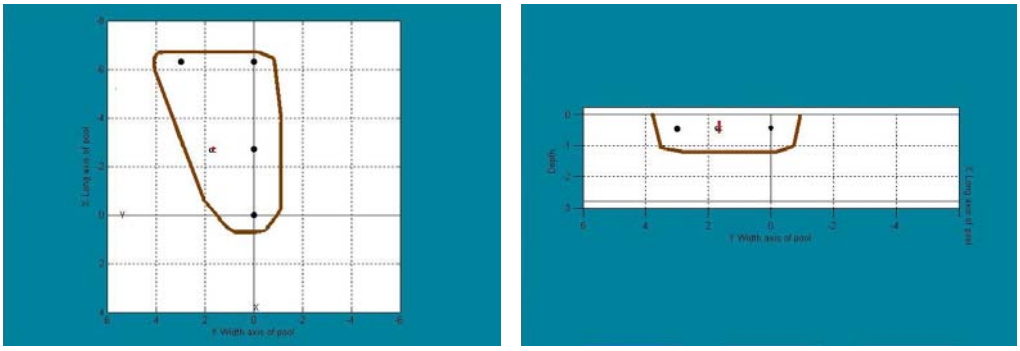

Fig. 6. Plan and side views (left and right respectively) of the MATLAB solutions for the acoustic source in the swimming pool. Approximate pool edge (▌), hydrophones (●), solutions (●) and acoustic source (∀).

The three dimensional solutions within the pool volume for the acoustic source as point sources are given in Table 1. The location of the source, and the locations of the 11 possible solutions predicted by the system for the given input parameters of Fig. 5 are given to the nearest centimetre. Mean solutions differ from the real location by 3 cm in the *X*-axis and 0 cm in the *Y*-axis. The mean solution in the Z-axis differed by 4 cm although the range of estimates was higher. The acoustic alarm is omni-directional (McPherson *et al*. 1999) with the piezo source in the centre. As the alarm is 5 cm in diameter and the acoustic signals

originate from the outside surfaces of the alarm with a 5 cm diameter in the *X-Y* dimension variation of <5 cm would be expected.

	X (m)	*Y* (m)	*Z* (m)
Acoustic source	**-2.70**	**1.65**	**-0.50**
Solution 1	-2.72	1.64	-0.40
Solution 2	-2.72	1.64	-0.45
Solution 3	-2.72	1.64	-0.50
Solution 4	-2.72	1.64	-0.55
Solution 5	-2.73	1.64	-0.35
Solution 6	-2.73	1.65	-0.40
Solution 7	-2.73	1.65	-0.45
Solution 8	-2.73	1.65	-0.50
Solution 9	-2.73	1.65	-0.55
Solution 10	-2.73	1.65	-0.60
Solution 11	-2.73	1.65	-0.66
MEAN estimate	**-2.73**	**1.65**	**-0.54**

Table 1. Locations (in metres) of the acoustic source and 11 possible solutions calculated by the MATLAB system in *X, Y, Z*-axis co-ordinates within the swimming pool.

The range of solutions in the depth plane (*Z*-axis) would be reduced further when at least one hydrophone was deployed at a greater depth than the others. This would be the case in an oceanic situation (McPherson *et al*. 2002).

The MATLAB system described above provides for the estimation of the location of a single acoustic source. The system has the ability to plot multiple locations of acoustic sources, whether from the same or multiple animals, with the provision for input of specific objects such as longline hook locations.

Bats overflying towed array in domestic swimming pool

During late evenings at the Principal Investigators home, a relatively large insectivorous bat with audible acoustic signals was heard vocalising in the vicinity of trees surrounding the swimming pool where the towed array was deployed below the surface. The regular search sonar pulses, as well as the quicker duration terminal stage depredation pulses emitted by the bat in the vicinity of the pool were readily detected by the array hydrophones deployed in the pool. The ability of submarine passive sonar to detect and categorise military aircraft is discussed by Urick (1983).

The bat emitted tonal signals with sharp inflections within the 9-15 kHz range. The signals were not unlike toothed whale communication whistles described by Rendell *et al*. (1999) in that the signals were tonal with frequency sweeps.

The sonar emissions of the bat were tracked during its normal feeding / socialising activity by the system while it was deployed in the swimming pool 0.5 m below the surface. Initially source locations were estimated using times modified for a speed in air of 330 m/sec with a speed of sound in water of 1540 m/sec for the distance to the hydrophone 0.5 m below the surface and at a grazing angle of 45°.

When the hydrophones were brought to the surface to eliminate media interface difficulties tighter source location boundaries were obtained (Fig. 7). The exact location of the bat was not known. It was tracked to be approximately 6-7 m above the level of the pool and at least 5 m away from the hydrophone at the origin of the array. It's flight path was known to be

constrained to between two trees 3 m apart adjacent to the pool. The estimated source locations of repeated calls were demonstrated to pass between these two trees, and at other areas around the pool area where the bats were known to frequent. The attributes of bat sonar, and how it is used during foraging, have often been compared to delphinid sonar systems (Au 1993).

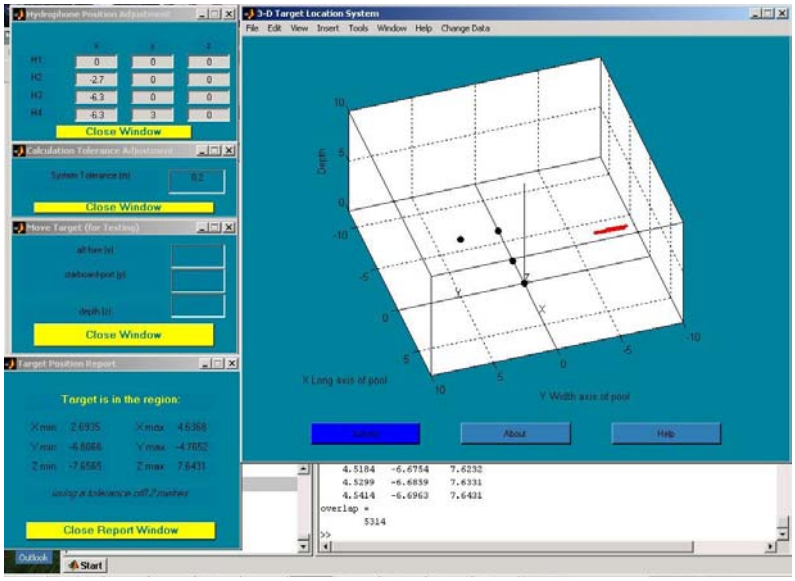

Fig. 7. MATLAB acoustic tracking system screen with input data screens and acoustic source solutions (●) in the swimming pool tracked by a 4-element array.

Alternative mammal tracking systems

Dr Andrew Madry (Madry Technologies) has developed a method for real time tracking of dolphins emitting sonar clicks. A pair of hydrophones records the TOADs of the sonar clicks (in milliseconds), and plots the lag time difference against a time sequence (Fig. 8). Repeated clicks from foraging dolphins may be plotted against time that permits an *X-Y* bearing angle to be established in real time.

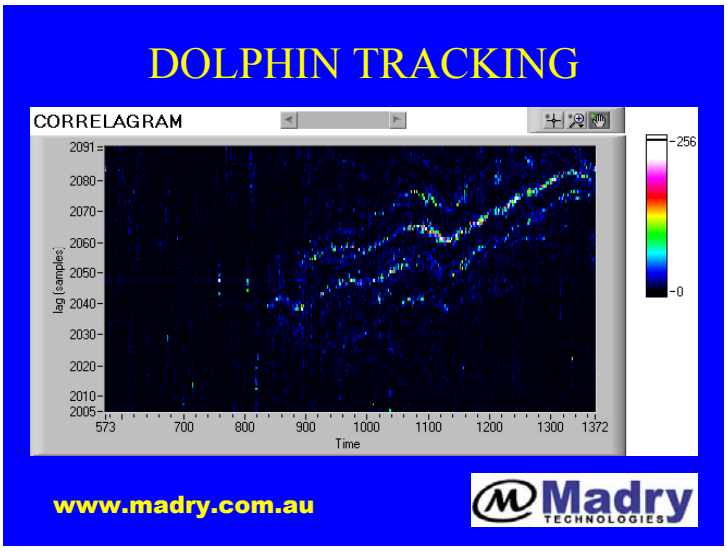

Fig. 8. Madry Technologies plot of hydrophone pair lag times for dolphin click train.

This system is straightforward in shallow two-dimensional situations provided a matched pair of hydrophones is deployed a short distance away to also assess bearing angle in order to eliminate the possibility of left-right ambiguity. Pairs of hydrophones in the depth dimension would permit three dimensional plotting of foraging clicks.

The strength of the system is that it permits real time, high speed tracking of sonar clicks that would be generated by toothed whales actively predating on hooked tuna during the hauling stage. Further development of this system is necessary to integrate with the MATLAB based hyperboloid tracking system in post-processing to provide three dimensional source location estimates.

Dr Dave Mellinger of the Pacific Marine Environmental Lab (National Marine Fisheries Service, Seattle) has provided preliminary three-dimensional tracking software based on MATLAB that uses a mathematical approach rather than the engineering approach described in McPherson *et al*. (2002). This system has not been used as yet as a trade-off between analysis speed and visual representation. Incorporation of the hydrophone signal amplification has permitted the utilisation of the 16-bit ISHMAEL program. Multi-channel ISHMAEL will be feasible when the multi-channel pre-amplification system is constructed. ISHMAEL is configured for a multi-channel National Instruments DAQcard.

Coral Sea toothed whale signals

In Phase I, McPherson *et al*. (2002) described burst-pulses, and echolocation runs toward a bait suspended immediately in front of a hydrophone deployed from a GBRT vessel. The echolocation clicks were therefore representative of source levels at 1 m re 1 micro Pascal at the instant of taking the bait. The toothed whale species responsible for the signals was arbitrarily attributed to false killer whales while it was noted that the bite patterns and industry observations suggested that a pilot whale (presumably short-finned pilot whale) could be responsible.

A 250 millisecond (250 ms) segment including a burst-pulse communication signal (Popper 1980) is expanded and presented in Fig. 9. The requency of the clicks is attenuated over 16 kHz due to limitations set on the recording system, namely 32 kHz sampling rate. Considerable burst-pulse energy existed down to at least 1 kHz while burst-pulse energy of an unknown level extended beyond 25 kHz.

Murray *et al*. (1996) provide a brief description of false killer whale click-trains, burst-pulses, whistles and considered that numerous states existed for a graduation between whistles and pulsed sounds (burst-pulses and clicks). There was no evidence for this form of graduation in the Coral Sea recordings, partly as no clear whistles were recorded. Scheer *et al*. (2003) reported a click vocalisation 'grunt' for Atlantic short-finned pilot whales assumed to be a burst-pulse with frequency components extending >24 kHz.

The available burst-pulse data are not sufficient to attribute species identification. Little is known of the frequency and relevance of toothed whale (presumably short-finned pilot whale) burst-pulses in open water, let alone around fishing gear when implicated in depredation events. Caldwell and Caldwell (1971) indicated that burst-pulses in spotted dolphins probably have a more emotional context while Overstrom (1983) linked burst-pulse behaviour with aggressive displays of bottlenosed dolphins resulting in auditory and tactile discomfort in conspecifics. McPherson *et al*. (2002) noted the comments of fishing crews that burst-pulses were the most common signals heard through the vessel hulls, rather than whistles.

Phase I (McPherson *et al*. 2002) presented a low frequency impulsive signal that coincided with a 1.2 second echolocation run, the acoustic signature of the terminal predation stage of a toothed whale toward, and taking, a bait suspended within 1 m of a 30 kHz hydrophone. The sonagram of the segment recorded by GBRT BALANCE is presented (Fig. 10).

McPherson et al. (2002) suggested the segment could be a low frequency component, or system tone, of an echolocation signal (Ken Schultz*, pers comm*.). Pairs of clicks were evident in the early or left hand component of the highlighted segment that were thought to represent multi-path transmission of low frequency clicks (Cato 1998; Kaschner *et al*. 1999). The first clear click was considered to be the direct path of the signal to the hydrophone, and the second indistinct click the reflected path of the signal off the water surface to the hydrophone. The time between the component clicks was approximately 2 ms.

The peak energy of the apparent click trains occurred between 3 and 4 kHz. Spectral analysis (SPECTRA PRO software) of the echolocation run with the hydrophone at 1 m from the bait indicated that source levels of the clicks varied from approximately 135 to 140 dB re 1 m at 1 micro Pascal.

The echolocation clicks of false killer whales usually have a peak frequency of approximately 40 kHz with energy extending down to about 10 kHz (Au *et al*. 1995). There are no data on clicks extending below 5 kHz.

The echolocation click data available for pilots whale species generally, are extremely limited and quite different to those of false killer whales. Brusnel *et al*. (1971) described each click of long-finned pilot whales as being composed of two component clicks separated in time by 1.25-2 ms with peak energy of each component click at around 3.2 kHz. Higashi *et al*. (1992) used a 8 kHz frequency hydrophone to identify a double click structure for some echolocation clicks of short-finned pilot whales. The peak energy of clicks was clipped to below 8 kHz by the system although peak energy appeared to occur between 5 and 7 kHz.

The echolocation runs recorded from the Coral Sea therefore appear to be those of a pilot whale species, presumably the tropical short-finned pilot whale. Tonal whistles were recorded however the signal-to-noise-ratio was so poor from the malfunctioning system (damaged DAT-hydrophone 3/8” and ¼” jack fittings) that descriptions were not possible.

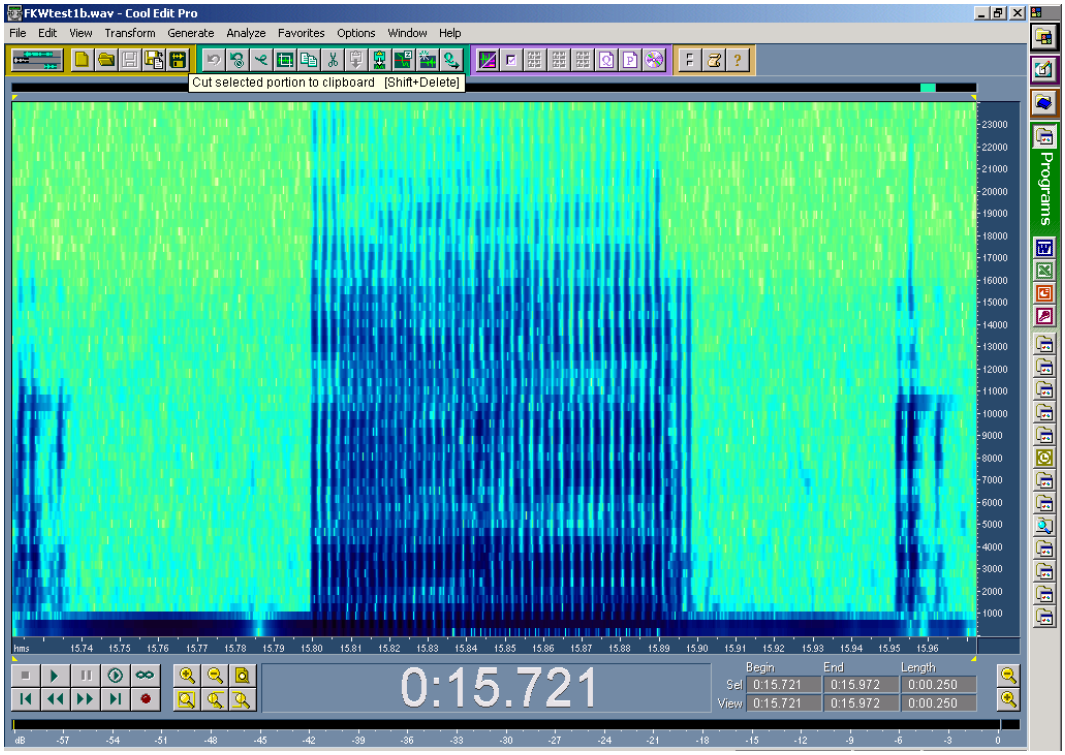

Fig. 9. Spectrogram of the time expansion of the burst-pulse highlighted above (Sample rate 32 kHz, FFT 64).

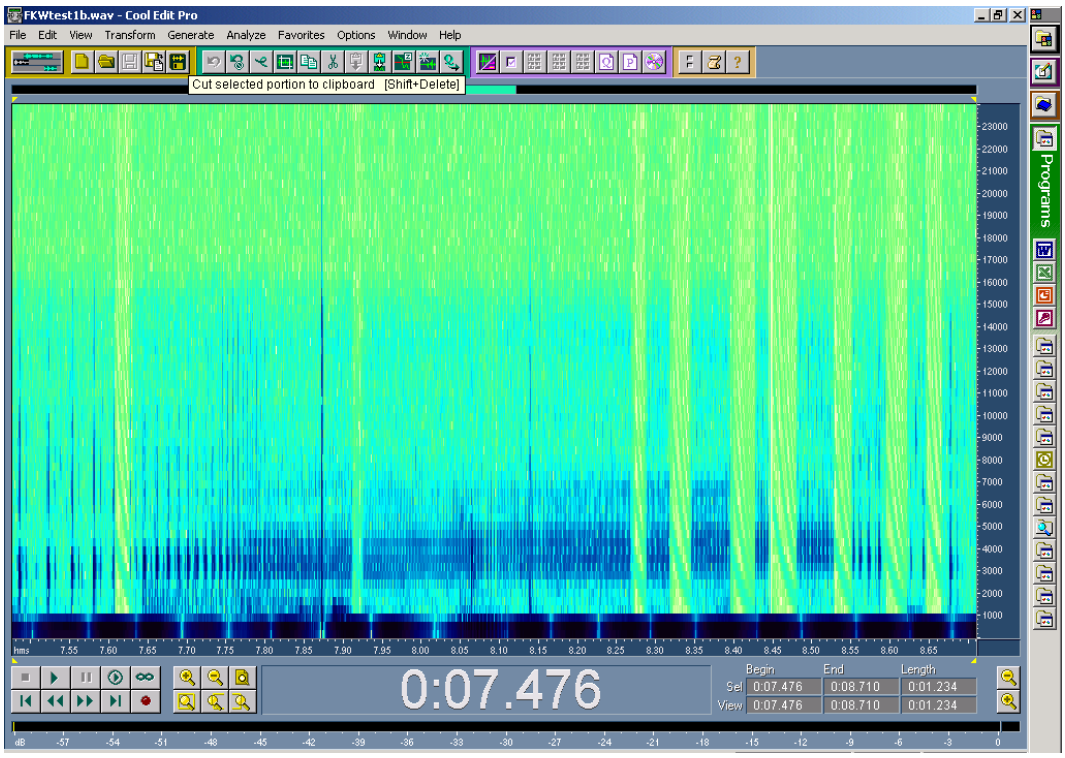

Fig. 10. Spectrogram of expansion of false killer whale highlighted presumed echolocation signal (Sample rate 32 kHz, FFT 64)

Diet and feeding behaviour of toothed whale species

McPherson *et al*. (2002) described two clear bite patterns from Coral Sea depredation events, one precise pattern attributed to false killer whales, and a ragged pattern attributed to short-finned pilot whales. The association between bite pattern and species is still speculation.

False killer whale depredation (visual sightings or presumed bite pattern) was the most common form of depredation during the period of the Japanese tuna handline fishery and developmental domestic longline fishery (McPherson, *pers. obs*.) up to the mid-1980's. Small numbers of false killer whales were identified around fishing gear and bite patterns identified in from field work conducted as part of an ECTUNAMAC funded examination of marlin bycatch in the longline fishery 1995 and 1996 (Campbell *et al*. 1997; *pers. obs*.). Evidence for false killer whale depredation was reported by industry from a restricted area of the Coral Sea during this study.

Nothing is known of the normal feeding behaviour of false killer whales in the Coral Sea. In the eastern Pacific false killer whales were most often seen chasing smaller dolphin species during tuna purse seine operations. Gut contents of false killer whales, from beached animals in temperate waters indicates that squid are a dominant prey (Alonso *et al*. 1999).

The crew of GBRT 'ENQUIRER' provided clear underwater photographs taken during fishing operations of toothed whales, identified as short-finned pilot whales by project staff, remaining next to hooked tuna and marlin, and appearing to be 'holding onto' fish, while they made repeated bites of the fish (Fig. 11). Toothed whales have also been observed removing the fish from the hooks with repeated bites and tugs, and taking the carcass away. These observations contrast sharply to the rapid and precise attack of false killer whales observed in the Coral Sea during the 1980's (McPherson, *pers. obs*.).

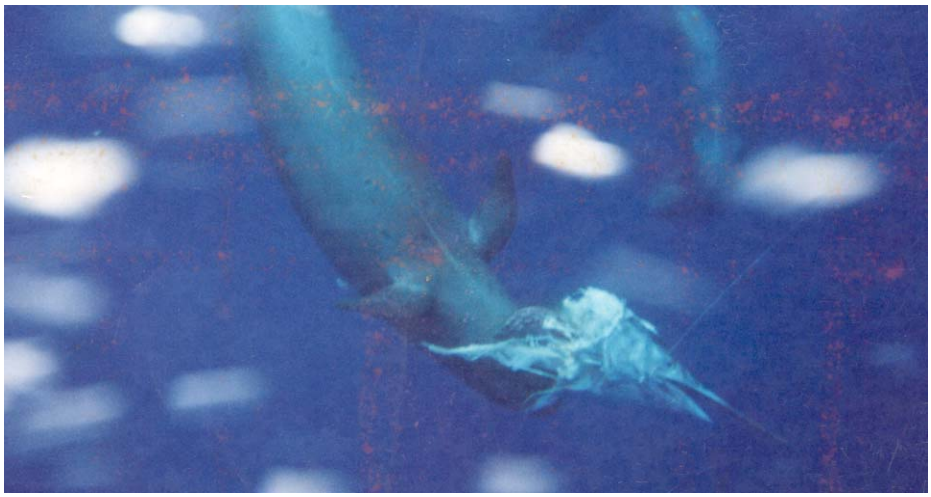

Fig. 11. Short-fin pilot whale depredating on hooked marlin remains. Two other whales are nearby.

The crew of GBRT 'BALANCE' provided tuna remains from Coral Sea depredation events that matched pilot whale depredation. Figures 12 and 13 are the plan and rear looking views of two tuna that were subjected to separate depredation events. The damage is ragged and could well represent the result of a 'chewing' action rather than a 'twisting' or 'snapping' action. Fig. 14 clearly shows the puncture mark of a large canine tooth in the cornea of the tuna eye.

Fig. 12. Plan view of tuna head after toothed whale predation.

Fig. 13 Front view of tuna head after toothed whale predation.

Fig. 14. Side view of tuna head after toothed whale predation showing canine teeth punctures in cornea.

Potential depredation mitigation methods

The AFMA/ECTUNAMAC Phase I study (McPherson *et al*. 2002) study identified the AQUAmark 200 dolphin bycatch reduction pinger built in the UK as a pinger device that offered potential for development into an acoustic depredation deterrent. The current production unit was never intended as a depredation mitigation device although it was considered that any depredation mitigation prototype would be of comparable size and weight.

Some of the eight random acoustic signatures of the AQUAmark 200 pingers spanned the echolocation click and peak acoustic sensitivity of false killer whales (Au 1993; Au *et al*. 1995; Thomas *et al*. 1988, Richardson *et al*. 1995; Thomas and Turl 1990; Rendell *et al*. 1999) and the presumed region of peak acoustic sensitivity of short-finned pilot whales assuming they have comparable attributes as other delphinids such as killer whales, false killer whales (Au 1993).

Loughborough University (UK) and IFREMER (France), are involved with the development of the AQUAmark pingers and are monitoring the effectiveness of AQUAmark 200 pingers in reducing depredation on line and net gear by large dolphins in Mediterranean waters under the ADEPT programme. Initial results of the program indicated that the AQUAmark devices had a very limited radius and the initial anticipated displacement, in the order of 200 m, may not be sustained as the animals could habituate (Dave Goodson, *pers. com*.). Later results of the ADEPT programme were published (STREP 2002). The units were effective for a trammel net fishery where landed catch weights increased, although inconclusive for other small-scale net fisheries. No reports were available for hook-based fisheries.

Vernicos *et al*. (2003) described the use of a multi-frequency acoustic device, one version specifically designed to deter dolphins depredating fishing nets in Greece. The devices reduced dolphin induced damage to the nets by >75%. Nets with reduced numbers of dolphin holes, produced significantly greater fish catches. The devices were distributed at 200 m along the net.

Deployment frequency and durability

The GBRT fishing crew determined that it was possible to deploy pingers at a rate of one pinger per branchline for relatively short to moderate longline lengths without affecting normal gear deployment. Pingers were initially trialled in three locations, namely

1. clipped to mainline
2. on the branchline at the clip
3. on the branchline attached to leaded swivel.

For simplicity, pingers could be attached on the mailine midway between branchline attachments that would provide comparable acoustic received level coverage. Pingers at the end of branchlines would not be difficult to deploy although they would occupy a large volume in the gear shooting boxes. Pingers attached to the lead swivels on branchlines would require substantial shooting box re-design.

Within two months of testing (approximately 30 longline sets) only three units were still functioning. Two units had been dropped or rolled overboard, while eight units had appeared to sustain external damage when striking the retrieving 'bullhorns' that coincided with unit failure. Most of the units failed over a two-day period when weather conditions were poor and identification of units coming up the line was difficult.

The units were not heavy (120 g in water) however the speed with which the units reach the 'bullhorns' then stop as the winch drum is braked to remove gear, may cause substantial damage to the operators hands as they are currently deployed on a short snood and tend to wrap around the hand of the operator. This could lead to some instances to unit loss.

A single malfunctioning pinger was shipped back to the UK manufacturer for examination. The manufacturer concluded that damage had occurred to the pinger casing although water intrusion was not a factor for the malfunction. The assessment of the manufacturer was that the sharp blows sustained during the retrieval process damaged the internal battery causing a short circuit (Edmund Ceurstemont, *pers. com.*).

Mammal bycatch reduction pingers attached to gillnets are usually protected from hauler damage (although approximately 50% slower than longline retrieval) by protection within small heavy fibre net bags. Given that only a single attachment point is included in these pingers to permit one end clear for unit start-up immersion sensors, an alternate deployment arrangement has been considered for longline retrieval for future generation pingers. As longline retrieval would not include the crushing effect that bycatch reduction pingers experience when passing through the 'bullhorn' equivalent, a small flexible wire cage is currently being considered that could readily be constructed/modified from existing stainless steel materials. The cage should minimise acoustic absorption of output that would be a factor with net bags.

The design was circulated to a number of GBRT commercial fishing crews. Specific concerns were raised about the danger of any heavy device on a branchline recoiling at great speed toward the crew member holding the gear when gear breaks occurred. Serious concerns already exist for weighted swivels recoiling toward crew members on deck. This safety issue could be exacerbated for heavier, or angular, depredation mitigation devices.

Effects of pinger deployment on depredation rates

Formal monitoring of depredation rates from longline gear was not anticipated for this project. QFS / SEANET experience with acoustic alarm / pinger development in Gulf of Carpentaria gillnet fisheries has demonstrated that logistic trials are essential prior to the development of feasible effectiveness trials.

While the logistic trials were underway the participating skipper considered that losses to depredation were either non-existent, or reduced primarily due to partial deployment of pingers along the gear. When the number of functioning pinger units had declined to three, the skipper noted that predation rates rapidly reached the same level as other vessels in the northwestern Coral Sea. The skipper did acknowledge that his observations, although encouraging, were merely conjecture and could well have been influenced by the relatively low incidence of toothed whale depredation events experienced that year up until the mid-January.

It should be noted that the QFS trials with the AQUAmark 200 devices were intended primarily for logistic reasons and do not reflect on the ability of the devices to function for the purpose they were designed for, namely bycatch mitigation. The initial observations in the Coral Sea were established on initial deployment distances of a minimum of approximately 280-300 m (*i.e.* at float intervals for the fishery at that time). With an assumed line shortening rate of 30% that would equate to a distance between buoys/pingers of 200 m at the conclusion of each set. The mechanism of possible aversion to the pingers is not known.

The AQUAmark manufacturer cited a nominal source level of 140 dB re 1 μ Pa at 1 m peak-to-peak, equivalent to 131 dB re 1 μ Pa at 1 m RMS for the pingers. A peak-to-peak source level around this level was recorded for approximately half of the eight random programs during tank tests. The tests were calibrated with an acoustic source previously calibrated by Defence Science and Technology Organisation at Pyrmont, Sydney.

Using the AQUAmark device manufacturers nominal source level, the received level of the signals experienced by a mammal along the longline with approximately 200 m spacing allowing for longline shortening, would range from a maximum of around 120 dB (RMS) the end of longline branchlines to 100 dB (RMS) at the mid-point between the pingers. The short duration and infrequent received levels in themselves would not be sufficient to cause any distress. Richardson *et al*. (1995) considered that short term hearing loss or discomfort would not be anticipated for long-term received continuous levels below 120 dB as a lower estimate. Transient signals could well be higher before the same effect occurred. The literature has expanded in this area including the workshop on the effects of anthropomorphic noise in the marine environment prepared by Gisiner (1998) and further investigation of this issue is warranted.

The frequency of the signals may have some bearing to any perceived confusion or aversion. The oceanic environment is generally devoid of any signals within the acoustic ultrasound range >20 kHz with exception of the bio-sonar systems of other toothed whales. Snapping shrimp have a significant ultrasound capacity up to 200 kHz, however they would not be present in the deep oceanic environment.

The presence of ultrasound signals within the peak sensitivity of the depredatory toothed whales may have a behavioural effect on the mammals. Given the appreciable acoustic absorption rates for signals >20 kHz (Richardson *et al*. 1995), omni-directional ultrasound signals at 40 kHz would be reduced to background levels within 1,000 m while transient acoustic power levels integrated to continuous levels would be even lower. Background noise levels in the Coral Sea at an arbitrary lower frequency of 1 kHz and at 40 kHz have not been established, although available data for tropical oceans with little vessel traffic and Beaufort Sea State 1 suggests ambient spectrum levels of 45 and 30 dB re 1 μ Pa / 1 Hz band of the above frequencies respectively (Cato 1999). Converting to a more general broadband level suggests ambient levels for comparative purposes of 69 dB re 1 μ Pa.

The directional hearing ability of false killer whales has been studied although little is known about pilot whales. For this report it is sufficient to say that dolphins generally would have difficulty in isolating the source of a sound if it was below background levels. For higher frequencies (40 kHz) improvement would occur if the source were within 30° of the dolphin cranium midline. There is indeed optimism for the development of specific acoustic depredation mitigation devices that would not be broadcast over great ocean expanses.

Alternative approaches to depredation mitigation systems

Passive acoustic systems

Passive systems involved modification of fishing methods. Japanese and Australian vessels that fished in the north-western Coral Sea during the 1980's would change course or leave areas of mainline without hooks to try to eliminate leaving a 'feeding' trail. The attempts rarely succeeded (McPherson *et al*. 2002). Australian and Papua New Guinea longline and dropline fishing vessels that currently experience depredation generally recognise that fishing vessels all have specific acoustic signatures and that toothed whales either detect the vessels

as they commence hauling operations, or appear to choose some vessels over others to focus their depredation behaviour.

A GBRT vessel 'TOTAL' was tentatively assessed for acoustic signature of engine at idle, engagement of the main engine gearbox that would signal commencement of fishing, and engagement of the hydraulic pump associated with the drum winch that would also signal commencement of fishing. The source level of the broadband lower frequency signature of the vessel at a nominal 1 kHz with all engines operating was approximately 110 db while the source level increased to about 120 dB when the gearbox was engaged with a transient higher level at the instant of engagement. The source level of the operating vessel at 3 kts would attain background levels within 500 m of the vessel. While toothed whales would hear a vessel at lower than background levels, identification of the direction of the source would be more difficult. Source levels < 1 kHz would be higher.

These fishing vessel source levels are compared to a freighter at 10 kts and destroyer at 20kts with broadband levels at 1kHz of 140 and 150 dB respectively (Urick 1973). Little data exists for the acoustic nature of fishing vessels.

Engaging the hydraulic pump on the fibreglass construction GBRT vessel of New Westcoaster design and construction produced a negligible acoustic signature. This was not the case for all vessels. Engaging hydraulic steering rams in prawn trawlers monitored in Trinity Inlet, Cairns, could be detected at ranges of at least 1,000 m. Hydraulic rams and other machinery in steel vessels would compete with gearboxes for production of a dominant signal.

Active acoustic systems

Anecdotal information from the Russian World Wildlife Fund indicates that the Russian Navy has assisted fisheries in the Bering Sea with potential predation mitigation systems (Stephen Powell, Environment Australia, *pers. comm.*). What appears to have been a military towed array was modified as an active transducer to replay loud signals considered appropriate for the fishery concerned, *e.g.* constantly updated local ocean killer whale sounds in fisheries where the mammals that predate on lines are usually in turn predated upon by killer whales. Other signals likely to interfere with toothed whale sonar systems, loosely described as jamming systems, were also broadcast in a directed manner with apparent effect.

Chemical / physiological

GBRT crews have observed the reactions of toothed whales to various forms of decaying marine mammal flotsam. Exposure to decaying mammals, and specific components in particular, have suggested avoidance from the wider vicinity of the fishing gear deployed by the vessel nearest the flotsam.

Mammal physiologists have tentatively identified the decaying component of the toothed whale flotsam that apparently evokes an avoidance response. There is scope for the probable decaying mammal protein responsible, to be synthesised, deployment may be an issue, especially for crew on the back deck.

Mammal behaviour

Fishing crews have observed behavioural interactions between small toothed whales and larger adults that appeared to be a selection of young animals by a pod of animals for 'training' by a large animal thought to be the largest male. A few incidents have been reported of the history of the domestic fishery in the Coral Sea since 1981 where gear systems were changed on successive days and the training at 'hook stealing' received by the small animals was inadequate to prevent accidental bycatch.

The effect of negative conditioning on the long-term modification of predatory behaviour of a wide range of terrestrial mammals has been the subject of recent research. There is scope to attempt these trials with toothed whales.

Toothed whale depredation workshop

In November 2002 the South Pacific Regional Environment Programme (SPREP) hosted a Workshop in Apia, Samoa on predation by toothed whales. A summary of the major Workshop objectives is presented, namely,

- Review the available evidence on the interactions between whales and commercial longline fishing operations and accurately define the scope of the problem in the South Pacific region;
- Review when and how such damage occurs;
- Identify species involved and the nature of interactions;
- Determine what kinds of actions have been taken by the fishermen to deal with the problem and evaluate the implications for cetacean populations;
- Search for common features as well as differences among the various fisheries;
- Propose possible mitigation strategies;
- Identify areas of research that are critical to evaluating/solving the problems;
- Develop a research program to investigate toothed whale behaviour around pelagic logline vessels and to field-test various mitigation strategies;
- Establish a mechanism to facilitate ongoing communication amongst participants.

The Workshop recommended that the term predation be replaced by depredation. This was to draw a distinction between the normal hunting behaviour of marine mammals *i.e. predation*, from the directed or opportunistic stealing/removal of fish from hooks or gillnets *i.e. depredation*.

A Plan of Action and Priorities for Research to Reduce Depredation on Longlines by Cetaceans was prepared on 15th November 2002. Salient points of the Plan of Action are given. They include,

- Acknowledgement that the first priority is for research into the extent and process of depredation;
- Acoustic behaviour of cetaceans was listed as key unknowns;
- A conclusion that "The workshop strongly encourages research into the development of acoustic and other approaches to mitigation and emphasised the need for rigorous scientific trials to demonstrate effectiveness before broad-scale adoption".

The Workshop concluded that the range of experiences with depredation mitigation methods tried to date (by November 2002) was that not one known method to have been tried was identified as successful, let alone fail-proof in the longer term. The participants were supportive of research to investigate the problem and acknowledged that it was a problem facing industry and fishery managers worldwide.

Depredation was not considered normal behaviour, rather opportunistic behaviour that should be reduced or prevented as long as the methods were compatible with the conservation of toothed whales. The workshop participants indicated that incidental take of cetaceans did occur in longline fisheries although comments were made indicating that the mortalities posed threats to the genetic diversity of the toothed whale species.

Western Pacific Acoustic Conference, Melbourne April 2003

The 8th Western Pacific Acoustic Conference was held in Melbourne, April 2003. A mammal bio-sonar session was instituted for the first time. A presentation was made detailing the progress made by the AFMA, ECTUNAMAC and SWTBMAC funded project to develop ecologically sustainable tuna longline fisheries (McPherson *et al*. 2003).

JCU Engineering Honours projects

Several projects relevant to toothed whale predation problems were nominated to the JCU School of Engineering for consideration and funding assistance by the project. Following consultation with supervisors one project was selected for commencement in March 2004.

Software controlled guidance system for tracking array

The Madry Technologies dolphin tracking system is composed of hydrophones deployed by any appropriate method (depending on vessel configuration) with a suite of stand-alone LABVIEW–based software that tracks dolphins swimming at high speed. The array provides a real-time assessment of bearing to target in two-dimensions, in real time.

In order to customise this system for commercial fishing operations (either longline or gillnet) where vessel forward motion occurs and the chance of gear entanglement is real, the hydrophones need to be protected while there would need to be an indication of array attitude for accurate tracking.

While an automated system for array control was partly beyond the scope of an Honours project, JCU lecturers believed that a data logger for monitoring of depth, fore-aft attitude (*i.e*. yaw) and bearing offered development potential. Direct software control of array orientation during towing operations is not seen as essential at this stage.

Costs of materials such as undersea connectors, saltwater temperature probes are being investigated for possible inclusion in the current project of as a desk study for incorporation into the proposed FRDC project.

DISCUSSION

The ability of the MATLAB system to track an acoustic source has been demonstrated at extremely close range in a domestic swimming pool. A source was tracked under disadvantageous conditions for the system, where small measurement errors would generate major source location variation. Despite this, the source was located within centimetres of the known source. The array configuration relative to the array origin could also be determined by the acoustic pinger system.

While the array was deployed underwater, it was capable of tracking the sonar emissions of nearby foraging insectivorous bats that have many acoustic and behavioural similarities to toothed whales including the use of high frequency short duration echolocation pulses and flexible, task dependent call repetition rates.

The system has therefore demonstrated its potential to track sound producing marine mammals in oceanic conditions where greater distances would nullify the constraints found, yet overcome, in the 9 m pool. Based on this small scale test, the full scale system developed for the Coral Sea tuna longline fishery in Phase I is expected provide locations of toothed whales around longline fishing gear with sufficient resolution to statistically estimate distance between the whales and the gear as the basis of an experimental evaluation of depredation mitigation methods.

The construction of a fully operational toothed whale tracking system has progressed in a cost-effective manner. However the towed array has now been deconstructed. The hydrophones will be reconstructed into the vertical component of the hard-wired array described in McPherson *et al*. (2002).

The hyperboloid tracking system of McPherson et al. (2002) is now operational. Determination of three dimensional locations are possible within the bounds of the array and up to five times the array aperture (minimum distance between any hydrophone pair) away from the array. Determination of a three-dimensional bearing to an acoustic source at ranges greater that 10 times the array aperture are also feasible. Software modifications and improved propriety multi-track recording software now permit automated, quasi real-time, acoustic source location. Signal filtering capacity also improves acoustic source localisation. The steps involved in source location previously described are,

1. Identify clear signal present on all 4 incoming channels.
2. Save the multi-track segment as WAV file.
3. Input WAV file name to MATLAB tracking system
4. MATLAB cross-correlation and source location procedures determine possible locations for acoustic source.
5. MATLAB source locations are output graphically, or by individual X, Y and Z co-ordinates.
6. MATLAB mean source locations or trajectories may be plotted sequentially in relation to specific regions such as fishing gear, or individual hooks. This routine is still being developed.

The objective for the development of a tracking system is not to have a tracking system *per se*. A tracking system, or range of systems, is viewed as an essential scientific tool to better assess the effectiveness of a range of predation mitigation strategies. The current emphasis of marine mammals in noisy oceanic environments is leading to rapid developments of systems to track marine mammals with the subsequent general release of these systems will be of significance to develop cost effective methods to track toothed whales around fishing gear. The current project has benefited, and will continue to benefit, from these developments.

Little data exist to confirm the species of toothed whale responsible for depredation events in the Coral Sea longline fishery. Current industry and project observational, acoustic, and depredation damage evidence suggests that a species of pilot whale (presumably short-finned pilot whales that have a tropical ocean distribution) is primarily responsible for the depredation. Evidence for false killer whale depredation that was so common during the early, then mid-1980's (*pers. obs,* 1983 Qld project leader FRDC tuna tagging, 1986 Qld project leader FRDC tuna biology) is restricted to a specific area of the Coral Sea. False killer whales still occur in the Coral Sea, and they could well dominate depredation again in future years, however the photographic evidence of current depredation by short-finned pilot whales provided by fishing crews were clear. The crews are to be congratulated for obtaining such photos taken under commercial fishing conditions in oceanic waters.

Available gut content data for beached short, and long-finned pilot whales in sub-temperate and temperate waters suggest that squid species are the major component of their diet. Stomach contents of short-finned pilot whales in tropical waters were dominated by squid (Hacker-Sinclair 1992). Seagars and Henderson (1985) described the general presumption that short-finned pilot whales consumed squid based on their presence within shools of squid. They cited the limited number of references that described squid beaks from stomach contents, and presented observations of squid in stomachs from short-finned pilot whales off California.

Deepest dives of Pacific short-finned pilot whales were recorded immediately after sunset in the Pacific (Leatherwood *et al*. 1973) and appeared to go past the shallower margins of the rising deep scattering layer. Deep dives to feed on squid were suggested. In the Coral Sea at the time of the tuna peak spawning and aggregation behaviour, the tuna rise to the surface at the same rate as the rise of the deep scattering layer (McPherson 1988, 1991) and feed on *Diaphus* sp.myctophids. There are no evidence of other species within the deep scattering layer that the tuna feed on.

Werth (1991) described long-finned pilot whales as being close range suction feeders. Squid were consumed mantle first, and small fish head first. If prey items were not sucked through to the stomach on the first attempt, the peg-like teeth and tongue were used to re-position the prey in preparation for another attempt. Considerable effort was expended to position the head to ensure the prey item was 'lined up' before the suction feeding process commenced.

With squid almost certainly the major component of pilot whale diet it would seem appropriate that tuna longline fisheries refrain from using squid as bait during periods when pilot whales are present in fishery areas. Presentation of a natural food source as a bait would positively reinforce the depredation response.

The diurnal diving behaviour of short-finned pilot whales in oceanic waters off Hawaii was recently studied by Baird *et al*. (2003). Deep diving behaviour presumably for feeding were reported during the day and night. Deepest dives (typically 600-800 m, maximum 27 minutes) were recorded during the day. Night-time dives were shallower (typically 300-500 m) that reflected a rise in the prey within the deep scattering layer. The number of deep dives (>100 m) was four times greater at night. Social activity occurred during long bouts of shallow (<100 m) diving during the day.

It is unlikely that the fishing gear of tropical tuna longline operations would exceed the dive range of short-finned pilot whales. These toothed whales will always be able to access longline hooked fish. It would not be feasible to expect that alternative gear setting arrangements would reduce interactions.

There are no data on the most common time of depredation on hooked fish, nor the depth range of depredation. Given that most interactions during the spring and summer in the

north-western Coral Sea occur during short duration daytime sets in shallower waters (<200 m) when tuna abundance is highest, it is likely that interactions between tuna gear and toothed whales coincide with the periods of peak social interaction. Whether a differential availability between natural prey (squid) or opportunistic prey (tuna) exists is not known, however it is possible that short-finned pilot whales may incorporate depredation behaviour into daytime social behaviour, as much as they do for 'serious' feeding.

Current acoustic data do not differentiate between pilot whale species. The role of eyesight and echolocation is not known in terminal stages of natural predation or depredation on longline caught fish. It is assumed that eyesight would not be useful for terminal phase depredation due to the orientation and wide spacing of their eyes, and inability to focus immediately in front of their jaw.

At this stage there are no data that suggests pilot whales or false killer whales feed naturally on the large tuna, marlin and swordfish species taken by longline gear in the Coral Sea. It is possible that the large mammals involved in depredation events may take the baits and hooked fish as they provide an easy source of prey and may not necessarily be a major item of their natural diet. This opportunistic and readily obtained food source may well have an adverse effect on the population biology of these large marine mammals.

A double echolocation click was described by Busnel *et al*. (1971) and Higashi *et al*. (1992). Some evidence existed for a double echolocation click from this study when pilot whales conducted echolocation runs directly toward suspended baits with a hydrophone directly behind. Relatively low frequency clicks of 3-4 kHz were observed, while Higashi *et al*. (1992) reported clicks with peak energy between 3-8 kHz.

The significance of this low frequency signal for tracking their major prey species squid, is not clear as the wavelength of the clicks would not be suitable for determining high target resolution better than that of a cube with sides 0.25 to 0.5 m. However even if pilot whales could not obtain fine resolution of the hooked tuna being attacked, they would likely be aware of high target strength 'glints' from metal hooks within a low resolution picture (Chris Clague*, pers. com.*), and would take steps to avoid the area of the fish containing the hook.

As the observations of Higashi *et al*. (1993) used hydrophones with a sensitivity to 10 kHz, and the present study used hydrophones with a sensitivity to 30kHz, it is unclear what echolocation capacity exists at higher frequencies >30 kHz for pilot whales. Future research should focus on this aspect.

The Coral Sea recordings featured regular broadband impulsive, yet single signals that extended to at least 16 kHz. On some occasions these impulsive signals occasionally appeared to grade into click trains. At the time there was some uncertainty about whether these single impulsive signals were artefacts from a malfunctioning DAT recorder.

However Thompson and Friedl (1982) using hydrophones with a flat sensitivity to 300 Hz, described a 500 Hz centred regular 'thump' that could occur with or be independent of, whistles and low frequency click trains. The thumps occurred in trains of 3 and 36 at a repetition interval of between 0.4 and 2.8 seconds. The authors found that thumps were geographically restricted and considered that they may have some sonar function. Whatever the origin or use of the thumps, they do provide an impulse signal for ready tracking by the MATLAB system.

The Coral Sea pilot whale burst-pulses extend to at least 25 kHz. As burst-pulses are produced by the same mechanism as echolocation clicks, it is reasonable to assume that their sensitivity to their own echolocation clicks extend to beyond 25kHz.

The auditory sensitivity (*i.e*. peak sensitivity) of pilot whales is not known. Matthews *et al*. (1999) noted an inverse relationship between delphinid size and communication frequency while Au (1993) presented data indicating another inverse relationship between delphinid size and peak auditory sensitivity. Matthews *et al*. (1999) noted that the largest delphinid, the killer whale, had a frequency for best hearing of 15-30 kHz (an apparent peak at 20 kHz), the smaller false killer whale 17-74 k Hz (an apparent peak at 60 kHz), and bottlenosed dolphin 15-110 kHz (an apparent peak around 70kHz). Given the inverse relationship noted between delphinid size and communication frequency (including pilot whales) and the inverse relationship between delphinid size and peak hearing sensitivity (no data available for pilot whales) it seems reasonable to assume a working hypothesis that pilot whale peak sensitivity would be approximately between 20-40 kHz.

Pilot whales have similarities to the largest toothed whale, although not a delphinid, the sperm whale. Pilot whales and sperm whales appear to feature a preference for squid, feature deep diving characteristics and feature low frequency echolocation clicks. Thode *et al*. (2002) questioned the relevance of low frequency echolocation clicks and detection of squid that are essentially water filled.

Thode *et al*. (2002) noted that the click spectra of sperm whales was dominated by energy at 4 kHz with some energy at 10 kHz. As the animals dived the energy of the click spectra peaked at 10 kHz and beyond 500 m rose to a peak at 15 kHz. The change was associated with a change in the structure of the sound production mechanism associated with depth. The four fold increase in peak frequency would also improve their ability to echolocate squid their main diet.

Pilot whales also feed beyond 500 m (Baird *et al*. 2003). It is likely that their echolocation output would change with depth with the observed surface clicks at 3-4 and 7-8 kHz potentially changing four-fold. Given this speculation, the echolocation frequency at their peak hunting depth could well be 12-32 kHz assuming a four-fold increase that would support a presumed peak sensitivity for the species at 20-40 kHz.

The concept of a peak sensitivity occurring at a higher frequency than those of recorded clicks and whistles may be partly explained by the change in frequency of clicks with increasing depth of sperm whales and pilot whales. The killer whale does not appear to have the same deep diving capacity as pilot and sperm whales yet is reported to have a peak sensitivity at 22 kHz, range of 18-42 kHz and maximum response at 100 kHz (Szymanski *et al*. 1999). The peak frequency of clicks occurred at a slightly lower 11-17 kHz (Bowles *et al*. 1987). It is not clear whether this differential could be optimised when killer whales echolocate at depths.

The significance for the acoustic observations of Coral Sea toothed whales is directly relevant to the choice of the most appropriate acoustic signals for depredation mitigation systems. The appropriate signals are those most likely to interfere with pilot whale echolocation, or deter them due to a behavioural response to a signal within their region of peak acoustic sensitivity.

The project commenced logistic trials with the Coral Sea tuna longline fishery to assess the deployment and longevity of gillnet bycatch mitigation pingers primarily as they would be the basis for a future acoustic predation mitigation device. While logistic improvements are required, some encouraging results for the devices although totally unexpected, were observed by one industry vessel. The encouraging results occurred only when whale numbers were low to moderate.

Akamatsu *et al*. (1993) conducted 68 three minute exposure trials on the two captive false killer whales over an eight day period to determine the sound source level and frequency most aversive to the species. Responses were variable. At the beginning of the experiments the received sound pressure level for most frequencies was about 160 dB re 1 micro Pascal

(presumably peak-to-peak levels). By the end of the experiments the sound pressure level that evoked a response increased by about 10 dB as the cumulative number of experiments increased.

The types of signals presented included low frequency (0.5-5 kHz) and stable and pulse modulated sounds (repetition rate and duration) at set frequencies throughout the ultrasonic range to 200 kHz including the frequency of peak sensitivity for the species of 16 to 74 kHz (Thomas *et al*. 1988). A simulated broadband echolocation click was also included.

Akamatsu *et al*. (1993) considered that pulse-interval and pulse-duration sounds at set frequencies seemed more difficult for the whales to acclimate to than stable sounds at the same frequency. Broadband pseudo-echolocation clicks performed well initially although with long term exposure, the animals' responses towards the end of the long series of exposure experiments. The single stable pulse signal that initially produced distinct aversive effect was a pulse at 24 kHz, the only frequency within the peak sensitivity estimates of Thomas *et al*. (1988) and Au *et al*. (1995).

Frequency, pulse-interval and pulse duration did not seem to be the decisive factors in producing aversive behaviour. In general, unexperienced or novel sounds above 170 dB (presumed to be peak-to-peak levels) and within the whales audition range were thought to be more effective that experienced sounds.

Extremely loud but low frequency signals 0.5-5.0 kHz were effective in causing aversive behaviour. The mechanism to produce such loud signals at these frequencies is not considered to be cost-effective for incorporation into longline fishing and especially not portable. It should be noted that Akamatsu *et al*. (1993) observed that explosive 'bombs' had no aversive effect.

The observations of STECF (2001), Goodson *et al*. (2001) and Vernicos *et al*. (2003) that frequency modulated pulses with source levels substantially lower than those used for duration modulated tones of Akamatsu (1993) modified dolphin depredation behaviour on gillnets in the Mediterranean are significant. The WAVESAVER acoustic devices used by Vernicos *et al*. (2003) are attributed with a peak output of 155 dB re 1 micro Pascal (presumed peak-to-peak) for at least one part of the frequency range.

These observations suggest that while future acoustic devices for toothed whale depredation in the Coral Sea should be directed toward the known acoustic ability of presumably short-finned pilot whales, minimum source levels should at least occur within the 140-155 dB range and based on the observations of Akamatsu *et al*. (1993) possibly attain 170 dB re 1 micro Pascal (at peak-to-peak). Current acoustic tags operate at these source levels at approximately 70 kHz although they utilise transducer sound sources in the vicinity of $200 each. Achieving comparable output at lower frequencies becomes technically more difficult and certainly more energy and unit size, demanding.

The available acoustic data for pilot whales suggest that it's calls extend from 3-4 kHz with low frequency clicks to well beyond 25 kHz. The source levels of clicks at 1 m appear to be in the vicinity of 140 dB re 1 micro Pascal (peak-to-peak). Matching this level is not difficult as it is directly is comparable to the LIEN (Cairns) alarm produced by QFS for mammal bycatch reduction (McPherson *et al*. 1999). Based on the inversely proportional comparisons between delphinid size and the click output and peak sensitivity, between the largest delphinid namely the killer whale to one of the smaller oceanic species the bottlenose, the best estimate is that the peak sensitivity of pilot whales is 20-40 kHz.

At this stage it seems appropriate that the acoustic signals that should be directed toward pilot whales must occur within the range 3-40 kHz. The data of Akamatsu *et al*. (1993) suggest

that set frequency tones must be high to evoke a substantive behavioural response, while those of Vernicos *et al*. (2003) suggest that frequency modulated tones are more appropriate to evoke a response expressed as less dolphin-caused depredation holes in gillnets.

Dr Sam Ridgway (Office of Naval Research, Marine Mammal Program, *pers. com*.) found that long duration, frequency modulated sweeps produce greater auditory evoked potentials and for an extended period than single frequency tones, suggesting that sweeps are extremely important to cetaceans. Therefore any acoustic mitigation system should feature frequency sweeps and source levels that at least reach 140 dB re 1 micro Pascal at <5 kHz to match recorded echolocation clicks, and exceed 150 dB re 1 micro Pascal (peak-to-peak) for short durations >20 kHz.

The project staff appreciates the observations made by fishing crews of depredation events in longline fisheries in eastern and western fishery areas. The information has been valuable in increasing awareness of the precise nature of the depredation events from different species. It is likely that final prototype systems used for future work will be based on the combined anecdotal observations from within industry. For the moment, project staff appreciate the hardship industry is experiencing from the predation of toothed whales on baits and hooked fish.

In November 2002, the South Pacific Regional Environment Program in Apia, Samoa hosted a toothed whale predation workshop. The essential elements of the Plan of Action from the Workshop were that a series of Priorities be established for mitigation approaches. Of real concern to longline industry management was the apparent Workshop recognition of toothed whales being taken incidentally as bycatch. This has EPBC Act significance for Australian tuna longline fisheries.

A significant conclusion was that the Workshop strongly "encouraged research into the development of acoustic and other approaches to mitigation and emphasised the need for rigorous scientific trials to demonstrate effectiveness before broad-scale adoption".

A positive Workshop finding was that participants recommended emphasis should be given to providing a pro-active message from mammal conservation groups that would continue to foster a positive involvement by the fishing industry. This is a more positive finding for the fishery than the observations of Bache and Evans (1999) that while Australian fisheries albatross bycatch policy was influenced by scientific data, environmental non-government organisations (NGO's) were instrumental in determining Government dolphin bycatch policy.

In conclusion, a number of recommendations are made for future investigations looking to assess effectiveness of acoustic and mechanical depredation mitigation devices. Discussions during the course of this project with defence scientists, and mammal acousticians, behaviourists and physiologists have provided optimism for a wider range of depredation mitigation approaches than initially thought. The approaches include;

- 'stealth' characteristics of fishing vessels, hulls, machinery, types of acoustic fish finding equipment, and 'acoustic' disguise of their fishing operations;
- modification / conditioning of mammal behaviour;
- chemical modification of mammal behaviour;
- more appropriate species specific deterrent acoustic signals, with signal focussing to raise source levels yet reduce overall omnidirectional anthropomorphic sound.

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'BALANCE' spent three weeks obtaining toothed whale hydrophone acoustic records at a time when the mammals were seasonally declining. The comments of the above skippers, and those of Peter Hibbert 'CONNECT', Keith Hendricks 'EXTRACTOR' and Rod Hansen 'HOOKED' also assisted in the development of requirements for a practical hydrophone array suitable for deployment from commercial vessels in offshore waters. GBRT provided incalculable assistance by providing unlimited access to longline vessels and crew assistance for exclusive testing of the towed array. Robbie Ryall skippered these vessels during these trials and provided valuable logistical expertise.

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