DEVELOPMENT OF PASSIVE ACOUSTIC TRACKING SYSTEMS TO INVESTIGATE TOOTHED WHALE INTERACTIONS WITH FISHING GEAR.

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Abstract

Depredation (=stealing) by toothed whale species of Coral Sea tuna longline catches threatens the viability of the fishery through direct removal of bait and hooked fish and behavioural modification of the target fish species. The false killer whales and short-finned pilot whales responsible for depredation on longline catches generate frequency modulated communication whistles, time constant broadband burst-pulses with a possible emotional context, and time variable broadband echolocation trains used in hunting. All vocalisations offer potential for passive acoustic tracking. A range of methods is being developed to mitigate depredation including acoustic, mechanical and chemical approaches. To assess the effectiveness of these methods, an integrated passive acoustic tracking system to determine movement trajectories of toothed whales relative to longline gear is under development for use in oceanic situations. A real-time tracking system for broadband clicks using a small aperture Mills Cross array to obtain an initial azimuth to source, is being integrated with a post-processing, wide aperture sonobuoy system for all vocalisations to obtain localisation in three dimensions. Data obtained from the small aperture array showed that comparable azimuth estimates were obtained for inshore toothed whales using both tracking systems. Trials over wide areas in oceanic conditions with larger arrays (1.5-1,000 m) to determine 3 dimensional trajectories, are yet to commence.

Introduction

Depredation (stealing of bait and fish) by toothed whales (large odontocete marine mammals, primarily members of the dolphin family. and sperm whales) on longline catches has increased dramatically over the past decade where it is now regarded as a major economic and unreported target species fishing mortality issue in offshore north-eastern and north-western Australian waters, and throughout tropical to sub-temperate oceans.

False killer whales (*Pseudorca crassidens*) and short-finned pilot whales (*Globiocephala macrorhynchus*) appear to account for the majority of depredation in the Coral and Tasman Seas, each species with a characteristic bite pattern. False killer whales were the dominant toothed whales responsible for depredation up to the mid-1980’s [1], with industry experience recognising short-finned pilot whales as the main offender in the Coral Sea up to 2003 [2]. Recent project experience is that false killer whales again appear to have been responsible for depredation events during 2004.

Towards the end of 2000 during the peak tuna fishing period in the north-western Coral Sea, levels of depredation were considered to be the worst in the history of the fishery [2]. Domestic industry assessment was that AUD$4.0 million of product was lost from the north-western Coral Sea fishery in 2000 due to direct depredation, or predator induced non-biting behaviour of the tuna species. These observations should be considered in the context of the review of depredation events for Japanese longline fisheries that considered the Coral Sea levels of mammal depredation the worst for the Indo-Pacific during the 1960's to 1970's [3].

While the longline fishery does take small numbers of black marlin, protocols have been introduced by industry to reduce fishing mortality of marlin [4]. Toothed whale depredation on marlin has increased this mortality rate.

Toothed whale species are currently protected under the Commonwealth Environment Protection Act. Reported bycatch of toothed whales in eastern longline fisheries is approximately two toothed whales of undetermined species each year [5]. Mortality of any of six species of toothed whales on Australian longline gear is rare, and a negligible component of each species stock total mortality, compared to the regularly occurring fatal mass strandings (100 individuals every 2.5 years on average) of at least three toothed whale species from the same presumed genetic stocks [6].

The South Pacific Regional Environment Programme Workshop on depredation [7] recognised that depredation by toothed whales was not normal behaviour, and that it should be reduced, provided the methods used were consistent with the well being of the toothed whales. Methods devised to reduce interactions with gear must at least meet Queensland Fisheries Service animal ethics provisions.

The most appropriate methods required to reduce depredation to date have proved to be elusive [7,8,9].

Many of the methods recommended involved avoidance of the problem, primarily to reduce interaction effects that were viewed as a source of concern for the toothed whales, but not for the viability of the fishery involved.

The basis of this study of toothed whale interaction with fishing gear is that a more precise technique for assessment of the effectiveness of any potential depredation mitigation device was required. The simple counting of landed fish during the time when depredation events occurred from the same time/area stratum of a fishery was not considered appropriate. Since 2001 the Australian Fisheries Management Authority, the Eastern Tuna Management Advisory Committee, the Southern and Western Tuna and Billfish Advisory Committee and the Fisheries Research and Development Corporation have funded studies to develop a more reliable method of assessment of depredation mitigation systems [2].

Tracking of inshore small toothed whales around fishing gear was conducted in shallow coastal waters by suspending a digital camera from a helium-filled balloon above a gillnet, to observe interactions and depredation between Spanish mackerel caught in the gillnet and bottlenose dolphins [10]. Comparable methods would not be effective in oceanic conditions where depredation events occurred over wide areas and to a depth of at least 100 m.

Toothed whales have a social and echolocation acoustic capability. While some acoustic data exist for these species in wild and controlled situations [11,12], no data exist for their acoustic behaviour around fishing gear during depredation events.

Passive acoustic tracking of the vocalising and swimming trajectories of deep diving toothed whales such as sperm whales, was developed for use with dedicated oceanic vessels with widely spaced rigid three-dimensional arrays [13]. Sperm whales were tracked with sonobuoy and towed array systems [14,15]. The wide aperture array tracking systems were based on the time-of-arrival-differences (TOAD's) between pairs of hydrophone receivers, to confine the source to a hyperbola of equal TOAD's in two, and hyperboloid in three, dimensions. TOAD's were estimated using a variety of techniques including cross-correlations of time-domain and band pass limited, whistles and echolocation clicks [13,14,15], to frequency modulated calls [16]. By adding sufficient numbers of hydrophone pairs into an array, the intersection of the hyperboloids would provide the location of the sound source.

Four receivers are required to determine the location of three-dimensional sources [13] with arguments existing for the requirement for over-determined arrays with five receivers [15,17]. Acoustic source localisations in oceanic conditions are subject to a range of errors caused by (a) hydrophone location variations, (b) measurement of time of arrival differences, and (c) speed of sound variations between acoustic sources and hydrophones [15,17,18,19].

Localisation using the hyperboloid intersection technique has configuration constraints. As the distance between the source and the receivers increases, the reliability of source locations in the dimension with the smallest hydrophone separation, usually the depth dimension, declines [13]. The hyperboloids intersect at increasingly parallel angles and become bearing angles or azimuths to the target when the distance to source exceeds 5-7 times the smallest hydrophone separation [13,15,16,20]. In order to obtain maximum effectiveness from the hyperboloid method, receiver pairs should be spaced at maximum distance given the logistic problems of the situation and the limitations posed by the amplitude, directionality and propagation of the sound of interest. Sources located within the boundaries of an array would be located with the least source of error [17].

Beamforming offers an alternate approach. Calculating phase differences of incoming signals in the time domain or the frequency domain provides an azimuth to a sound source [21,22]. Beamforming is more effective where the distance to the source is >7 times the aperture of the array. In concert with additional widely spaced beamforming arrays, the location of a source could be determined [22,23,24].

The objective of this study is to determine the presence of toothed whales around Coral Sea longline gear in oceanic conditions, and to passively track them with sufficient resolution to determine movement trajectories around to the gear. Movement would be assessed relative to depredation mitigation devices.

Methods

Logistical constraints

Development of a passive acoustic tracking system has proceeded for the Coral Sea tuna longline fishery given a range of logistical constraints:

- Fishing operations occur in offshore waters greater that 80 km from the Queensland coast – therefore shore-based facilities were not available.
- All equipment should be deployed from co-operating commercial fishing vessels - therefore equipment size and deployment capabilities from these vessels that lack lifting or towing booms, nor have high masts for aerial deployment, was paramount.
- Acoustic signals would include whistles, higher frequency burst-pulses, and echolocation clicks over a wide acoustic bandwidth – therefore wide frequency transmission bandwidths are required.
- Toothed whale acoustic source levels were not known. Whistles would propagate omni-directionally up to 5,000 m, clicks would be more directional.
- Depredation activity was rarely constant, occurring over all or segments of longline that could extend 5 to 75 km. An acoustic monitoring system was therefore required for gear sections up to 2,000 m.
- Longline gear is dynamic and changes shape – therefore the geometry of acoustic receivers attached to gear would require constant re-configuration.

Data recording hardware and software

All data input is based on a Madry Technologies anti-aliasing filter and a National Instruments 500 kHz unbalanced sampling rate 12-bit Data Acquisition Card. The DAQcard provides a four track 96 kHz sampling rate for short intervals, and up to six tracks at 48 kHz sampling rate for longer durations.

Multitrack data is recorded by SONAMON software developed using LabVIEW® with real-time bearing and spectrum processing, with filtering capability. Data are stored as PCM format WAV files.

Tracking hardware

The small aperture beamforming array is based on four closely spaced hydrophones in a Mills Cross antenna configuration (*i.e.* square antenna). Two hydrophone pairs at right angles are required to determine an unambiguous azimuth to a source. This project is assessing a variable aperture (i.e. 10 cm to 1.5 m) Mills Cross array for deployment from commercial vessels. The dimension of the aperture would be determined by the requirements of the tracking method, the type of vocalization, and its frequency.

The hydrophone data from the wide aperture array (three at 20 m depth spaced no more than a total of 2,000 m apart, and one at up to 100 m directly below one of the shallow hydrophones) will be received from sonobuoys fitted with a 15 kHz bandwidth UHF radio system developed by Madry Technologies. Acoustic data from up to two of the input channels of the small array could be used for the hyperboloid tracking system (particularly at the larger aperture of 1.5 m) to generate an over-determined array with greater than four receivers [17].

The sonobuoys have a UHF triggered acoustic pinger system for hydrophone location. Each sonobuoy has a GPS data logger. Sonobuoys have been modified from radio direction finding buoys provided by industry.

A UHF signal receiver system for the sonobuoy hydrophones based on existing audio products has been assembled by Madry Technologies. The UHF system incorporates controls for 3.5 kHz pingers associated with each sonobuoy hydrophone, used to determine the sensor spacings by calculating time-delay measurements made by sequentially pinging from one hydrophone/pinger and listening at all other hydrophone/pinger locations.

Tracking software

SONAMON developed by Madry Technologies determines real-time azimuths to broad bandwidth signals of toothed whales using time domain beamforming methods. The software indicates what gear sections are under threat from depredation, given appropriate propagation conditions, to reduce post-processing search time of hydrophone data to subsequently localise the whales in three dimensions.

3DLOC developed by Phil Turner and Craig McPherson (James Cook University Electrical Engineering [2]) is a post-processing hyperboloid intersection system that uses MATLAB® software to determine source locations in three-dimensional space with up to six receivers. Hyperboloid parameters such as surface 'thickness' and resolution may be varied within a pre-determined sea surface region to achieve the minimum number of intersections. The direct algebraic approach used for most hyperboloid-based tracking systems based on GPS-type mathematical calculations appears computationally faster, although appears to yield unacceptable errors compared to the current 3DLOC 'data search' method. An error analysis will be undertaken to determine the sources of error.

Results

Inshore toothed whale tracking

Passive tracking trials were conducted on inshore bottlenose dolphins at Port Stephens in NSW. A trial 75 cm aperture Mills Cross antenna with 4 hydrophones and SONAMON recording software was used to record whistles and echolocation clicks of foraging dolphins. With the majority of acoustic vocalisations observed as broadband echolocation clicks, SONAMON and the array dimension was configured for click detection. The SONAMON bearing display of click trains from at least two dolphins is shown in Figure 1. One approached at a mean azimuth of 160-180° to port, the other 160 and 175° to starboard of the array. Clicks for the dolphin approaching from the starboard side are dispersed over 15° due to a range of possible factors including multipath effects for an array <1 m below the surface. The dolphins were in water approximately 20 m deep.

The 3DLOC screen output for the direction to the a single click from one of the click trains is given in Figure 2. Initial output indicated that the target lay along an azimuth of 175.06° with an elevation of –9.47°.

As the array was constructed in a flat plane without a deep hydrophone to estimate depth, 3DLOC also determined a range of possible depth estimates many of which could be eliminated as occurring above the water surface. This would be useful for tracking bats and aircraft over-flying water, but not useful for tracking toothed whales that are usually confined to below the sea surface, or at up to 3 tonnes weight, should be.

Confirmation of the same approximate position for a click train by SONAMON, and a single click within the train by 3DLOC, effectively validates the two independent methods for the localisation of toothed whale clicks.

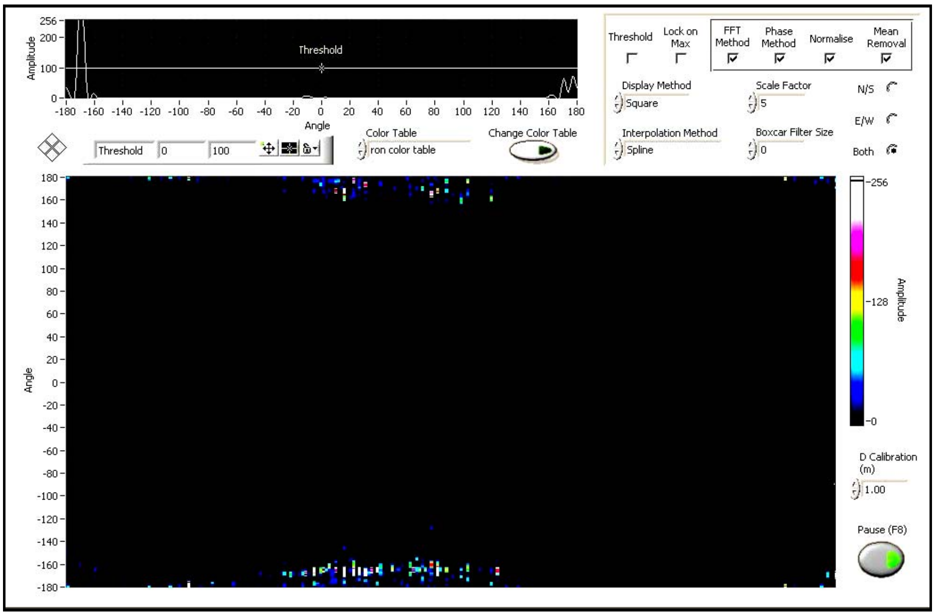

Figure 1. SONAMON screen display of echolocation runs from two approaching dolphins approximately 160-180° to port (positive azimuth-upper left of screen), and to starboard 160-175° (negative azimuth lower left of screen) of the array.

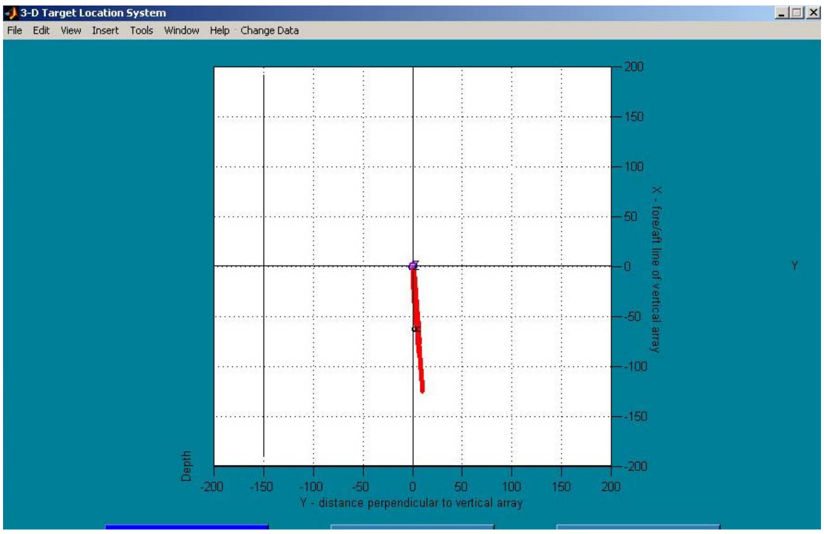

Figure 2. 3DLOC screen output of the possible location track for the source of a single click within the starboard dolphin echolocation click train of Figure 1 (elevation angle not shown).

Offshore toothed whale tracking

Trials for the integrated tracking system have yet to commence in offshore waters. The narrow aperture array is under trial on commercial vessels, recent logistical constraints necessitating a smaller deployment system than that initially constructed. Sonobuoys for the wide aperture array, are under construction, and modification after trials, in association with commercial fishing operations.

Pelagic fish taken on tuna longlines such as snake mackerels (family Gempylidae) readily sever unprotected hydrophone and pinger cables [25]. Up to 200 of 500 hooks deployed in a single set in the Coral Sea in 2004 were lost due to fish damage. With damage to hydrophones also expected from pelagic sharks, all hydrophones and cables have been shielded with stainless steel mesh braid.

Acoustic source locations in oceanic conditions are subject to a range of errors [15,17,19] with hydrophone positions the major source of error. Surface hydrophone locations are determined by GPS where all relatively closely spaced receivers (<2,000 m) should be measured with the same error at the same instant, and subsurface depths recorded by high-resolution depth loggers.

Hydrophones are also located by sequential acoustic pings between hydrophone/pinger pairs, with receiver locations determined relative to one receiver using linear Cartesian geometric methods for the time/distance between receivers. Modelling demonstrated that the array could be ‘focussed’ [2] on the fishing gear to provide optimal localisation with a triangular configuration of hydrophones. In offshore conditions the shallow hydrophones will be located at either end of the section of longline to be monitored, with a shallow and deep hydrophone sonobuoy deployed almost midway between the ends of the sonobuoys on the longline and 200-300 m perpendicular to the longline forming the apex of a triangle.

As the acoustic sources move outside and away from a three-dimensional array, the accuracy of the estimated source locations in the depth dimension declines relative to the horizontal dimension parameters. However, as the locations of toothed whales occur further away from fishing gear, the project requirement to accurately resolve depth location is also reduced.

The acoustic pinger hydrophone localisation method may generate behavioural interactions with the toothed whales. Sperm whales reacted to low frequency tone burst pingers by stopping vocalisations [26], while small delphinid toothed whales reacted aggressively to 10 kHz pinger signals [27]. An aggressive reaction of a 1-3 tonne toothed whale to a project hydrophone/sonobuoy could prove to be expensive, or modify the behaviour of the toothed whales being tracked passively. Judicious use of pingers will be required for this method of hydrophone positioning and localisation of sub-surface gear.

Echolocation clicks appear to be the most common vocalisation generated by toothed whales around longline gear. Clicks were also recorded away from gear. Clicks occur as isolated broadband signals up to 300 msec apart, or as isolated time-varying click trains as close as 2 msec. Manual cross-correlation of clicks from SONAMON output at ±20 μsec is appropriate to determine TOAD’s where isolated clicks and click trains overlap. Isolated burst-pulses, packets of time constant broadband clicks possibly with an emotional context [28], have been recorded during depredation activity and when animals appeared to be ‘socialising’ in the vicinity of gear. Where clicks were sufficiently isolated, the MATLAB wav-read function establishes TOAD’s.

Whistle vocalisations around longline gear are relatively infrequent. TOAD’s for whistles have been manually determined from band pass filtered signals in the time-domain. TOAD’s from the frequency domain have not yet been determined [16,21,29].

Discussion

This integrated passive acoustic tracking system is intended as a high-resolution acoustic source location system, providing an initial azimuth to toothed whale vocalisations with a more refined estimate during post-processing. With a passive tracking system as a novel fisheries research experimental tool, appropriate acoustic, mechanical or chemical methods for toothed whale depredation mitigation may be trialed, and their effectiveness assessed. The tracking system would also determine movement trajectories of vocalising marine mammals around gillnet fishing gear.

Modelling demonstrated the tracking system will provide location estimates of vocalising whales in the vicinity of the longline gear with sufficient resolution to distinguish between individual branchlines deployed along the gear [2]. The location errors could be in the order of the volume of the animals themselves, with most of the error in the depth dimension. Errors are expected to be reduced by using an optimised array configuration where the swimming trajectories of vocalising toothed whales occurs within the dimensions of the three-dimensional tracking array [2,15,17].

As the distance between the whales and the gear increases, errors generated by uncertainties in hydrophone location, speed of sound variation, and sound arrival measurement arise [17,19]. However the requirement for precise source localisation would also decline with distance from gear.

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References

[1] McPherson, GR “Reproductive biology of yellowfin tuna in the eastern Australian Fishing Zone with special reference to the north-western Coral Sea”. *Australian Journal of Marine and Freshwater Research* 42, 465-477. (1991).

[2] McPherson, GR, Turner, P, McPherson, C, and Cato, D. “Depredation of large marine mammals (Family Delphinidae) on longline and dropline target species. Phase II. Pilot study of the acoustic mechanism of predation”. Final Report presented to Australian Fisheries Management Authority and Eastern TUNAMAC. 50p. September 2003.

[3] Nishida, T and Tanio, M, “Summary of the predation surveys for the tuna longline catch in the Indian and the Pacific Ocean based on the Japanese investigation cruises (1954, 1958 and 1966-81),” Indian Ocean Tuna Commission, Working Paper on Tropical Tunas, 1, 17p, 2001.

[4] Campbell, R, Whitelaw, W, and McPherson. G. Domestic longline fishing methods and the catch of tunas and non-target species off north-eastern Queensland. 1st Survey: October-December 1995. Report to Eastern Tuna MAC. Fisheries Research Series. 70p. 1997.

[5] Lynch, AW “Eastern Tuna and Billfish Data Summary 2002-2003”. Logbook Program, Australian Fisheries Management Authority, Canberra. 36p. 2003.

[6] Bannister, JL, Kemper, CM and Warneke, RM Action Plan for Australian Cetaceans. Department of Environment and Heritage, Canberra. 246p. 1996.

[7] Report of the workshop on interactions between cetaceans and longline fisheries. Apia, Samoa, November 2002. Donoghue, M, Reeves, R and

Stone, G eds. New England Aquatic Forum Series Report 03-1, 49p. New England Aquarium Press Boston, May 2003.

[8] STECF. Report of the Scientific, Technical and Economic Committee for Fisheries. Incidental catches of cetaceans, 10-14 December 2001, SEC 376, 83p. 2002.

[9] ICRAM. Report of the Workshop on interactions between dolphins and Fisheries in the Mediterranean: Evaluation of Mitigation Alternatives. Reeves, R, Read, AJ and Notarbartolo-di-Sciara, G eds. 44p. Rome 4-5 May 2001.

[10] Read, AJ, Waples, DM, Urian, EW and Swanner, D. "Fine-scale behaviour of bottlenose dolphins around gillnets" *Proceedings of the Royal Society, London, Series B: Biological Sciences* 270(1): 90-92. (2003).

[11] Rendell, LE, Matthews, JN, Gill, A, Gordon, CD and Macdonald, DW "Quantitative analysis of tonal calls from five odontocete species, examining interspecific and intraspecific variation," *Journal Zoological Society, London.* 249, 403-410. (1999).

[12] Au, WWL, Pawloski, JL, Nachtigall, PE, Blonz, M and Gisner, RC "Echolocation signals and transmission beam pattern of a false killer whale (*Pseudorca crassidens*)". *Journal of the Acoustical Society America* 98(1):51-59. (1986).

[13] Watkins, WA and Schervill, WE "Sound source location by arrival times on a non-rigid three dimensional hydrophone array". Deep Sea Research 19: 691-706. (1972).

[14] Thode, A, Mellinger, DK, Stienessen, S, Martinez, A and Mullin, K. "Depth–dependent acoustic features of diving sperm whales (*Physeter macrocephalus*) in the Gulf of Mexico". *Journal of the Acoustical Society America* 112(1):308. (2002).

[15] Wahlberg, M, Møhl, B and Madsen, PT "Estimating source position accuracy of a large-aperture hydrophone array for bioacoustics". *Journal of Acoustical Society of America* 109(1): 397-406. (2001).

[16] Clark, C and Ellison, WT "Calibration and comparison of the acoustic location methods used during the spring migration of the bowhead whale, *Balaena mysticetus*, off Pt. Barrow, Alaska, 1984-1993. *Journal of the Acoustical Society America* 107(6): 3509-3517. (2000).

[17] Spiesberger, JL "Hyperbolic location errors due to insufficient numbers of receivers", *Journal of Acoustical Society of America* 109(6): 3076-3079. (2001).

[18] Ehrenberg, JE and Steig, TW "A method of estimating the position accuracy of acoustic fish tags". *ICES Journal of Marine Science* 59: 140-149. (2000).

[19] Spiesberger, JL and Wahlberg, M. "Probability density functions for hyperbolic and isodiachronic locations". *Journal of Acoustical Society of America* 112(6): 3046-3052. (2002).

[20] Cato, DH. "Simple methods of estimating source levels and locations of marine animal sounds" *Journal of Acoustical Society of America* 104(3): 1667-1678. (1998).

[21] Miller, PJ and Tyack, PL A small towed beamforming array to identify vocalizing resident killer whales (*Orcinus orca*) concurrent with focal behavioural observations. *Deep-Sea Research (*II Topical Studies in Oceanography) **45**(7), 1389-1405. (1998).

[22] Thode, A, Norris, T and Barlow, J. "Frequency beamforming of dolphin whistles using a sparse three-element towed array". *Journal of Acoustical Society of America* 107(6): 3581-3584. (2000).

[23] Thode, A, Mellinger, DK and Martinez, A. "5aAB5. Passive three-dimensional tracking of sperm whales using two towed arrays during the 2001 SWAMP cruise". *Journal of Acoustical Society of America* 112(5 Pt2): 2399. (2002).

[24] Thode, A, Howarth, ES, Martinez, A. and Stamates, J. "5aAB7. Automated two-dimensional passive tracking of free ranging dolphins using two towed arrays and frequency-domain beamforming". *Journal of Acoustical Society of America* 112(5 Pt2): 2399. (2002).

[25] Johnson, CS, McManus, MW and Scronce, BL. Study of fish bite on AN/BQR-15 towed array. Technical Report, U.S. Naval Ocean Systems Center NOSC-TR-867, 23p. 1982.

[26] Watkins, WA and Schervill, WE. "Sperm whales (*Physeter catodon*) react to pingers". Deep Sea Research 22: 123-127. (1975).

[27] McPherson, GR, Ballam, D, Stapley, J, Peverell, S, Cato, DH, Gribble, N, Clague, C and Lien, J. "Acoustic alarms to reduce marine mammal bycatchfrom gillnets in Queensland waters: optimising the alarm type and spacing". *Acoustics Australia* (this issue).

[28] Overstrom, NA. "Association between burst-pulse sounds and aggressive behaviour in captive Atlantic bottlenose dolphin (*Tursiops truncatus*)". *Zoological Biologica* 2(2): 93-103 (1983).

[29] Mellinger, D." ISHMAEL 1.0. Integrated System for Holistic Multi-channel Acoustic Exploration and Localisation". 2001.