THE NEW GENERATION OF ELECTRONIC CLICK DETECTOR (ECD): DEVELOPMENT AND FIELD TRIALS DATA.

D. Newborough[1], C. Blomqvist[2], P.A. Lepper[3] and A.D.Goodson[1]

[1] Loughborough University, UK. d.newborough@lboro.ac.uk
[2] Kolmarden Wild Animal Park, Sweden. christer.blomqvist@kmf.gu.se
[3] NewLeap Ltd, UK. paul@newleap.com

1. ABSTRACT

The use of envelope detection methods to reduce the bandwidth of an echolocation click into the audio-band is not a new concept. However, the increasing popularity of portable digital recorders with excellent signal to noise performance needs such signal processing if ultrasonic transient data needs to be captured. Similarly, this approach allows high frequency information to be recorded onto video recorder sound tracks providing the advantage of synchronised sound with images for behavioural studies. This paper describes the development of a new generation of ECD with improved performance and includes cetacean echolocation data recorded using this equipment in two independent studies.

KEY WORDS: Biosonar; echolocation; dolphin; porpoise; transient detection.

1. INTRODUCTION

The electronic click detection (ECD) system described here was developed from tools created to aid studies of dolphin and harbour porpoise echolocation behaviour in the wild and in captivity. The concept of an ECD is to pre-process pulsed ultrasonic data in order to reduce its bandwidth so that it becomes audible and recordable on audio-band (20Hz – 24kHz) recording equipment. Whilst hetereodyne and frequency division methods have been employed for similar purposes to aid the study of bats the envelope detection method discussed here has been optimised for small cetacean sonar signals. ECD signal processing enables the recording of high dynamic range ultrasonic echolocation signals on portable digital recorders that have excellent signal to noise (Digital Audio Tape R-DAT, 16 bit, 90 dB dynamic range). The echolocation power spectrum employed by cetaceans varies from species to species [1], may also depend on the age of the animal, and can range from 40kHz – 160kHz. The Loughborough University designed ECD circuitry [2], originally developed for a 1994 harbour porpoise study in Scotland, has now been supplied to a number of institutes including the University of Southern Denmark (Odense) to aid studies of captive harbour porpoise echolocation behaviour. Other users include the Fjørd and Bælt Centre at Kerteminde (project EPIC) [6]; Kolmårdens Djurpark, Sweden; WTD Eckernförde, Germany and the circuitry was supplied for incorporation into the underwater camera equipment used in behavioural studies of free swimming Atlantic spotted dolphins (*Stenella frontalis*), Dudzinski *et al* [3].

Whilst the original ECD circuitry has performed well in a wide variety of bio-sonar applications the latest redesign incorporates a number of improvements and the circuit has been miniaturised to take advantage of surface mount assembly techniques. The standard ECD filter configuration has been designed for recording the sonar behaviour of bottlenose dolphins (*Tursiops truncatus*) with sensitivity in the 70kHz and 120kHz bands[4]. The filter characteristics of a standard ECD board is shown in Figure 2, with the option of selecting either or both frequency bands. The 8^{th} order onboard filter can be configured as either a single 8^{th} order bandpass or two 4^{th} order bandpass filters, of which the outputs can be combined. The high-order filter offers excellent signal to noise performance, and severely attenuates out-of-band sea-state/boat/pump/precipitation noise. The improved filter design combined with a low-noise preamplifier with onboard gain selection allows the boards to be configured quickly and easily for a variety of environments.

The main features of the new ECD are listed below:-

- integrated low-noise preamplifier
- onboard selectable preamplifier gains settings
- line input option for hydrophones systems incorporating a preamplifier
- input overload protection
- reconfigurable filter characteristics to suit other applications (during manufacture)
- frequency band mixer
- output gain options
- nine selectable onboard gain configurations (60dB-12dB)
- uni-polar or bi-polar power supply options
- wide input voltage range (+12V to +50V or ±6V to ±25V)
- on-board power regulation (system performance is maintained with varying battery voltage).
- small robust computer assembled surface mount board

OPERATION

To explain how the ECD circuit converts an echolocation click signal in the 60kHz – 160kHz frequency (f_1) band into an audio-band signal refer to Figure 1. The block diagram illustrates the sequence of operations that the ECD circuitry performs on the received waveform.

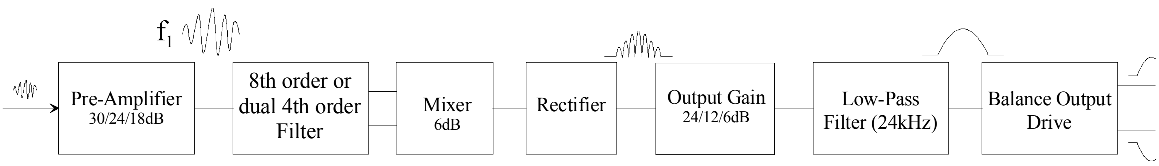

Figure 1. ECD Block diagram

The on-board low-noise preamplifier amplifies the high frequency echolocation clicks received on a suitable hydrophone (wide-band). The gain of the pre-amplifier can be changed by rotating an on-board switch, giving three gain settings for different environments. The amplified signal is then filtered by either a single 8^{th} order bandpass (Bessel/Butterworth/Chebshev) or two 4^{th} order bandpass filters enabling two frequency bands of interest to be monitored with a single ECD board (standard configuration). The frequency response of the standard configuration is shown in Figure 2. The plot shows the inter-band isolation (>15dB) achieved by the two 4^{th} order filters enabling discrimination of click band energy. Also, audio-band signals received are attenuated by 40dB (F1) and >50dB (F2), which reduces audio-band feed through and low frequency seastate or pump noise significantly. The two frequency bands can then be mixed together if required by switching both channels into the mixer. The output of the mixer is then precision rectified and amplified by the output level amplifier with three selectable gain options. The signal is then low-pass filtered (24kHz) to remove all f_1 and 2 x f_1 signals generated by rectifying the click signal (f_1). The signal at this stage is now a uni-polar audio-band signal that replicates the envelope of the echolocation click signal received. The ECD does not distort the pulse duration, inter pulse period or amplitude of the echolocation click signal, however the frequency and phase information is lost. The audio-band output signal is then buffered to provide a balanced output signal. Figures 4 and 5 show the signal processing performed by the ECD; a simulated porpoise echolocation click (120kHz) is fed into the input and Figure 5 shows the corresponding balanced output.

In communication terms, the echolocation click signal may be regarded as an amplitude modulated (AM) carrier frequency. The ECD circuit can then be considered as a demodulator, as this circuit removes the carrier frequency leaving the modulation data (the waveform envelope).

Figure 3 shows the assembled circuit board. The use of surface mount technology helps to improve the signal/noise performance, reduce the package size and increase the reliability. The board is assembled using a computer controlled 'pick and place' machine enabling large volume production with repeatable and reliable performance. The circuit dimensions are 80 mm (3.15inches) long x 35 mm (1.38 inches) wide x 10 mm (0.4 inches) high (this small size is highlighted by the presence of a UK one pound coin).

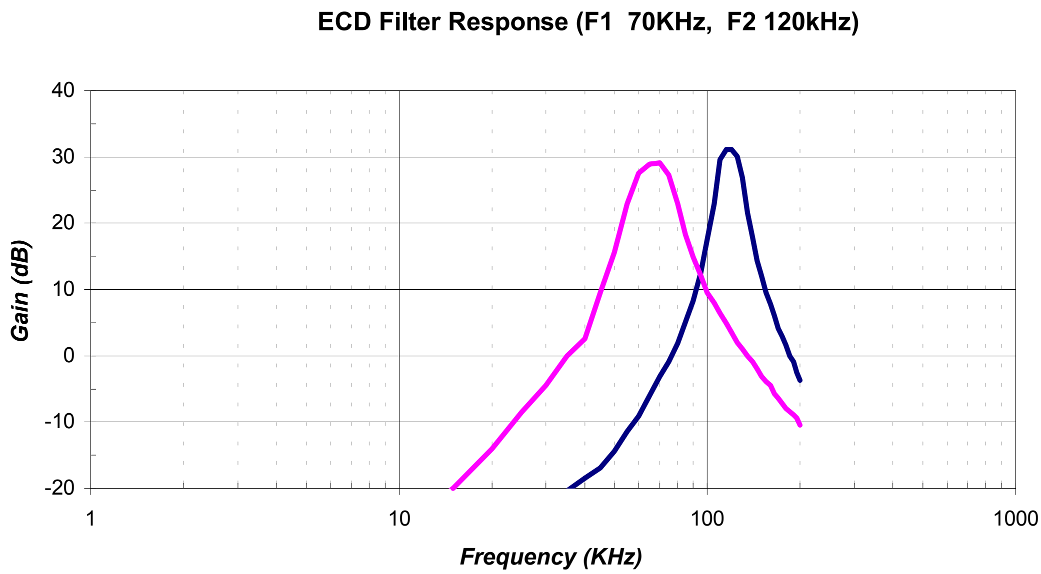

Figure 2 - Filter characteristics of the standard ECD board

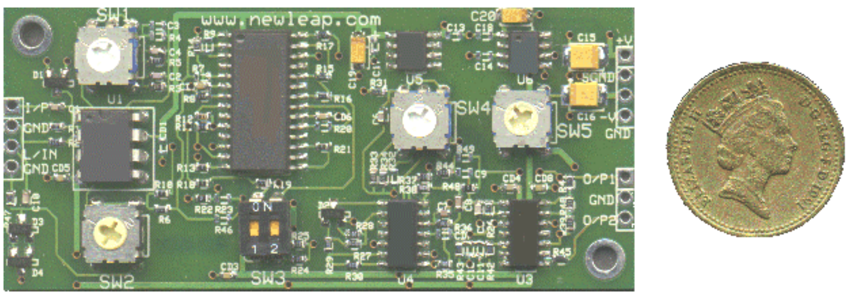

Figure 3. - ECD Circuit - CAM surface mount assembly - with £1 coin for scale

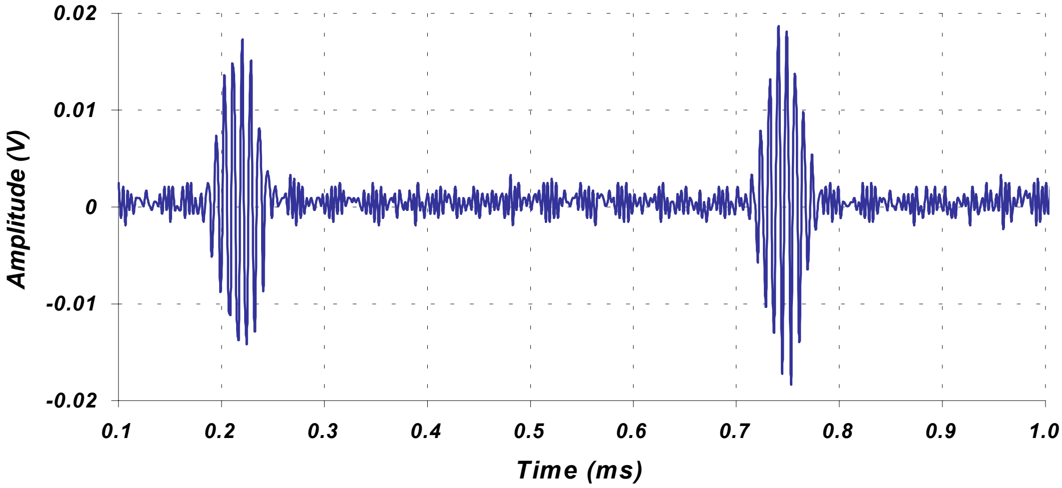

Figure 4. Simulated harbour porpoise echolocation click (f =130kHz)

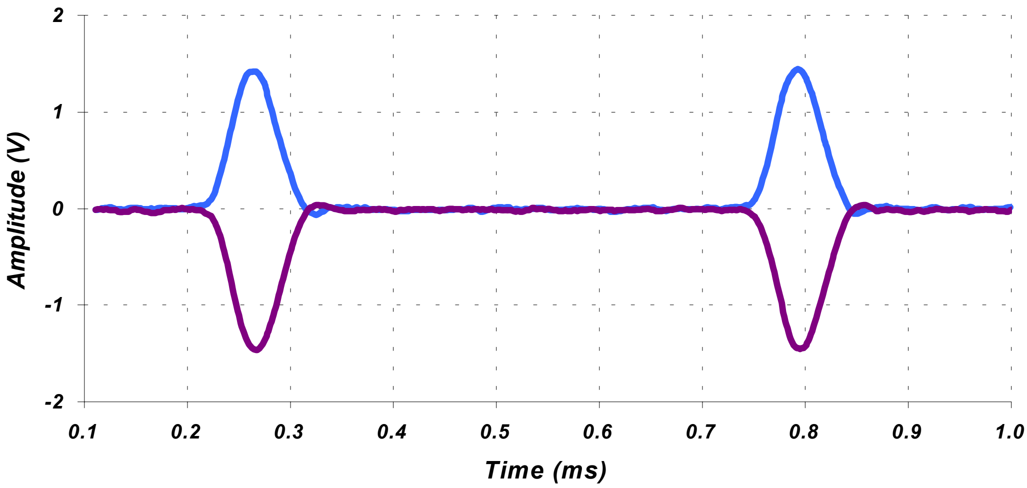

Figure 5 - Balanced output from the ECD, corresponding to figure 4 input

Figures 3 and 4 show 130kHz (synthesised) porpoise click signals recorded through the system together with the corresponding ECD output. From the plots it can be seen that the shape of the pulse, pulse width and the inter-pulse period has been accurately reproduced by the ECD system. There is a small but constant propagation delay of about 50µs introduced by this signal processing. This very slight time shift may need consideration when raw acoustic data is re-mixed with the processed output, however in most applications it can be ignored.

2. FIELD STUDIES (1)

2.1 Dolphin acoustic communication studies at the Kolmården Dolphinarium in Sweden

To study the burst-pulse sounds emitted in free-swimming aggressive interactions in bottlenose dolphins (*Tursiops truncatus),* a mobile recording unit, called MOSART (MObile Submarine Acoustic Recorder of Transients) was developed. The unit is attached to the dorsal fin of a dolphin by means of suction cups. The main objective was to study the potential use of the highly directional, high frequency components of these sounds, to address the social signals to specific individuals. Concurrent behaviour of the dolphins was filmed with underwater and in-air video cameras, and recorded on VCRs, synchronized with the MOSART recordings. The MOSART unit picks up the broad band pulsed sounds by means of a ½ inch HS150 hydrophone (SONAR Products; 1-130 kHz ±2 dB). The detected sounds are diverted into two separate channels, each with a NewLeap ECD, with an 8^{th} order band pass filter (f_c = 70 and 120 kHz respectively, 3 dB bandwidth 10 and 12 kHz). The 120 kHz filter channel records mainly the narrow core of the sound beam, whereas the 70 kHz channel picks up the more omni-directional parts of the sounds. Both channel outputs are stored separately on a portable stereo Minidisc recorder (SONY MD; MZ-R55) having a maximum recording time of 80 minutes. The recorded signals retain amplitude, click duration and click repetition rate but not their full frequency content.

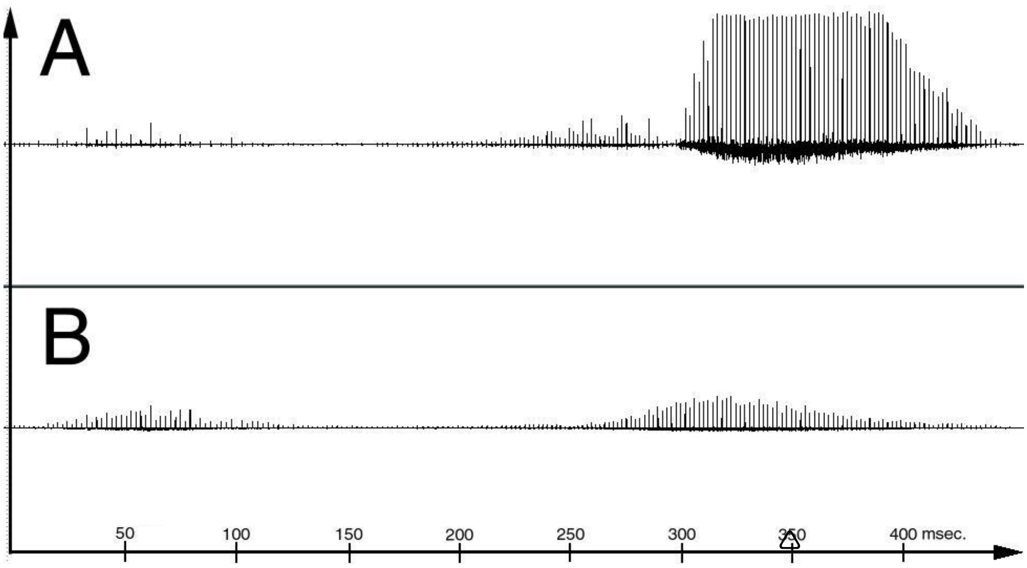

Figure 6. Pulse burst sounds recorded on two audio channels A and B, each containing an ECD from NewLeap equipped with band pass filter of the 8^{th} order (A) f_c = 120 kHz and (B) f_c = 70 kHz. Trace A shows how the narrow beam core has been quickly swept passed the MOSART unit during a 500 cps pulse burst. The low amplitude of the 70 kHz trace shows that the pulses are mainly containing frequencies above 100 kHz. △ marks the zoomed in section presented in Figure 7

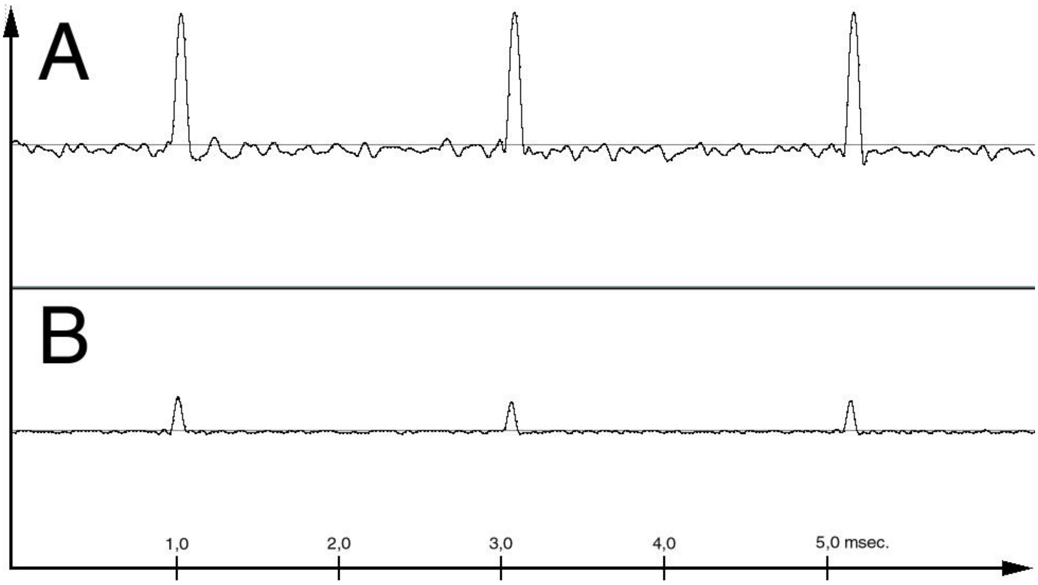

Figure 7. Shows three consecutive pulses within the pulse burst signal presented in figure 1. Inter-click interval is 2.057 msec., Corresponding to a pulse repetition rate of 486 cps.

3. FIELD STUDIES (2)

3.1 Determining the reaction thresholds of bottlenose dolphins to acoustic deterrent signals

The second field test discussed here formed a part of the European Commission DG XIV 98/019 (project ADEPT) [7] special study, which provided an opportunity to use the new ECD system with captive bottlenose dolphins to capture acoustic responses while presenting an acoustic stimulus at progressively increasing sound pressure levels. The study was arranged to determine the reaction thresholds for bottlenose dolphins to acoustic signals with similar spectral characteristics to the commercial fishery AQUAmark100™ porpoise deterrent. These tests were conducted in February 2001 under carefully controlled conditions using bottlenose dolphins at Zoomarine in Portugal.

The staff at Zoomarine enthusiastically supported this investigation and the ADEPT team from the UK was supplemented by researchers visiting from the University of the Algarve and from Unidade de Investigacao em Eco-Etologia Instituto Superior de Psicologia Aplicada in Lisbon.

The Zoomarine facility includes two large dolphin pools. One, Figure 8 is a complex of interlocking pools equipped with polycarbonate windows at the front that permit good underwater viewing. The other is a single large lagoon design providing rather different acoustics as it was constructed from a polymer lined excavation with smooth, more natural, vertical profile. Fifteen dolphins were available for study, eight in the main pool and seven in the lagoon. The dolphins ages ranged from 3 years to 43 years.

The initial objective of the study was to determine the naïve reaction detection threshold at which the dolphins showed by a change in swimming behaviour that they had detected the slowly increasing level of the sound signals under test. A second objective was to try to determine a naïve 'aversive' threshold at which the increasing sound level appeared to induce an avoidance behaviour. These tests were then repeated at intervals throughout a one week period in order to look for evidence of 'desensitisation'.

3.2 Acoustic and Video Equipment

Sound synthesis equipment - purpose built for the project EPIC tests on porpoises in Denmark comprised:

A precision digital attenuator that could be programmed to 'ramp up' the amplitude of a test signal on defined steps over a set period.

Built-in signal synthesis modules generating frequency swept signals similar to those generated by the PICE/AQUAmark [5] deterrent but with the capability of altering the pulse duration and the inter-pulse periods. For this experiment the signal type was confined to 'SQWEEP' - a 20kHz to 70kHz frequency swept square wave with the peak energy tuned by the transducer to 70kHz and with harmonics which extended above this. Pulse lengths used were 256 ms and the inter-pulse period randomised between 2 and 6 seconds.

External fixed attenuators were also added to limit the maximum signal transmitted to a predetermined level of 140dB re 1 μPa at 1m. (The AQUAmark100 has a peak Source Level of around 145dB.)

An HS70 hydrophone was used as a transmit transducer and deployed in the connecting channels just behind the channel gates into the main pool. (The sound source positions could be mirrored.)

An HS150 hydrophone was also deployed close to the transmit transducer to record both the transmitted activity and the dolphins own acoustic signals.

An R-DAT digital audio recorder was employed to capture the recorded sounds with one channel recording audio frequencies and the second recording signals pre-processed by an ECD system. The pre-processed signals from the ECD channel are shown in Figures 9 and 10. Figure 9 shows a click train aimed directly at the transmitting hydrophone with a repetition rate of about 50Hz (inter-click period of 20ms). In open water conditions this repetition might suggest a target of interest at a range of less than 15 meters, however as the transmitting transducer was deployed in the mouth of an inter-pool connecting channel the level of reverberation experienced by the animal may have modified this. Correlating the click rate information with the video data would clarify the range to target and may explain explain reason for the observed gradual reduction in click energy. The pulse-to-pulse amplitude variations show a cyclic component suggesting a head scanning action through a small angle - a typical dolphin investigative behaviour.

A miniDV video camera and a Hi-8 camcorder were also used to record the swimming behaviour of the dolphins from a viewing position high in the public stands. The camera utilised a polarising filter to minimise the surface glare for most of the day and an alternate camera position permitted tests to continue when the sun was directly inline with the first position.

3.3 Methodology

Tests were carried out from a prepared randomised table, which included some 'non-acoustic' tests to reduce possible observer bias. The acoustic observers were positioned behind a wall and out of sight of the dolphins. Trainers and other staff (and the public) were kept away from the pool during the actual tests although some potential disturbance could have occured in the later tests when painters were working in the stands. Two observers in the stands operated the video cameras but these were 'locked off on tripods to maintain a fixed view of the pool surface.

Each test started with a 5 minute Pre-Test period to establish a base-line of normal swimming and vocalisation activity.

A 5 minute test period was then started and the sound source slowly ramped up by the digital attenuator over 2-3 minute period while the actual attenuator settings were logged for later use. The video cameras and R-DAT recorder were carefully time synchronised by their internal clocks to a nominal 1 second accuracy.

A 5 minute 'recovery' period completed the test to determine when baseline behaviour returned.

The source level of the sound signals transmitted at the start of each test was reduced by the attenuator to 91dB re 1µPa at 1m as at this sound pressure level the acoustic signals were nominally masked by background noise. Given that the distance between the source transducer and the dolphins further attenuates the sound pressure through spreading and absorption loss. An animal swimming at the far end of the pool would be exposed to a sound pressure level some 30dB below this. The digital attenuator was then stepped up in 3dB increments with each step time logged to permit analysis of the timecoded recordings. With the 13 dB external attenuator attached the actual SLs generated at each step were:

Atten	-42	-39	-36	-33	-30	-27	-24	-21	-18	-15	-12	-9	-6	-3	0
SL@1m	91	94	97	100	103	106	109	112	115	118	121	124	127	130	133

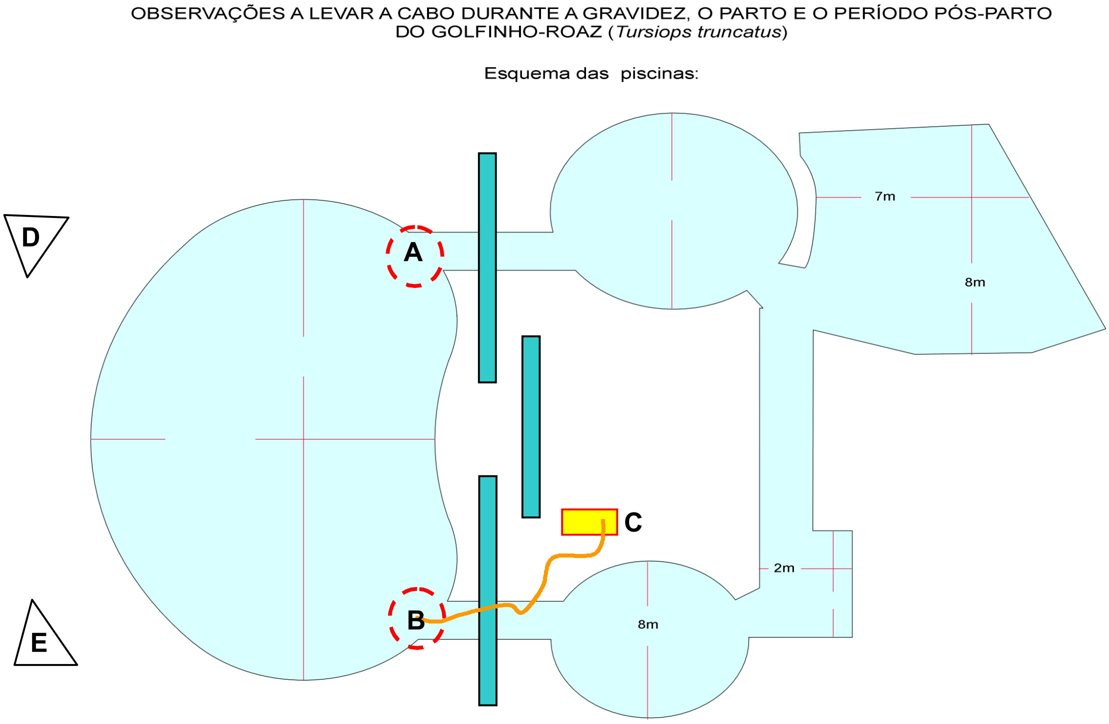

Figure 8. - Plan view of main display pool at Zoomarine. A & B (circled) mark the positions in the connecting channels used for the hydrophone sound sources etc. C - Acoustic Equipment D & E - Video camera positions looking down from the public tiered stands.

3.4 Preliminary Results

The youngest dolphins were observed to react first, quickly followed by most of the adults - with one exception. Echolocation 'interrogation' of the sound source usually started at a transmitted SL of 100 dB re 1 μPa at 1m. As these sounds became detectable to the dolphins, their first reaction was to investigate and several animals would be positioned close to the channel gate and they would echolocate directly on the hydrophone used as the stimulus transducer. In all of these tests the response of the oldest dolphin, a 43 year old male, lagged well behind the other animals and it seems likely that this animal suffers from age impaired high frequency hearing - a phenomena that has recently been reported elsewhere (D.Ketton *pers comm*).

As the sound levels were progressively increased the dolphins started to move away from the source and they then congregated at the far end of the pool. This change is evident in the audio tapes from the cessation of echolocation activity aimed on the source hydrophone and by their departure to the other end of the pool which can be seen on the video recordings. This 'aversive' response seemed to start at SLs around 112 to 118 dB (but these sound pressure levels are derived from the cessation of echolocation and the timing of their actual departure away from the source will need corroboration when the video analysis is completed.

As the series of tests continued the dolphin behaviour changed, and whilst the general pattern of behaviour remained similar they appeared less disturbed and swam in closely associated groups progressively recovering more of the pool area during the later tests.

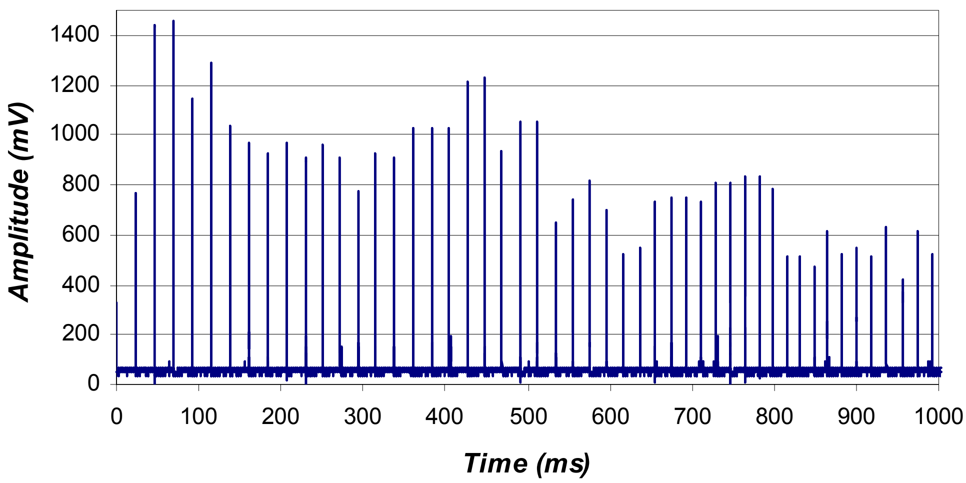

Figure 9 - ECD Channel (70kHz & 120kHz band mixed)

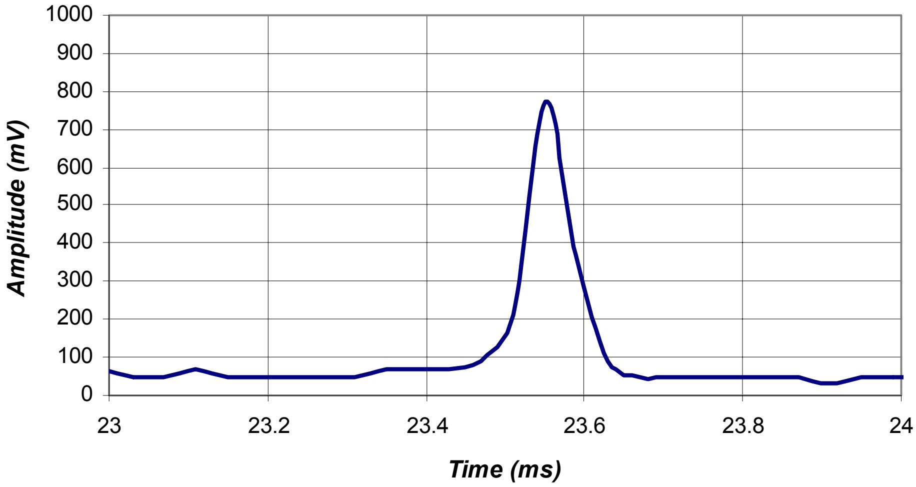

Figure 10 - ECD Channel (70kHz & 120kHz) Zoomed

3.5 Discussion

The younger animals showed more curiosity than the adults and clearly had better hearing.

The ECD system enabled the observers to hear when echolocation activity changed in the pool. The onset of the dolphin's interrogation of the sound source then provided an unmistakable marker confirming that 'detection' of the sounds had occurred. Correlating the sound pressure level transmitted at the time when the echolocation interrogation ceased indicated the aversive threshold and examination of the video data has confirmed that the animals moved away from the sound source at this point.

This dolphinarium behaviour when exposed to 'deterrent' acoustic signals at low level suggests that in a 'threat-free' environment curiosity is encouraged and newly introduced unusual stimuli are accepted very quickly. Such captive studies need to be extrapolated with care and this approach is unlikely to successfully address a popular concern regarding 'habituation' to pingers in the wild. The behaviour observed in this exceedingly short test is unlikely to be replicated by wild dolphins swimming in a more threatening environment as any initial aversive response will result in movement to much greater distances, and the effort needed to return in order to investigate will offer little reward.

4. CONCLUSIONS

The early Loughborough designed ECDs have proved extremely useful in the field of echolocation and behavioural studies in the wild and captivity. This new design builds on this experience and with its built-in preamplifier and more selective filtering offers some advantages. Earlier devices were hand built in the University laboratory as required for projects. However, the frequent requests received for a commercial source of this device have now been addressed and the ECD device described here has been engineered for volume production by NewLeap Ltd. The features of the new ECD design allows the unit to be quickly and easily configured for optimum performance in a wide range of working environments from short range captive studies to much longer detection range requirements when working in the open sea. The 8^{th} order filter provides improved discrimination against out-of-band interference and as result the better signal-to-noise ratio enhances echolocation click detection allowing longer range detection of these animals in the wild. The increased dynamic range obtained matches the digital recorders better, maximising their performance. The compact surface mount design improves reliability and the small size enables the unit to be used in a variety of underwater and surface equipment enclosures.

5. ACKNOWLEDGEMENTS

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