# Detection of beaked whale clicks in underwater noise recordings

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## ABSTRACT

Combined visual and acoustic surveys for beaked whales (BWs) were carried out between 15th August and 25th September 2008, and between 8 July and 2 August 2009 in an area of the Coral Sea used for naval exercises. These surveys were part of a collaborative project between the Universities of Sydney, Queensland, Curtin University and the Defence Science and Technology Organisation (DSTO) aimed at trialling methods for detecting BWs, and determining their distribution across the exercise area. One of the methods trialled in the survey was the deployment of high-frequency (HF) noise loggers on drift moorings for 2-3 days at a time. A HF noise logger was developed by the Centre for Marine Science and Technology (CMST) at Curtin University specifically for this project. The HF noise loggers were deployed autonomously on drift moorings for durations ranging from 1 hour to over 3 days during the Coral Sea surveys. Over the two surveys, there were 14 deployments in the survey area, which combined recorded 225 hours of underwater sound sampled at 192 ksps. Thousands of clicks that are likely to be BW echolocation clicks were detected in the HF noise logger recordings.

## INTRODUCTION

Combined visual and passive acoustic surveys for beaked whales (BWs) were carried out in 2008 and 2009 in an area of the Coral Sea used for naval exercises. These surveys were part of a collaborative project between the Universities of Sydney, Queensland, Curtin University and the Defence Science and Technology Organisation (DSTO) aimed at trialling methods for detecting BWs, and determining their distribution across the exercise area (Cato *et al.*, 2010). The main role of the Centre for Marine Science and Technology (CMST) at Curtin University in this survey was to supply and deploy high-frequency (HF) noise loggers on drift moorings in selected sites to record beaked whale clicks, carry out preliminary data analysis and develop methods for automatic beaked whale detection.

### Beaked whales

BWs are a family of toothed whales (*Ziphiidae*) that are usually found in deep waters beyond the continental shelf, and spend a relatively small time at the surface (MacLeod and D'Amico, 2006). BWs are among the least known of marine mammals as they are difficult to observe visually. A considerable amount of what is currently knowledge about BWs is based on stranded specimens. Several mass strandings have also led to investigations of the impact of anthropogenic noise on BWs (Cox *et al.*, 2006). The main objective of this project was to map the spatial distribution of BWs in a naval exercise area in the Coral Sea to allow environmental management and mitigation for exercises. Due to BW's elusive behaviour, visual surveys have limited capability to determine their presence; whereas passive acoustic monitoring can be an effective way to locate them (Barlow and Gisiner, 2006). Hence, in this study visual and acoustic techniques were combined to locate BWs.

### Detecting beaked whale echolocation clicks

Johnson *et al.* (2004) used sound recording tags (Dtags) to record echolocation clicks from Curvier's (*Ziphius cavirostris*) and Blainville's (*Mesoplodon densirostris*) BWs. *Ziphius* and *Mesoplodon* produced frequency modulated clicks approximately 200 μs in duration with maximum energy at 30-50 kHz. Similar clicks have been recorded in other studies for Baird's BW (*Beradius bairdii*) (Dawson *et al.*, 1998) and Gervais BW (*Mesoplodon europaeus*) (Gillespie *et al.*, 2009), which had maximum energy at 23-42 kHz and 30-50 kHz, respectively. Significantly, BW echolocation clicks have been found to be distinct from clicks produced by other cetaceans (Zimmer *et al.*, 2005).

Detection of known BW clicks requires an underwater noise recording system capable of sampling sound up to at least 60 kHz. Also, the short duration of BW clicks (less than 400 μs), makes manual detection of clicks in large datasets labour intensive. Therefore, methods for automatic detection of BW clicks were developed as part of the project (Parnum, 2010). The aims of this paper are to compare the properties of clicks detected on the HF noise loggers in the Coral Sea with those those for BWs reported in the literature; and document the development of a BW click detection algorithm.

## METHODS

### Survey area

The survey area within the Coral Sea in which the HF noise loggers were deployed is shown in Fig. 1. The NW corner of the survey area is 22°20′ S, 154°00′ E. In the survey area, the water depth varied from 300 m to over 3,500 m. Combined visual and acoustic surveys for BWs were carried out between 15 August and 15 September 2008, and between 8 July and 2 August 2009 aboard HMAS *Labuan*.

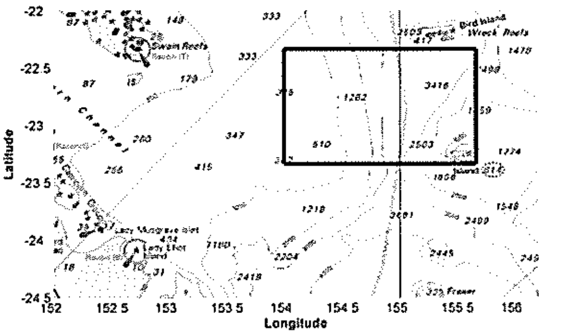


Fig. 1: Chart showing the location of the survey area (black box).

## High-frequency noise loggers

Two HF noise loggers were constructed and deployed in the Coral Sea. Each HF noise logger consists of a Reson TC4033 hydrophone, pre-amp (20 dB), anti-alias filter, Sound Devices 722 digital audio recorder, micro controller, battery pack and aluminium housing.

The Reson TC4033 hydrophone contains a spherical piezoelectric element that is omni-directional between 1 Hz and 140 kHz. The hydrophone cable was taped to the housing so that the hydrophone fell free 1.5 m below the housing. The hydrophone was connected to the housing via a Teledyne Impulse underwater connector with a screw lock on the end cap. The (20 dB) pre-amplifier was built into the end cap, the amplified incoming signal was then passed through a 6$^{th}$ order Butterworth anti-aliasing filter with a –3dB frequency of 60 kHz. The incoming filtered signal was then passed to the Sound Devices (SD) 722 digital audio recorder where it was sampled at 192 ksps using 24 bit sample depth and a system gain of 18 dB (the maximum gain setting). The micro controller was programmed so that the SD 722 recorded the incoming signal for 5 minutes of every 15 minutes (i.e. 33 % duty cycle); these recordings were then saved as wave (*.wav) files on the internal hard disk drive of the SD 722. The SD 722 also wrote its time code information to the *.wav file. The HF noise logger systems were calibrated for gain and frequency response by injecting a calibrated white noise signal into the preamplifier, thus allowing absolute sound levels to be extracted from the wave files.

Each HF noise logger was deployed on a drift mooring suspended by a combination of ropes, bungee cord and a damping disk (1 m diameter) that were attached to buoys and a radio beacon at the surface (Fig. 2). The noise loggers were suspended 400 m (and 200 m for one deployment) below the surface with the damping disk halfway between the logger and the sea surface. HF noise loggers were deployed autonomously for durations ranging from 1 hour to over 3 days during the Coral Sea surveys but longer deployments are possible. In 2008, there were a total of eight deployments in the survey area, which recorded 130 hours of underwater sound. In 2009, there were six deployments, which recorded 95 hours of underwater sound.

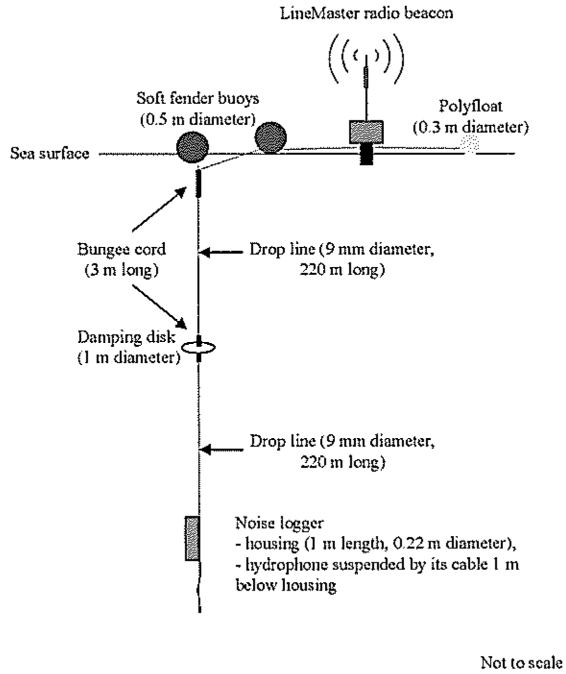


Fig 2: Schematic of noise logger mooring arrangement.

## Data analysis

For each deployment an 'average' spectrogram was calculcated by stacking the power spectrum density (PSD) of each of the 5 minute recordings. These average spectrograms were used to identify intense periods of noise in the frequency bandwidth of BW clicks (i.e. 20-50 kHz). Envelope, and spectral parameters of the clicks from the Coral Sea were compared with clicks made by *Mesoplodon* and *Ziphius* recorded using Dtags by Johnson et al. (2004). The -3 and -10 dB envelope width were calculated from the waveform with the envelope estimated by a Hilbert transformation. The second central moment or frequency standard deviation of the PSDs (which is referred to here as the effective bandwidth) was calculated. The frequency modulation of the clicks was examined using the instantaneous frequency of the waveforms. The instantaneous frequency of a signal is proportional to the first differential of its phase. The phase of the recorded waveforms was derived using a Hilbert filter. The average chirp gradient was calculated using the positive instantaneous frequency values within the -10 dB envelope width. Further details and equations can be found in Parnum (2010).

## Beaked whale click detection

A BW click detection algorithm was developed, which can be broken down into the following steps:

1. Initial event selection

2. Establishing training data

3. Classification of BW clicks from HF logger data

Potential BW clicks were defined as events 3 dB above the background noise, with a -10 dB envelope width between 100 and 500 μs, and the ratio of spectral energy between 10-20 kHz and 30-40 kHz greater than 10 dB. Before these criteria were applied, a 5 kHz high-pass filter was used to improve the SNR of potential BW signals. After filtering, events that met the BW initial criteria were collected by sampling 500 μs either side of the peak of the event to ensure the whole waveform was captured. This was carried out for all deployments from the 2008 and 2009 surveys.

Training datasets were established for 2008 and 2009 by randomly sampling the initial events and then visually classifying them as one of three classes:

1. Beaked whale (BW) - the waveform and spectra look like it was likely from a BW.

2. Non Beaked Whale Clicks (non-BW) - was unlike that from a BW.

3. Unsure - this was assigned where there was uncertainty as to whether it was a BW click.

The random sampling was performed until there were at least 100 representative samples of each of the BW and non-BW class. This was to allow enough samples to build up statistics of different parameters; this also provided an estimate of the *a priori* probability of each class.

A total of 14 parameters were used to discriminate between BW clicks and non-BW clicks. These parameters can be grouped into three main types: envelope, spectral and cepstral, which are listed in Table 1. A total of 7 cepstral coefficients were calculated for each 125 μs of time within the event extracted, this generated 56 features per event. Linear Discriminate Analysis (LDA) was used to reduce these features to the optimal linear combination to separate out BW and non-BW clicks.

Supervised classification of the 2008 and 2009 datasets was carried out using the 'classify' function in Matlab ®. The classify routine fits a multivariate normal density function to each class in the training data (i.e. BW and non-BW) and then uses it to calculate the *posterior* probability of each event in the whole dataset being a BW or non-BW; the higher probability of the two is used to assign the class. Both linear and quadratic functions were tested, and *a priori* probabilities were estimated from the relative frequencies of the classes in the training data. The training error was calculated to evaluate the different parameters and the success of classification method. The training error is the percentage of observations in training that are misclassified, weighted by the prior probabilities for the groups.

Table 1: The mean ± (one) standard deviation of the different envelope, spectral and cepstral parameters for BW and non-BW signals.

| Parameter | BW | | | | | | Non-BW | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2008 | | | 2009 | | | 2008 | | | 2009 | | |
| Envelope -3 dB width (μs) | 109 | ± | 32 | 108 | ± | 30 | 34 | ± | 14 | 43 | ± | 20 |
| Envelope -10 dB width (μs) | 242 | ± | 36 | 246 | ± | 41 | 106 | ± | 45 | 145 | ± | 61 |
| Envelope 95 % energy width (μs) | 604 | ± | 360 | 572 | ± | 306 | 1086 | ± | 328 | 840 | ± | 327 |
| Envelope 97 % energy width (μs) | 803 | ± | 408 | 766 | ± | 350 | 1223 | ± | 290 | 1001 | ± | 327 |
| Envelope entropy | 33 | ± | 8 | 33 | ± | 7 | 30 | ± | 9 | 29 | ± | 9 |
| Chirp slope (Hz/μs) | 65 | + | 22 | 60 | + | 29 | -28 | + | 223 | -12 | + | 69 |
| Chirp intercept (kHz) | 25 | ± | 4 | 25 | ± | 4 | 33 | + | 22 | 34 | ± | 5 |
| Spectral peak frequency (Hz) | 31 | ± | 3 | 30 | ± | 3 | 36 | + | 17 | 32 | ± | 7 |
| Spectral mean frequency (Hz) | 32 | ± | 2 | 31 | ± | 2 | 36 | ± | 8 | 32 | ± | 4 |
| Effective bandwidth (kHz) | 4 | ± | 1 | 4 | ± | 1 | 11 | ± | 7 | 6 | ± | 3 |
| Spectral -3 dB bandwidth (kHz) | 10 | ± | 2 | 9 | ± | 3 | 7 | ± | 4 | 6 | ± | 3 |
| Spectral -10 dB bandwidth (kHz) | 18 | ± | 3 | 18 | ± | 4 | 26 | + | 10 | 19 | ± | 6 |
| Spectral energy ratio (dB) | 20 | ± | 5 | 18 | ± | 4 | 13 | ± | 2 | 13 | ± | 3 |

## RESULTS

Using the automatic detection methods developed in this study, over 4000 BW like clicks were detected from these recordings from 8 of the 14 deployments. The training error for the classification was less than 2 %. A separate error assessment found the false alarm rate and misdetection rates were 5 % and 2 % respectively. There were approximately 50 distinct clicks trains, each click train had between 5-1000 clicks and on average approximately a few hundred.

One deployment where BW like clicks were detected was between the 12th and 15th July 2009. The average spectrogram from this deployment is shown in Fig. 3. A period of intense noise between 20 and 60 kHz can be identified in Fig. 3 at 18:20 on the 13th July 2009. Fig. 4 shows 5 seconds (s) of the waveform from this period, which shows a click train. The median inter-click interval (ICI) for the click train in Fig. 4 was 354 ms. The ICI measured for a foraging *Mesoplodon densirostris* using a Dtag by Johnson *et al.* (2006) during the approach phase was between 300 and 400 ms.

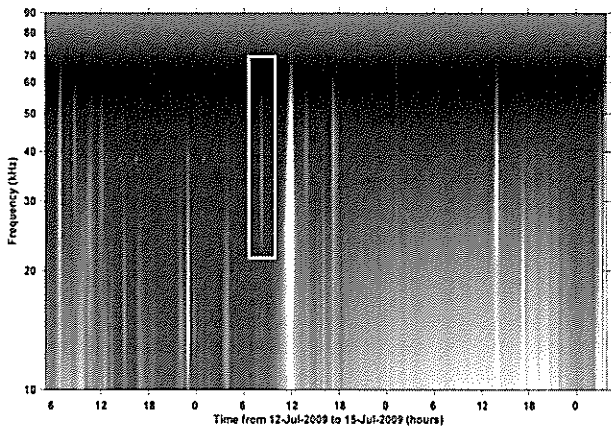


Fig. 3: Average spectrogram calculated from the recordings made by a HF noise logger deployed in the Coral Sea between 12th and 15th July 2009. The white box indicates area of intense sound recorded between 20 and 60 kHz at 18:20 on the 13th July 2009.

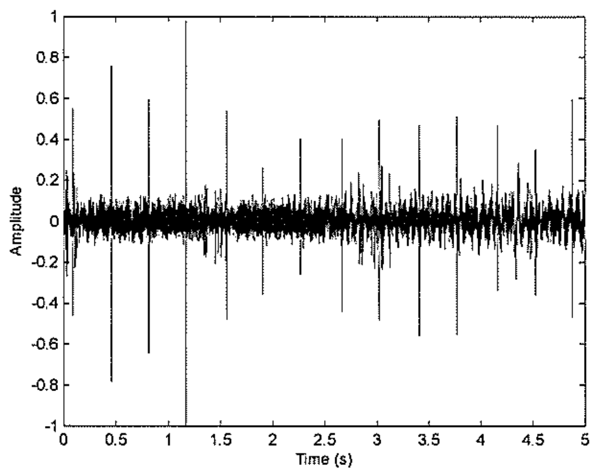


Fig. 4: Part of the time series recorded at 18:20 13th July 2009 by a HF noise logger.

Individual waveforms of the clicks shown in Fig. 4 are very similar to that BW clicks reported in the literature. The mean -3 dB envelope width of the clicks shown in Fig. 4 was 96 ± (one standard deviation) 38 µs, which is similar to those from *Mesoplodon* and *Ziphius* recorded on Dtags which were both 99 µs. However, the mean -10 dB envelope width of the clicks shown in Fig. 4 was slightly higher at 261 ± 57 µs compared with 198 and 188 µs for *Mesoplodon* and *Ziphius*, respectively.

The similarity between the clicks detected in the Coral Sea and BW clicks is also supported by comparing the spectral properties. The effective bandwidth of the individual clicks shown in Fig. 4 was 4 ± 1 kHz, compared with 5 and 3 kHz for *Mesoplodon* and *Ziphius*, respectively. The mean peak frequency of the Coral Sea clicks was slightly lower at 34 ± 4 kHz compared with 40 and 39 kHz for *Mesoplodon* and *Ziphius*, respectively. However, the mean peak frequency of the clicks recorded in the Coral Sea was still within the range of those reported in the literature for BWs. The clicks shown in Fig. 4 have a similar upsweep chirp to the BW clicks recorded on the Dtags, the average chirp gradients being 105, 119 and 72 Hz $\mu s^{-1}$ for the Coral Sea click, *Mesoplodon* and *Ziphius*, respectively.

## CONCLUSIONS

An autonomous HF underwater noise logger that is capable of recording sounds up to 90 kHz has been developed. HF noise loggers were deployed 14 times over two separate surveys on a drift mooring and recorded a combined 225 hours of underwater noise in an area of the Coral Sea used for naval exercises. A BW click detection method has been developed based on the classification of envelop, spectral and cepstral parameters. Thousands of clicks that had similar waveform and spectral properties to BW echolocation clicks recorded on Dtags were detected.

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