In situ source levels of mulloway (*Argyrosomus japonicus*) calls.

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ABSTRACT

Mulloway (*Argyrosomus japonicus*) in Mosman Bay, Western Australia produce three call categories associated with spawning behavior. The determination of call source levels and their contribution to overall recorded sound pressure levels is a significant step towards estimating numbers of calling fish within the detection range of a hydrophone. The source levels and ambient noise also provide significant information on the impacts anthropogenic activity may have on the detection of *A. japonicus* calls. An array of four hydrophones was deployed to record and locate individual fish from call arrival-time differences. Successive *A. japonicus* calls produced samples at various ranges between 1 and 100 m from one of the array hydrophones. The three-dimensional localization of calls, together with removal of ambient noise, allowed the determination of source levels for each call category using observed trends in propagation losses and interference. Mean source levels (at 1 m from the hydrophone) of the three call categories were calculated as: 163 ±16 dB re 1μPa for Category 1 calls (short call of 2-5 pulses); 172 ±4 dB re 1μPa for Category 2 calls (long calls of 11-32 pulses); and 157 ±5 dB re 1μPa for Category 3 calls (series of successive calls of 1-4 pulses, increasing in call rate).

Keywords: source level, soniferous, range, localization, passive acoustics, fish calls

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I INTRODUCTION

Many species of fish use vocalizations as social cues for spawning behavior (Winn, 1964, Myrberg and Spires, 1972, Fine *et al.*, 1977) and often aggregate in large numbers to call *en masse* (Luczkovich *et al.*, 1999, Parsons *et al.*, 2006). Such choruses are often used to delineate areas used by spawning aggregations (Luczkovich *et al.*, 1999, Parsons *et al.*, 2006). However, the ultimate goal of fisheries passive acoustics is the unbiased estimation of abundance. The determination of absolute numbers of mobile animals such as aggregating fish requires the ability to simultaneously census large volumes of water and to eliminate bias from multiple detections of the same fish. The sensitivity of hydrophones in areas of low ambient noise allows the discrimination of fish calls emitted at large ranges from the receiver and in some cases the ability to monitor individual fish over time, by listening and localizing their calls (Parsons *et al.*, 2009).

One method of estimating the number of fish vocalizing within the detection range of a hydrophone is to measure the contribution of individual callers to the overall sound pressure levels (SPLs) received (McCauley, 2001, Sprague and Luczkovich, 2002). To achieve these caller density estimates *a priori* knowledge of species call source level (SL) is required (Sprague and Luczkovich, 2004). In addition to SL, the transmission characteristics of a call in its local environment require quantification to assess the proportion of emitted energy that is received by the hydrophone (McCauley, 2001).

To quantify a call SL it is necessary to isolate energy associated with the signal. Mulloway (*Argyrosomus japonicus*) often spawn in groups (Ueng *et al.*, 2007) and can produce high densities of overlapping calls in the wild (Parsons *et al.*, 2006), complicating the discrimination of separate calls. However, during the commencement of an evening spawning cycle in the Swan River, Perth, Western Australia, calls are of sufficiently low density to offer the opportunity to monitor individual fish (Parsons *et al.*, 2009).

The accurate measurement of SL requires the determination of source range. Short ranges can be easily observed *in aquaria*; however, internal tank reflections and reverberation often contribute significant complications towards SL calculation. *In situ* SLs of fish calls are rarely reported (Cato, 1998, McCauley, 2001) and *in situ* visual confirmation of vocalization at a known reference distance is even less frequent. One example of such audio and visual recording was of an individual sciaenid, a silver perch (*Bairdiella chrysoura*), fortuitously caught on camera at the time of vocalization (Sprague and Luczkovich, 2004). For Sciaenidae, this elusive behavior is in part due to their propensity to vocalize in turbid waters after sunset, thereby inhibiting discrimination of source range by visual methods. Thus the identification of source position or range remains the restricting factor in the accurate determination of *in situ* fish call SL.

Fish calls offer significant information about the caller to the intended recipient and, inadvertently, the observer. The size of the individual can be related to both the call SL and spectral peak frequency (Connaughton *et al*., 2000). However, calls emitted by the same fish are not all necessarily of the same SL. For example, Lagadere and Mariani (2006) proposed that the short grunts of French meagre (*A. regius*) are weaker than the long grunts. Similar results from *in situ A. japonicus* calls have been observed, but it was not confirmed whether pressure wave amplitude differences were due to range, weaker swim bladder twitches or multiple ray-path interference (Parsons *et al.*, 2006, 2009). Therefore measurement of many SLs may be required to categorize a fish call. It is the aim of this study to determine SL ranges for each category of call exhibited by *A. japonicus* in an aggregation in Mosman Bay, Swan River.

II METHODS

A passive acoustic hydrophone array was deployed in Mosman Bay (Figure 1) to localize individual fish within a spawning aggregation of *A. japonicus.* In Mosman Bay the river banks descend rapidly to a 21 m deep channel comprising a sand/silt substrate, a few artificial reefs and several depressions, some of which reach 22 m deep at high tide. At four locations calibrated, omni-directional, HTI 90-U and 96-min hydrophones (Hi-Tech Inc., MS, USA) were attached either to an autonomous sea-noise logger (developed at Curtin University of Technology, Western Australia and the Defence Science and Technology Organisation (DSTO)), or to Sony Digital Audio Tape (DAT) recorders. The deployment duration encompassed an *A. japonicus* evening spawning period in approximately 21 m of flat water above a relatively uniform silt substrate riverbed. Recordings were sampled at 10,416 Hz and were time synchronized on a half hourly basis by the implosion of a light bulb at a known location and depth (Parsons *et al*., 2009). To limit sound energy from sources other than the *A. japonicus* calls (Parsons, 2010), hi- and low-pass filters of 50 and 1000 Hz were applied to the data.

Calls were localized by the arrival-time difference technique (Cato, 1998) and location error ellipses provided for each call. The localization of calls and associated error ellipsoids from the hydrophone array allowed the determination of source ranges, the details of which were outlined by Parsons (2010) and Parsons *et al.* (2009). To minimize noise error, calls analyzed for SL in this study were recorded at a time of relatively little background noise, an example of which is shown in Figure 2.

A. japonicus have been shown to emit three categories of swim bladder driven calls (Parsons, 2010, Parsons *et al*., 2006, 2009, 2010; Figure 3). Each of these call categories varies in duration and has been suggested to have different associated behaviors. Categories were therefore analyzed separately to observe variations in SL. Category 1 calls are short, comprising 2-5 swim bladder pulses. Category 2 calls comprise 11-32 pulses while Category 3 calls are a series of 1-4 pulse calls in quick succession.

Sound pressure level (SPL) or sound level L_p is a logarithmic measure of the effective sound pressure of a sound relative to a reference value. It is measured in decibels (dB) above a standard reference level:

$$L_p = 10\log_{10}\left(\frac{{p_{rms}}^2}{{p_{ref}}^2}\right) = 20\log_{10}\left(\frac{p_{rms}}{p_{ref}}\right) \text{ dB} \qquad (1)$$

where p_{rms} is the root-mean-square pressure and p_{ref} is the reference pressure.

To accurately determine fish call SL it is necessary to first remove the background noise. For this purpose *A. japonicus* calls and background noise were considered as incoherent signals. By Parseval's Theorem, the time-averaged squared total pressure recorded by the logger was equal to the sum of the time-averaged squared partial pressure of each constituent signal (Sprague and Luczkovich, 2004). The level of fish call signal (L_s), once background noise is removed, is given as:

$$L_s = 10\log_{10}(10^{\frac{L_{s+n}}{10}} - 10^{\frac{L_n}{10}}) \qquad (2)$$

where L_{s+n} was the level in dB re 1 μPa of the overall signal and L_n is the background noise level (McCauley, 2001).

The method of call energy level analysis in this study is based on theory protocols from McCauley (2001). For a plane wave, which is taken to be a good approximation for recordings, the energy per unit area (or "energy flux"), over the duration T of a signal where T_0 and T_e denote the signal start and end, is given by:

$$\frac{E}{A} = \int_{T_0}^{T_e} I dt = \int_{T_0}^{T_e} \frac{p_{s+n}^2(t)}{\rho c} dt \qquad (3)$$

where E is the signal energy; A the unit area; and I the intensity, defined by the combined signal and noise pressure p_{s+n}, and the characteristic acoustic impedance ρc. The mean-squared pressure values ($\overline{p_{s+n}{}^2}$) of the total received signal can be derived as:

$$\overline{p^2} = \frac{1}{T}\int_{T_0}^{T_e} p^2(t) dt \qquad (4)$$

Thus, from Equation 4 the 'equivalent signal energy', $E_s(t)$ is given by:

$$E_s(t) = \int_0^T p_{s+n}^2(t)dt - \int_{T_n}^{T_n+T} p_n^2(t)dt \qquad (5)$$

and the peak-to-peak pressures (p_{pp}) are given as:

$$p_{pp} = \max[p(t)] + |\min[p(t)]| \qquad (6)$$

where max[$p(t)$] and min[$p(t)$] are the respective maximum positive and minimum negative values from the pressure wave form (McCauley, 2001, Southall *et al.*, 2007). Figure 4 displays three of the steps involved in analyzing the acoustic pressure attributable to a call and determining the frequency band over which the majority of call energy occurs. A digitized segment of the recording, including the call and encompassing a minimum of 500 sample points either side of the call, was converted to pressure wave form (Figure 4A). An estimation of the 'sound exposure level' (SEL) was made by integrating the pressure squared over the duration of the call in the form of:

$$E_s(t) = T_s \sum_{i=1}^{i=k} (p_{(s+n)_i}^2 - \overline{p_n^2}) \qquad (7)$$

where T_s is the signal length, $p_{(s+n)_i}$ is the i^th element of the pressure wave form (containing signal and noise), k is the last sample point and $\overline{p_n^2}$ is the mean-squared noise pressure from noise samples, obtained from the level of p^2 immediately before or after the call (McCauley, 2001). Pressure levels within the 5% and 95% region of the total cumulative energy curve (Figure 4B) were calculated (Malme *et al.*, 1986) thus standardizing the averaging time to that at which 90% of the energy from the entire signal (less noise) had passed. The call length was taken as the time for 90% of the signal energy to pass. A power spectral density of each call was produced to observe spectral peak frequencies compared with each calculated energy level (Figure 4C) and aid confirmation of repetitive calling by individual fish (Parsons *et al*., 2009).

The received level (RL) can be related to the SL and simple transmission loss (TL) in the form of:

$$RL = A \log_{10} r + SL \qquad (8)$$

where A is the transmission loss constant, r is the slant range (the shortest range between two points of differing altitude; Urick, 1983). RL is thus assumed a linear function of $\log_{10}r$. Linear regression of RL against $\log_{10}r$ (Walpole and Myers, 1985) was carried out to provide estimates of the TL constant (A) and the SL. Correlation values (R^2) were calculated to determine the variance in RLs explained by the regression models. The 95% confidence intervals for the estimates of A and B were calculated using the methods described by Walpole and Myers (1985), as were 95% confidence intervals for predictions of received levels from sources at any given range along the regression curve. These are shown as the 95% confidence interval boundaries on the transmission loss plots in this report.

The estimate of losses due to geometrical spreading provides a minimum loss on which to base initial calculations (Sprague and Luczkovich, 2004). Although surface reflections were observed in the reported data, in the context of SL calculation spherical spreading was considered as a minimum estimate for transmission losses for calls in 20 m depth water, at ranges of less than 100 m (Cato, 1980). Losses due to absorption and water movement were considered of negligible impact. The estimated transmission loss trends were compared to spherical ($20\log_{(10)}(r)$) and cylindrical ($10\log_{(10)}(r)$) spreading losses, where r is measured in meters (Urick, 1983), to help validate the regression models.

Signal SL is often presented in a variety of formats and to help comparison of the results reported here with other data the regression models were applied to estimate SLs not only in SPL (dB re 1μPa at 1 m), but also sound exposure level (SEL) and peak-to-peak pressure for each call category. Sound exposure is the integral of the pressure squared over the duration of the call and SEL is given in dB re 1μPa^2.s at 1 m. Additionally, as TL is not always calculated during estimates of signal SL a final method of estimating SL was to backstep from a RL at known range to a range of 1 m using spherical spreading $20\log_{10}r$ as the TL. All SLs were estimated to the reference pressure at a range of 1 m from the source.

III RESULTS

Parsons *et al.* (2009) localized 213 calls (65 and 148 Category 1 and 2 calls, respectively) using the array. Several calls of each category included overlap with adjoining calls, background vessel noise, or insufficient number of sample points for noise removal, and were discarded. The remaining calls, which contained sufficient noise sample points, were analyzed to determine received SPLs. Of the total localized calls, 53 Category 1 and 112 Category 2 calls at ranges of approximately 20 to 100 m offered signals of sufficient clarity to analyze SPLs. One fish, in particular, was tracked (Parsons *et al*., 2009), which produced 65 Category 2 calls over a 4-minute period for SPL analysis in this study. Source levels and regression-determined transmission losses of call categories are shown in Table I and are discussed with the results of each call category.

Figure 5 illustrates the effects of transmission loss with range for localized Category 1 calls. Category 1 call wave forms originating from different fish were often disparate in structure (Parsons, 2010). These calls varied, not only in the number of pulses, but in the pressure amplitude of those pulses. In 62% of the Category 1 calls the maximum amplitude of the first pulse was less than 80% of that of the second pulse (Parsons, 2010). The linear regression of SPLs from all the 53 Category 1 calls produced a SL of 163 ±16 dB re 1μPa at 1 m and estimated spreading losses of 25.4 $\log_{(10)}(r)$ (Figure 5 and Table I). The transmission losses evident in the data of the Category 1 calls more closely resembled that of spherical spreading than cylindrical spreading (Figure 5, compare the slope of the regression determined continuous line with the dashed and dot-dash lines of spherical and cylindrical spreading, respectively). Correlation of call SPLs with the transmission loss curve was lower than any other call category (Table I, $R^2 = 0.41$).

Category 2 calls exhibited little variation of regression-calculated SL (Figure 6, $R^2 = 0.82$). Similar to Category 1, the Category 2 call transmission losses more closely resembled spherical than cylindrical spreading losses (Figure 6, continuous, dash and dot-dashed lines, respectively). The Category 2 call SL was determined as 172 ± 3.6 dB re 1μPa at 1 m (Table I). Similar to the tracked individual reported by Parsons *et al*. (2009), SPLs from all Category 2 calls exhibited ray multi-path interference features, evident as the received signal level oscillating with range. This interference appeared to be more pronounced in the SPLs of the single caller at ranges between 50 and 100 m (Figure 6, circles).

During localization recordings an individual fish emitting Category 3 calls approached the bottomed hydrophone. The range was determined by geometry from the arrival-time difference between the initial wave form peak associated with the call and the first surface reflection of this peak received by the hydrophone (Parsons *et al.,* 2010). One of the calls was emitted from within 1.6 meters of the hydrophone and therefore the fish must have been swimming close to the riverbed. For range determination purposes it was assumed that the fish continued at the same depth. Localization of Category 2 calls has shown that they were generally emitted from positions on, or near, the riverbed (Parsons *et al.,* 2009). The individual fish provided both single (n = 11) and double (n = 17) pulse calls for SL analysis, at a variety of ranges up to 16 m. Ranging of Category 3 calls of greater than 2 pulses was not conducted.

Based on the assumption that the individual remained in the same orientation throughout its calls, the recordings as the fish swam past the hydrophone provided a comparison of SL between orientations of head towards and away. It was assumed that the fish was swimming forwards and not drifting backwards with the current at an alternate orientation. The consistency of call time with range suggests that a direct route at approximately 0.5 ms^{-1} was the case. Figure 7 displays the received SPL with range for the fish swimming towards, and past, the hydrophone. The 'o' and 'x' markers indicate 1 and 2 pulse calls respectively, emitted as the fish approaches (dashed line) and departs (dot-dashed line). Once the fish was approximately 16 meters past the hydrophone the calls were emitted in such quick succession, with very little range variation, that neither toward or away orientation was assumed. The least squares regression curve for all Category 3 calls, together with 95% confidence limits are shown in Figure 7 by the continuous and dotted lines respectively.

The regression model for all Category 3 calls estimated a SL of 157 ± 5.2 dB re 1µPa at 1 m, lower than both Category 1 and 2 calls. Calculated SLs of calls employing two swim bladder pulses in both orientations were greater than those of the single pulse calls (6.2 and 2.4 dB re 1µPa at 1 m greater towards and away from the hydrophone respectively). In both types of call the SLs were greater with fish facing towards the hydrophone (greater by 4.7 and 8.5 dB re 1µPa at 1 m for single and double pulse calls respectively; Table I, Figure 7). The sample size was small for the Category 3 calls, and even smaller when grouped into the 1 and 2 pulse calls and the orientation. Considering the sample size and the large overlapping confidence intervals (partially as a result of the sample size; Table I) these observations are not statistically significant. However, it was only the fortuitous passing of the calling fish at close range that allowed the inference of orientation and therefore the grouping of these Category 3 calls. This is an unlikely event and difficult to reproduce, especially without inducing behavioral bias, thus the differences in SL between the four types of Category 3 calls are reported as a point of note only.

Figure 8 shows the distribution of SLs for each category based on the determined transmission losses to the receiver for each category, which were back calculated from the recorded SPLs and range. It is thought that the lack of variance in Category 2 call SL distribution was due to the fact that more than half the calls were emitted by one fish. By comparison, the Category 1 call SLs were derived from a number of fish. In addition, the variability observed in short calls (between 1 and 4 pulses) has a greater effect than that found in Category 2 long calls (11-30 pulses). The SL distribution of all Category 3 calls was affected by the differing orientation of the fish and pulse number.

The SL regression models were repeated to determine the SEL and peak-to-peak pressure SLs for each category (Table II). In each category the difference between SPL and SEL is determined by the call lengths. This is because the root-mean-square SPL (dB re 1 μPa) is equal to the SEL (dB re 1 $\mu Pa^2.s$) minus $10\log_{(10)}$(call length).

Mean background noise levels during the course of these recordings were observed at 108 dB re 1μPa (over the same 50-1000 Hz bandwidth as the call frequency analysis). However, during the course of Mosman Bay recordings in this study noise levels which include vessel traffic and/or calling *A. japonicus* have been known to reach 148 dB re 1μPa. The background noise has significant impact on the detection range of a call to both intended recipient and observer (Urick, 1983, Sprague and Luczkovich, 2004). For simple comparative purposes a maximum detection range of the regression determined SL was calculated for each call category (Table III). This is the range at which the signal would have attenuated to background noise level using signal processing based on the estimated transmission losses and also using spherical spreading as the transmission loss. It does not use statistical analysis of the probability of signal detection or account for fish hearing critical ratios and so could not be used as an estimation of the ranges over which fish may detect calls. The ratio of detection ranges of a call with and without the noise of a passing vessel, however, is comparable and shows that, even under near ideal detection conditions, anthropogenic activity can reduce detection of such calls from hundreds of meters, to less than 10 m.

IV DISCUSSION

A simple method to determine fish call SL would be concurrent calibrated audio and visual recording, at a known distance from the hydrophone, similar to that reported by Sprague and Luczkovich (2004). However, visual confirmation of behaviorally unbiased, *in situ*, fish calls, in dark or turbid waters, is improbable at such short ranges. In typical SPL calculations the origin is considered as a point source. Due to visibility, a caller in dark or turbid waters would be required to be at such close range that it may no longer be considered as a point source. Furthermore, the observed disparities in SL, due to different fish and interference suggests that a range of observed call SPLs is required to model the species SLs. Therefore precisely locating individuals from call arrival-time differences to determine accurate source ranges of species-specific calls is the most appropriate method for recording SLs.

Estimated SLs of 163, 172 and 157 dB re 1μPa at 1 m with associated confidence limits for *A. japonicus* call Categories 1, 2, and 3 have been established. Transmission losses observed in the linear regression models for Categories 1 and 2 were within acceptable range of spherical spreading to ‘practical’ spreading loss (Coates, 1990) and significantly greater than that of cylindrical spreading. Spherical spreading has been considered satisfactory to ranges of around 50 m in water depths of approximately 20 m (Cato, 1998).

Due to the variability of the call structure Category 1 calls displayed comparatively low correlation with the least squares regression transmission loss model, compared to that of the other call categories. The difference in amplitude between the first two pulses of a call varied significantly throughout all three call categories. This variation had greater impact on SLs of short calls comprising fewer pulses. Therefore determined confidence limits of 148 and 179 dB re 1μPa at 1 m with a correlation of R^2 = 0.42 for the best fit ($25.39\log_{(10)}(r)$) transmission losses were deemed a reasonable estimate of SL range for Category 1 calls.

SLs increased through Categories 3, 1 and 2 as more pulses were included in calls. This was due, in part, to an increase in amplitude over the first three pulses of several calls. Parsons (2010) highlighted that in many long Category 2 calls the first one, two or three pulses were of lower amplitude than subsequent pulses. To corroborate this, double pulse Category 3 calls when the fish was orientated towards the hydrophone produced SLs comparable with those of the Category 1 calls (Table I). Lagadere and Mariani (2006) observed similar traits in the short calls of *Argyrosomus regius* and suggested these were less intense than long grunts, a hypothesis in agreement with findings of this study. After the initial pulses the detected maximum amplitude often reached a plateau, and as a result, Category 2 call SLs were more consistent than those of Category 1. It is suggested that the high correlation of Category 3 call SL within the single and double pulse trends were due to the single source origin. Whether this trait is characteristic of an individual is unknown.

Source levels of each *A. japonicus* category of call were significantly greater than the reported SLs of calls from other species. *In situ,* silver perch (*Bairdiella chrysoura*) and oyster toadfish (*Opsanus tau*) reportedly have maximum SLs of 135 and 132 dB re 1µPa at 1 m, respectively (Sprague and Luczkovich, 2004; Barimo and Fine, 1998), and typically grow to total lengths of 30 and 43.2 cm, respectively (Robins and Ray, 1986). As call SLs are related to fish size (Connaughton *et al.*, 2000) and these species are considerably smaller than *A. japonicus* captured in the Swan River (greater than 1 m; Farmer, 2008), the comparatively lower SLs are to be expected. Cato (1980) and McCauley (2001) reported SLs of 148 (± 4) and 149 (± 2) dB re 1µPa at 1 m, respectively, from sources speculated to be *Protonibea diacanthus*, a Sciaenidae of similar sound production mechanism to *A. japonicus*. Both of these reports comprised calls of similar spectral peak frequencies (250 - 400 Hz) to those of *A. japonicus* (Parsons, 2010, Parsons *et al*., 2006). *P. diacanthus* caught in a recent study around the Northern Territory were of comparable length to the Swan River *A. japonicus* (Phelan, 2008). However, sampling conducted in Cape York Peninsula waters in 1999 and 2000 yielded predominantly 750-799 and 600-649 mm specimens, respectively (Phelan *et al*., 2008). It is not known whether the sounds reported by Cato (1980) and McCauley (2001) originated from similar sized fish.

Each study has shown significant variability in the estimated SLs. Regardless, the *A. japonicus* SLs are greater than those of previously reported species, as are the SLs of other similar sized Sciaenidae, where the call structure is similar (Cato, 1980; McCauley, 2001). While the two previous reports did not test as many samples as this study, the difference in SL is large and the authors suggest several possible reasons for this:

(1) The sizes of *P. diacanthus* callers were unknown and if of considerably smaller size may contribute to the intensity difference;

(2) Previous reports of fish SLs have estimated transmission losses at $20\log_{(10)}(r)$, in contrast with this study where transmission losses were calculated through best fit regression and found to be greater than spherical spreading (Table III). The substitution of $20\log_{(10)}(r)$ for transmission loss reduced the *A. japonicus* SL for categories 1, 2 and 3 to 153, 165 and 156 dB re 1μPa at 1 m, respectively (Table II). If the SEL is calculated using a $20\log_{10}(r)$ transmission loss the determined SL becomes 162 ± 2.7 dB re $1\mu Pa^2$.s at 1 m, more comparable with the 150 dB re $1\mu Pa^2$.s at 1 m reported by McCauley (2001) for the speculated *P. diacanthus*;

(3) The most comparable sound between those of *A. japonicus* above and those reported for *P. diacanthus* differ in length and structure. McCauley (2001) noted that the *P. diacanthus* calls persisted for longer than a second, much longer than the 0.35-s *A. japonicus* calls. The amount of energy required to produce calls increases with duration for the same SPL (Mitchell *et al*., 2008). Hence for the same amount of energy use, shorter sounds would have higher SLs. The *P. diacanthus* calls reduced in amplitude in the latter half of the call (McCauley, 2001), similar to those of the Atlantic cod (*Gadhus morhua*). Nilsson (2004) attributed this reduction to buildup of lactic acid in the sonic muscle. So the greater call length and possible lactic acid buildup are suggested to account for the lower SL.

This study has provided some observations of *in situ* fish call directivity. The estimated SL of Category 3 calls recorded as the fish passed the hydrophone displayed a 5 to 8.5 dB difference between orientations. If the assumption of forward motion is correct, and the individual was not swimming against a current drifting backwards past the hydrophone, calls were greater in front of the caller than behind. This finding is in contrast with Barimo and Fine (1998), who hypothesized that directivity in sound production of *O. tau* would be reduced in the direction of the fish ears and observed a 3 to 5 dB re 1μPa decline in SL moving from the rear to the front of the fish. The reason for this difference is unknown, though if the *A. japonicus* Category 3 caller was swimming into, and drifting backwards with the current the directivity would result in a reduced SPL in front of the fish. Although the sample size of different Category 3 calls is small and the variance large (in part due to the small sample size), the differences in SL between orientation is notable. This would not be expected given that the wavelength of each call is large compared with the range to the receiver, but is a phenomenon similar to that reported by Barimo and Fine (1998).

Although *A. japonicus* calls contain energy across the frequency bandwidth from 50 to 1000 Hz, the tone burst dominates the call such that often one or more of the spectral peak frequencies are 10 dB re 1μPa greater than other amplitude modulated frequencies. As a result ray multi-path interference was observed in the SLs (Figure 6). This was observed to be more prominent at the farther regions of the test ranges; however, this may be due to the cluster of calls emitted by one fish rather than close range measurements where the effect was masked by the variability of different callers.

Source level relative to background noise is a significant factor in determining the maximum range at which a call can be detected by its intended recipient. Table III has shown some coarse estimates of maximum range at which a call would have attenuated to background noise level based purely on a) the transmission losses estimated in this study and b) transmission losses estimated using spherical spreading. It does not use statistical analysis of the probability of signal detection, frequency bandwidths used by fish when detecting sounds or account for fish hearing critical thresholds and so could not be used as an estimation of the ranges over which fish may detect calls. To assess such communication ranges requires considerable effort and has been deemed future work. However, from a management perspective such detection ranges may have specific impacts on the spawning success rates of an aggregation. Wind driven waves can also produce background noise at a level similar to that of passing vessels and it is possible that the fish have adapted to continue their behavior despite increased noise levels. However, waves which would produce noise of that level are rare compared with the vessel presence in Mosman Bay.

A. japonicus in Mosman Bay form aggregations of low density calling by comparison with other reports (Sprague and Luczkovich, 2004). Thus individuals can often be detected at comparatively long ranges (Parsons *et al.*, 2009). During periods of low background noise, such as those reported here, regression models predict a signal processing detection range of approximately 120, 400 and 110 m for calls of Categories 1, 2 and 3 respectively. However, periods of high background vessel noise were frequent at the study site. Vessel noise of water skiers passing directly above calling fish has reportedly masked calls at distances of less than the water depth (Parsons *et al.*, 2009) and received vessel noise greater than 150 dB re 1µPa would mask all calls at distances of near 1 m (assuming spherical spreading). The ratio of detection ranges between those identified with and without the noise of a passing vessel (Table III) are comparable and show that, even under near ideal detection conditions, anthropogenic activity can significantly reduce detection ranges of such calls. Anthropogenic noise therefore poses a significant impact which needs assessing to determine what, if any, effect it has on spawning success.

V CONCLUSIONS AND RECOMMENDATIONS

To utilize the SL of *A. japonicus* calls is to begin the process of absolute biomass estimates. Hydrophone array studies have provided an insight into separation distances and distributions of calling *A. japonicus* in Mosman Bay. Proposed future work involves the combination of the determined SL ranges and distributions with call counting techniques to estimate the number of calling *A. japonicus* within the hydrophone detection range. The issue of determining the ratio of calling/non-calling fish remains to be resolved. In an ideal world this would involve an isolated aggregation of randomly distributed sized males and females of known number. Thus the number of calls could be related to the overall population. In the absence of this possibility, ratios will have to be repeatedly obtained from *aquaria*.

The accurate determination of ranges at which fish can detect calls is an important step towards assessing the impact of anthropogenic noise on communication. This requires statistical analysis of the probability of signal detection and an evaluation of the critical hearing ratio of the fish involved. Ranges given in this paper are only an identification that, at the SLs of *A. japonicus* calls in Mosman Bay, passing vessels can reduce detection, even using advanced signal processing, from hundreds of meters to less than 10 m.

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Table I. Extrapolated call sources levels for each category of *A. japonicus* call from least squares linear regression. Values display SPL source levels and equivalent spreading losses together with 95% confidence limits and the curve correlation with data points.

Call Category		Orientation	Number Calls	Source Level (dB re 1 µPa) (± 95% confidence limits)	Transmission Loss (log(r)) (± 95% confidence limits)	R^2
Category 1	All	N/A	53	163 (148, 179)	-25.39 (-35, -16)	0.42
Category 2	Individual	N/A	65	172 (163, 180)	-23.94 (-30, -17)	0.61
	All	N/A	112	172 (168, 176)	-23.74 (-26, -22)	0.82
Category 3	All	N/A	28	157 (152, 162)	-23.04 (-27, -19)	0.88
	One pulse	Towards	7	156 (151, 162)	-18.67 (-26, -11)	0.89
		Away	4	152 (144, 159)	-19.17 (-27, -11)	0.98
	Two pulse	Towards	3	163 (98, 227)	-27.53 (-102, 47)	0.96
		Away	10	154 (150, 158)	-18.81 (-24, -14)	0.93

Table II. Values of source levels with standard deviation, based on recorded values. Source levels (dB re 1µPa at 1 m) using $20\log_{(10)}(r)$ losses are shown. Data is also for 3 type of source level as they are often reported (SPL, SEL equivalent energy and peak-to-peak pressures). For each method and call category the calculated source level, transmission loss curve constant and correlation coefficient are shown. Mean call lengths for each category are also shown.

		Call Category 1	**Call Category 2**	**Call Category 3**
Source level (dB re 1µPa) 20log(r) transmission loss (s.d.)		153 (6)	165 (2)	156 (4)
Sound pressure level (dB re 1µPa at 1 m)	Source level (95% c.l.)	163 (148, 179)	172 (168, 176)	157 (152, 162)
	Transmission loss ($\log_{(10)}(r)$) (95% c.l.)	-25.4 (-34.6, -16.2)	-23.7 (-25.9, -21.6)	-23.0 (-26.6, -19.5)
	R^2	(0.42)	(0.82)	(0.88)
SEL (dB re 1µPa^2.s at 1 m)	Source level (95% c.l.)	152 (138, 166)	165 (156, 173)	136 (132, 139)
	Transmission loss ($\log_{(10)}(r)$) (95% c.l.)	-22.9 (-31.1, -14.6)	-21.8 (-27.2, -16.5)	-17.4 (-21.2, -13.5)
	R^2	(0.64)	(0.64)	(0.74)
Peak-peak pressure (dB re 1µPa at 1 m)	Source level (95% c.l.)	183 (173, 195)	194 (189, 201)	167 (165, 170)
	Transmission loss ($\log_{(10)}(r)$) (95% c.l.)	-25.2 (-31.7, -18.6)	-27.2 (-30.8, -23.6)	-16.1 (-18.8, -13.5)
	R^2	(0.77)	(0.86)	(0.83)
Mean call length (s) (s.d.)		0.054 (0.021)	0.346 (0.063)	0.018 (0.015)

Table III. Maximum detection ranges (r) for all call categories (using basic signal processing) when emitted during two levels of background noise (110 and 150 dB re 1μPa), calculated by assuming the regression calculated TL determined from the data and losses due only to spherical spreading. Call/vessel noise energy was computed over broadband spectra. As this calculation does not account for critical hearing ratios, frequency bandwidths used by *A. japonicus* to detect calls and no probability of signal detection has been applied, this is a simple calculation of the range at which the signal attenuates to background noise levels.

Detection Range (m)

Call Category	Source level (dB re 1μPa at 1 m)	Regression calculated transmission loss and noise levels (dB re 1μPa)		Spherical transmission loss and noise levels (dB re 1μPa)	
		110	150	110	150
1	**163**	**123**	**3**	**231**	**2**
2	**172**	**396**	**8**	**660**	**7**
3	**157**	**112**	**2**	**117**	**1**

Figure 1. Map of Western Australia with a magnification of the Swan River and Mosman Bay, highlighting the location of the hydrophone array.

Figure 2. Spectrogram of 20 seconds of *A. japonicus* call period from a hydrophone positioned on the riverbed in 18 m of flat water. Individual *A. japonicus* calls (grey-black areas) are clearly visible above minimum background noise (white areas). Spectrum produced using a 1024 point Hanning window with 0.5 overlap and frequency resolution of 5.09 Hz.

Figure 3. Example wave forms of Category 1 short calls (A), Category 2 long calls (B) and single pulse Category 3 calls (C) as recorded by a 'bottomed' hydrophone.

Figure 4. Example sound pressure level (dB re 1µPa) calculation of an *A. japonicus* Category 2 long call. A) Wave form of example call with noise removal zone 500 samples before (circles) and after (squares) shown. Crosshairs mark the points at which 5 and 95% of the total energy occurs within the analyzed region. B) Cumulative energy of the call showing pressure squared per second with 5 and 95% region markers shown. C) Power spectral density of call.

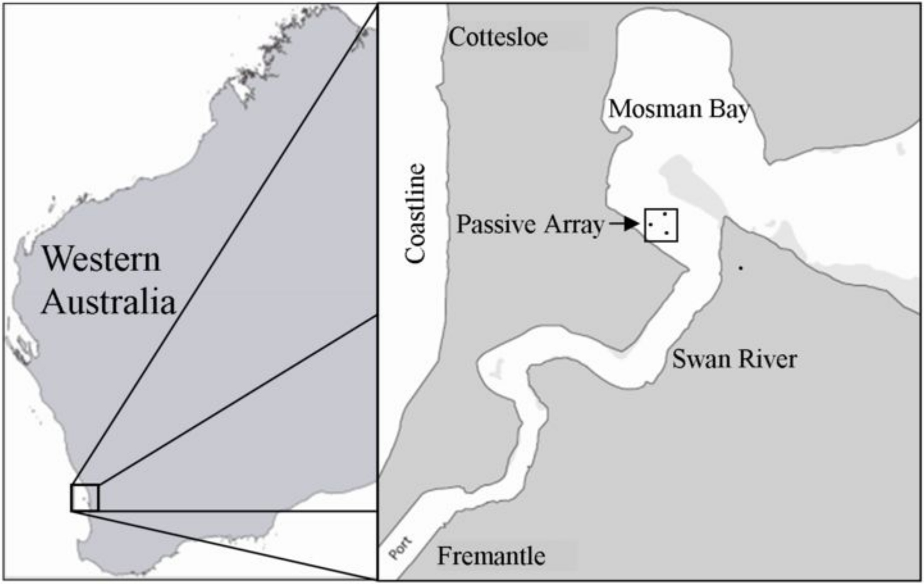
Figure 5. Detected sound pressure levels (dB re 1µPa) with range (log scale) for 53 Category 1 calls. Continuous line illustrates linear regression model of transmission losses with 95% confidence limits of source level shown (dotted lines).

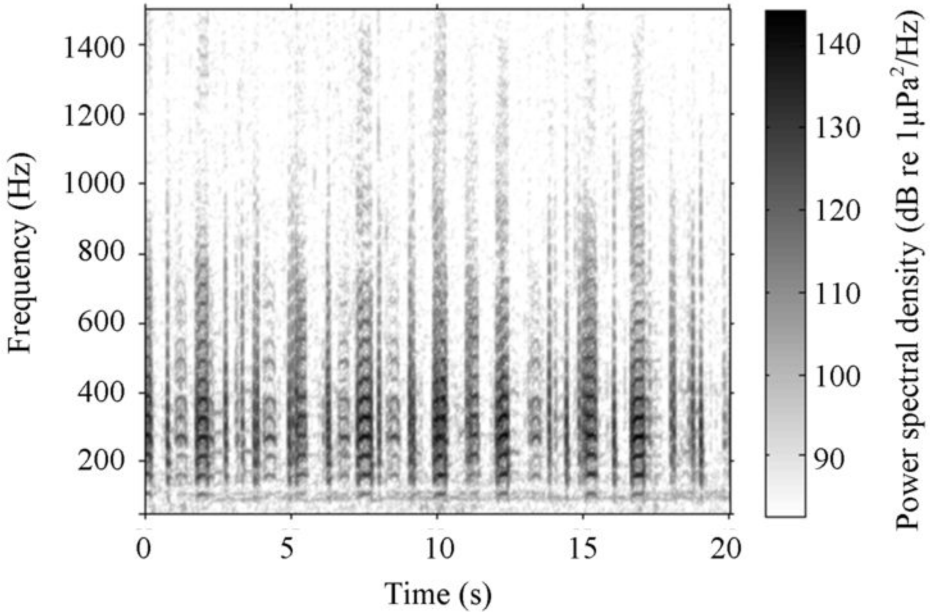
Figure 6. Detected sound pressure levels (dB re 1µPa) with range (log scale) for Category 2 calls. Calls of a tracked individual fish (○) and those of all remaining fish (x) are shown. Continuous line marks the linear regression determined transmission losses with 95% confidence limits (dotted lines).

Figure 7. Time of fish calls with $\log_{10}(r)$ (A) highlighting the order of 1 pulse (o and □) and 2 pulse (x and +) Category 3 calls. Sound pressure levels (dB re 1µPa) against range (log scale) as detected by the bottomed hydrophone (B) as the fish approached (□ and +, dashed line) and then passed (o and x, dot-dashed line) the hydrophone. The positions of the o, □, x and + illustrate whether the fish was orientated towards or away from the hydrophone and whether the call was a single or double pulse call. Least squares regression curve, together with 95% confidence limits are shown by the continuous and dotted lines respectively. The order of calls is indicated by arrows. Calls not suitable for range analysis have been omitted.

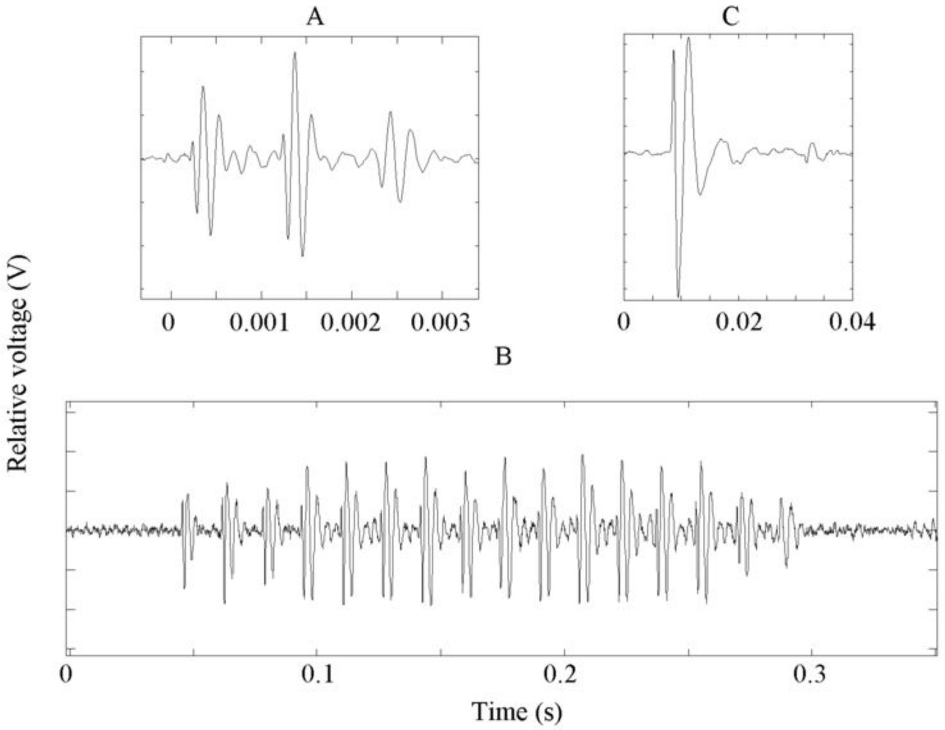
Figure 8. Distribution of source levels (dB re 1µPa at 1 m) from recorded sound pressure levels for each *A. japonicus* call category based on the estimated transmission losses only.

A

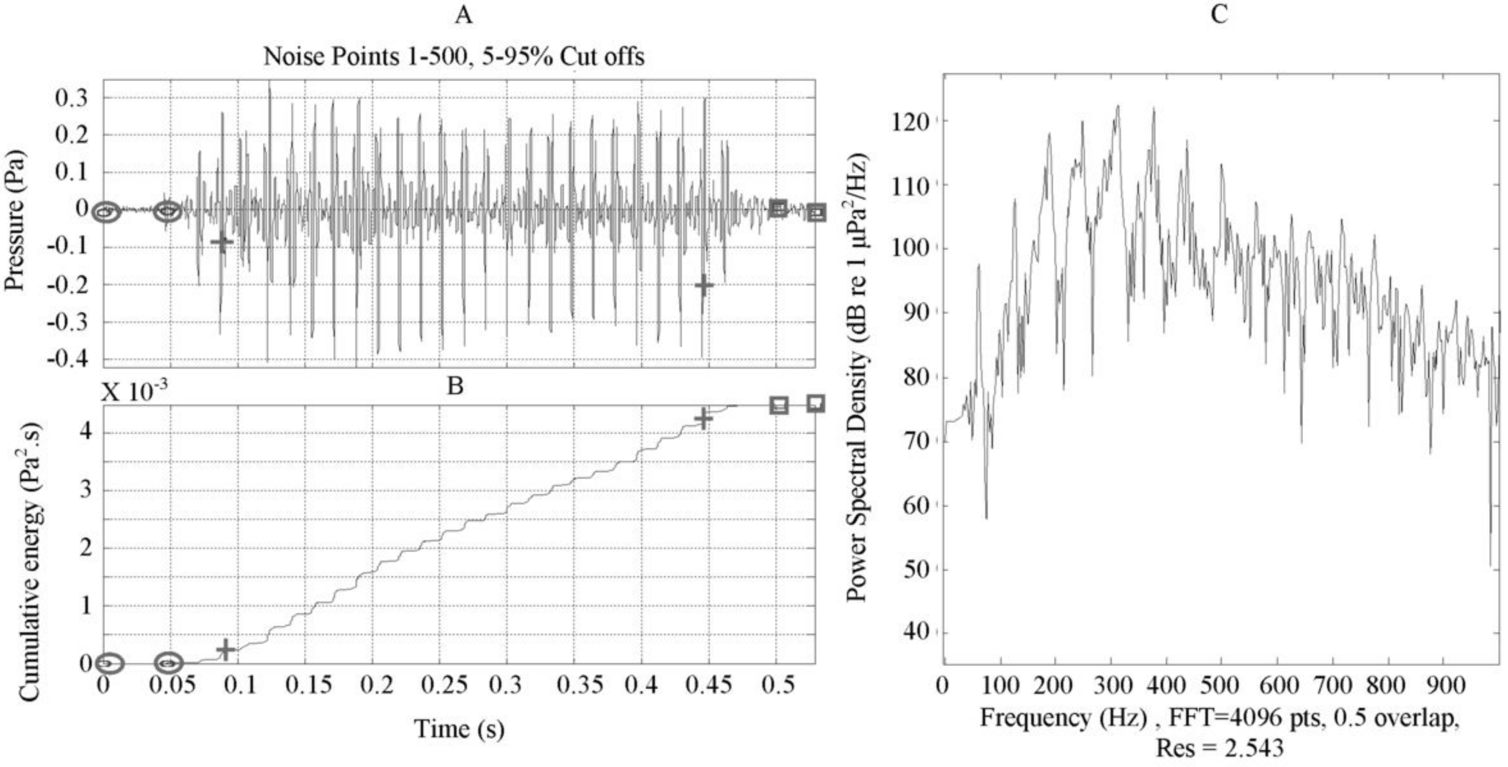

Western Australia
Cottesloe
Mosman Bay
Coastline
Passive Array
Swan River
Port
Fremantle



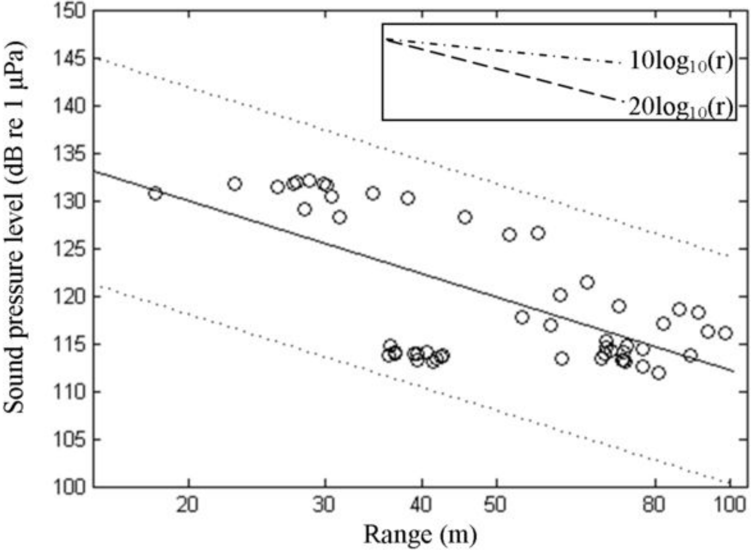
1400
1200
1000
800
600
400
200
Frequency (Hz)
0
5
10
15
20
Time (s)
140
130
120
110
100
90
Power spectral density (dB re 1μPa²/Hz)



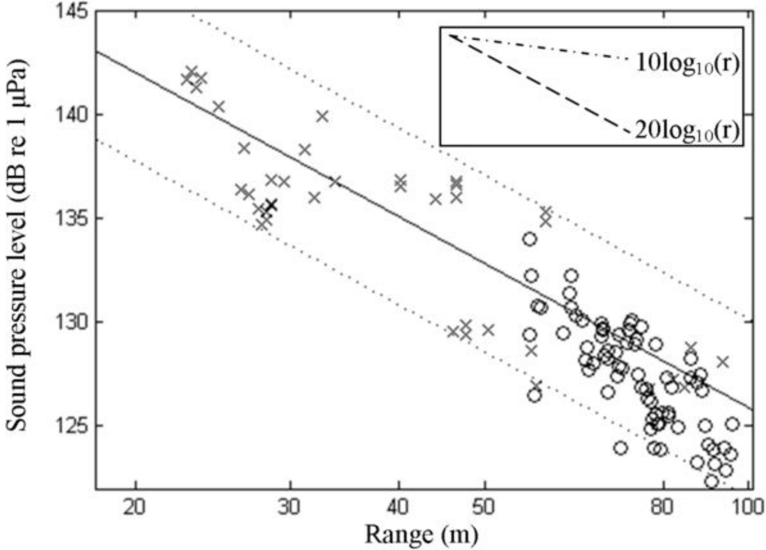
A
C
B
0
0.001
0.002
0.003
0
0.02
0.04
Relative voltage (V)
0
0.1
0.2
0.3
Time (s)

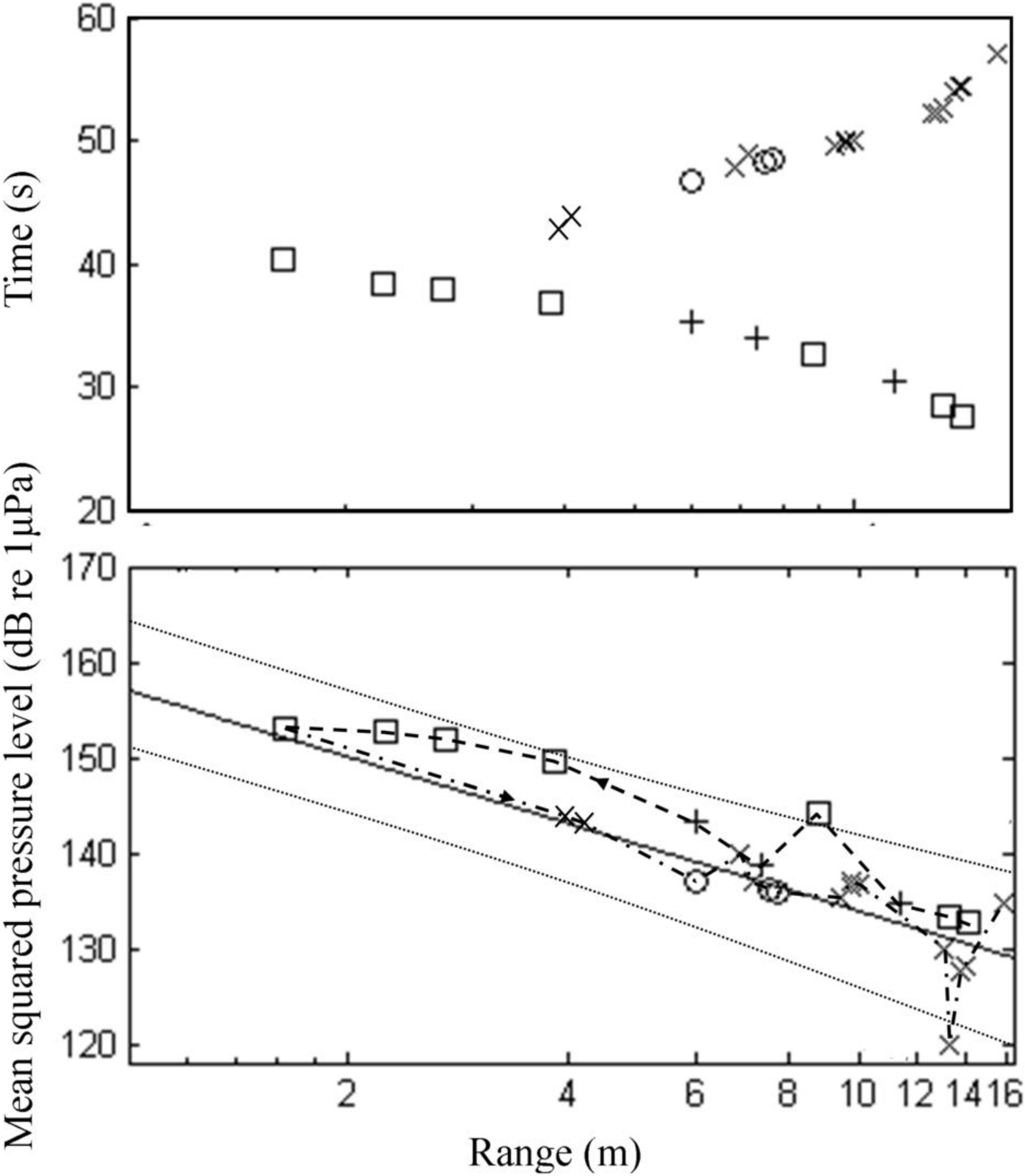


A
Noise Points 1-500, 5-95% Cut offs
Pressure (Pa)
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
B
X 10-3
Cumulative energy (Pa2.s)
4
3
2
1
0
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Time (s)
C
Power Spectral Density (dB re 1 μPa2/Hz)
120
110
100
90
80
70
60
50
40
0
100
200
300
400
500
600
700
800
900
Frequency (Hz) , FFT=4096 pts, 0.5 overlap,
Res = 2.543

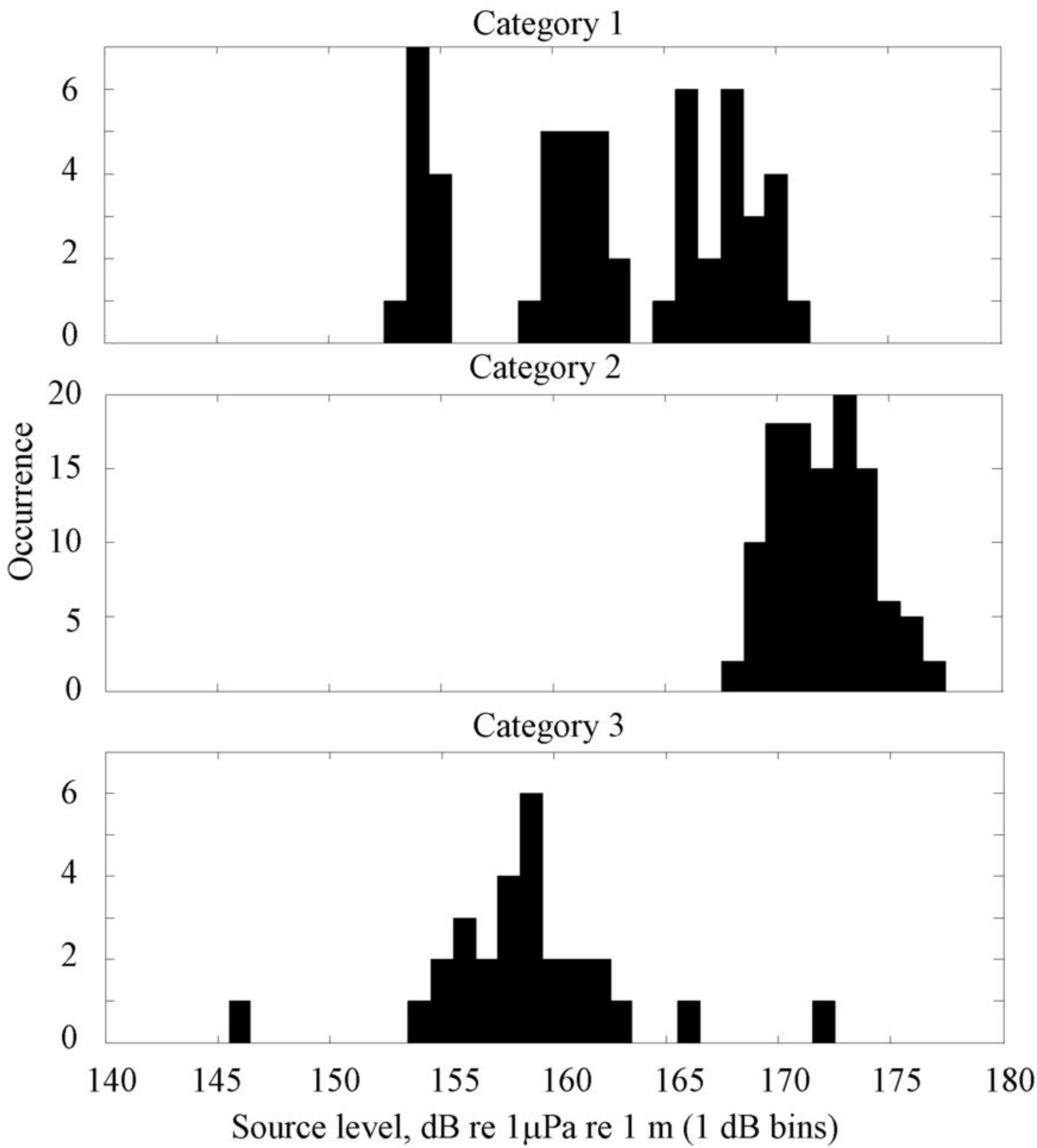


Sound pressure level (dB re 1 μPa)
150
145
140
135
130
125
120
115
110
105
100
20
30
40
50
80
100
Range (m)
10log10(r)
20log10(r)


145
140
135
130
125
Sound pressure level (dB re 1 μPa)
20
30
40
50
80
100
Range (m)
10log10(r)
20log10(r)



Time (s)
60
50
40
30
20
Mean squared pressure level (dB re 1μPa)
170
160
150
140
130
120
2
4
6
8
10
12
14
16
Range (m)


Category 1
Category 2
Category 3
Occurrence
0
2
4
6
0
5
10
15
20
140
145
150
155
160
165
170
175
180
Source level, dB re 1μPa re 1 m (1 dB bins)