

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

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27 **ABSTRACT**

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29 Mullet (*Argyrosomus japonicus*) in Mosman Bay, Western Australia produce three
30 call categories associated with spawning behavior. The determination of call source
31 levels and their contribution to overall recorded sound pressure levels is a significant
32 step towards estimating numbers of calling fish within the detection range of a
33 hydrophone. The source levels and ambient noise also provide significant
34 information on the impacts anthropogenic activity may have on the detection of *A.*
35 *japonicus* calls. An array of four hydrophones was deployed to record and locate
36 individual fish from call arrival-time differences. Successive *A. japonicus* calls
37 produced samples at various ranges between 1 and 100 m from one of the array
38 hydrophones. The three-dimensional localization of calls, together with removal of
39 ambient noise, allowed the determination of source levels for each call category using
40 observed trends in propagation losses and interference. Mean source levels (at 1 m
41 from the hydrophone) of the three call categories were calculated as: 163 ± 16 dB re
42 $1 \mu\text{Pa}$ for Category 1 calls (short call of 2-5 pulses); 172 ± 4 dB re $1 \mu\text{Pa}$ for Category 2
43 calls (long calls of 11-32 pulses); and 157 ± 5 dB re $1 \mu\text{Pa}$ for Category 3 calls (series
44 of successive calls of 1-4 pulses, increasing in call rate).

45

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

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51 **I INTRODUCTION**

52

53 Many species of fish use vocalizations as social cues for spawning behavior (Winn,
54 1964, Myrberg and Spires, 1972, Fine *et al.*, 1977) and often aggregate in large
55 numbers to call *en masse* (Luczkovich *et al.*, 1999, Parsons *et al.*, 2006). Such
56 choruses are often used to delineate areas used by spawning aggregations (Luczkovich
57 *et al.*, 1999, Parsons *et al.*, 2006). However, the ultimate goal of fisheries passive
58 acoustics is the unbiased estimation of abundance. The determination of absolute
59 numbers of mobile animals such as aggregating fish requires the ability to
60 simultaneously census large volumes of water and to eliminate bias from multiple
61 detections of the same fish. The sensitivity of hydrophones in areas of low ambient
62 noise allows the discrimination of fish calls emitted at large ranges from the receiver
63 and in some cases the ability to monitor individual fish over time, by listening and
64 localizing their calls (Parsons *et al.*, 2009).

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

73

74 To quantify a call SL it is necessary to isolate energy associated with the signal.
75 Mulloway (*Argyrosomus japonicus*) often spawn in groups (Ueng *et al.*, 2007) and

76 can produce high densities of overlapping calls in the wild (Parsons *et al.*, 2006),
77 complicating the discrimination of separate calls. However, during the
78 commencement of an evening spawning cycle in the Swan River, Perth, Western
79 Australia, calls are of sufficiently low density to offer the opportunity to monitor
80 individual fish (Parsons *et al.*, 2009).

81

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

94

95 Fish calls offer significant information about the caller to the intended recipient and,
96 inadvertently, the observer. The size of the individual can be related to both the call
97 SL and spectral peak frequency (Connaughton *et al.*, 2000). However, calls emitted
98 by the same fish are not all necessarily of the same SL. For example, Lagadere and
99 Mariani (2006) proposed that the short grunts of French meagre (*A. regius*) are
100 weaker than the long grunts. Similar results from *in situ* *A. japonicus* calls have been

101 observed, but it was not confirmed whether pressure wave amplitude differences were
102 due to range, weaker swim bladder twitches or multiple ray-path interference (Parsons
103 *et al.*, 2006, 2009). Therefore measurement of many SLs may be required to
104 categorize a fish call. It is the aim of this study to determine SL ranges for each
105 category of call exhibited by *A. japonicus* in an aggregation in Mosman Bay, Swan
106 River.

107

108 **II METHODS**

109

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

125

126 Calls were localized by the arrival-time difference technique (Cato, 1998) and
127 location error ellipses provided for each call. The localization of calls and associated
128 error ellipsoids from the hydrophone array allowed the determination of source
129 ranges, the details of which were outlined by Parsons (2010) and Parsons *et al.*
130 (2009). To minimize noise error, calls analyzed for SL in this study were recorded at
131 a time of relatively little background noise, an example of which is shown in Figure 2.

132

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

140

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

$$144 \quad L_p = 10 \log_{10} \left(\frac{p_{rms}^2}{p_{ref}^2} \right) = 20 \log_{10} \left(\frac{p_{rms}}{p_{ref}} \right) \text{ dB} \quad (1)$$

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

146

147 To accurately determine fish call SL it is necessary to first remove the background
148 noise. For this purpose *A. japonicus* calls and background noise were considered as

149 incoherent signals. By Parseval's Theorem, the time-averaged squared total pressure
 150 recorded by the logger was equal to the sum of the time-averaged squared partial
 151 pressure of each constituent signal (Sprague and Luczkovich, 2004). The level of fish
 152 call signal (L_s), once background noise is removed, is given as:

$$153 \quad L_s = 10 \log_{10} \left(10^{\frac{L_{s+n}}{10}} - 10^{\frac{L_n}{10}} \right) \quad (2)$$

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

156

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

$$161 \quad \frac{E}{A} = \int_{T_0}^{T_e} I dt = \int_{T_0}^{T_e} \frac{p_{s+n}^2(t)}{\rho c} dt \quad (3)$$

162 where E is the signal energy; A the unit area; and I the intensity, defined by the
 163 combined signal and noise pressure p_{s+n} , and the characteristic acoustic impedance ρc .

164 The mean-squared pressure values ($\overline{p_{s+n}^2}$) of the total received signal can be derived
 165 as:

$$166 \quad \overline{p^2} = \frac{1}{T} \int_{T_0}^{T_e} p^2(t) dt \quad (4)$$

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

168
$$E_s(t) = \int_0^T p_{s+n}^2(t) dt - \int_{T_n}^{T_n+T} p_n^2(t) dt \quad (5)$$

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

170
$$p_{pp} = \max[p(t)] + |\min[p(t)]| \quad (6)$$

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

180
$$E_s(t) = T_s \sum_{i=1}^{i=k} (p_{(s+n)_i}^2 - \overline{p_n^2}) \quad (7)$$

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

189 observe spectral peak frequencies compared with each calculated energy level (Figure
190 4C) and aid confirmation of repetitive calling by individual fish (Parsons *et al.*, 2009).

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

$$193 \quad RL = A \log_{10} r + SL \quad (8)$$

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

204

205 The estimate of losses due to geometrical spreading provides a minimum loss on
206 which to base initial calculations (Sprague and Luczkovich, 2004). Although surface
207 reflections were observed in the reported data, in the context of SL calculation
208 spherical spreading was considered as a minimum estimate for transmission losses for
209 calls in 20 m depth water, at ranges of less than 100 m (Cato, 1980). Losses due to
210 absorption and water movement were considered of negligible impact. The estimated
211 transmission loss trends were compared to spherical ($20\log_{10}(r)$) and cylindrical
212 ($10\log_{10}(r)$) spreading losses, where r is measured in meters (Urick, 1983), to help
213 validate the regression models.

214

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

224

225 **III RESULTS**

226

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

238

239 Figure 5 illustrates the effects of transmission loss with range for localized Category 1
240 calls. Category 1 call wave forms originating from different fish were often disparate
241 in structure (Parsons, 2010). These calls varied, not only in the number of pulses, but
242 in the pressure amplitude of those pulses. In 62% of the Category 1 calls the
243 maximum amplitude of the first pulse was less than 80% of that of the second pulse
244 (Parsons, 2010). The linear regression of SPLs from all the 53 Category 1 calls
245 produced a SL of 163 ± 16 dB re $1\mu\text{Pa}$ at 1 m and estimated spreading losses of 25.4
246 $\log_{10}(r)$ (Figure 5 and Table I). The transmission losses evident in the data of the
247 Category 1 calls more closely resembled that of spherical spreading than cylindrical
248 spreading (Figure 5, compare the slope of the regression determined continuous line
249 with the dashed and dot-dash lines of spherical and cylindrical spreading,
250 respectively). Correlation of call SPLs with the transmission loss curve was lower
251 than any other call category (Table I, $R^2 = 0.41$).

252

253 Category 2 calls exhibited little variation of regression-calculated SL (Figure 6, $R^2 =$
254 0.82). Similar to Category 1, the Category 2 call transmission losses more closely
255 resembled spherical than cylindrical spreading losses (Figure 6, continuous, dash and
256 dot-dashed lines, respectively). The Category 2 call SL was determined as 172 ± 3.6
257 dB re $1\mu\text{Pa}$ at 1 m (Table I). Similar to the tracked individual reported by Parsons *et*
258 *al.* (2009), SPLs from all Category 2 calls exhibited ray multi-path interference
259 features, evident as the received signal level oscillating with range. This interference
260 appeared to be more pronounced in the SPLs of the single caller at ranges between 50
261 and 100 m (Figure 6, circles).

262

263 During localization recordings an individual fish emitting Category 3 calls
264 approached the bottomed hydrophone. The range was determined by geometry from
265 the arrival-time difference between the initial wave form peak associated with the call
266 and the first surface reflection of this peak received by the hydrophone (Parsons *et al.*,
267 2010). One of the calls was emitted from within 1.6 meters of the hydrophone and
268 therefore the fish must have been swimming close to the riverbed. For range
269 determination purposes it was assumed that the fish continued at the same depth.
270 Localization of Category 2 calls has shown that they were generally emitted from
271 positions on, or near, the riverbed (Parsons *et al.*, 2009). The individual fish provided
272 both single (n = 11) and double (n = 17) pulse calls for SL analysis, at a variety of
273 ranges up to 16 m. Ranging of Category 3 calls of greater than 2 pulses was not
274 conducted.

275

276 Based on the assumption that the individual remained in the same orientation
277 throughout its calls, the recordings as the fish swam past the hydrophone provided a
278 comparison of SL between orientations of head towards and away. It was assumed
279 that the fish was swimming forwards and not drifting backwards with the current at an
280 alternate orientation. The consistency of call time with range suggests that a direct
281 route at approximately 0.5 ms^{-1} was the case. Figure 7 displays the received SPL with
282 range for the fish swimming towards, and past, the hydrophone. The 'o' and 'x'
283 markers indicate 1 and 2 pulse calls respectively, emitted as the fish approaches
284 (dashed line) and departs (dot-dashed line). Once the fish was approximately 16
285 meters past the hydrophone the calls were emitted in such quick succession, with very
286 little range variation, that neither toward or away orientation was assumed. The least

287 squares regression curve for all Category 3 calls, together with 95% confidence limits
288 are shown in Figure 7 by the continuous and dotted lines respectively.

289

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

305

306 Figure 8 shows the distribution of SLs for each category based on the determined
307 transmission losses to the receiver for each category, which were back calculated from
308 the recorded SPLs and range. It is thought that the lack of variance in Category 2 call
309 SL distribution was due to the fact that more than half the calls were emitted by one
310 fish. By comparison, the Category 1 call SLs were derived from a number of fish. In
311 addition, the variability observed in short calls (between 1 and 4 pulses) has a greater

312 effect than that found in Category 2 long calls (11-30 pulses). The SL distribution of
313 all Category 3 calls was affected by the differing orientation of the fish and pulse
314 number.

315

316 The SL regression models were repeated to determine the SEL and peak-to-peak
317 pressure SLs for each category (Table II). In each category the difference between
318 SPL and SEL is determined by the call lengths. This is because the root-mean-square
319 SPL (dB re 1 μ Pa) is equal to the SEL (dB re 1 μ Pa².s) minus $10\log_{(10)}(\text{call length})$.

320

321 Mean background noise levels during the course of these recordings were observed at
322 108 dB re 1 μ Pa (over the same 50-1000 Hz bandwidth as the call frequency analysis).
323 However, during the course of Mosman Bay recordings in this study noise levels
324 which include vessel traffic and/or calling *A. japonicus* have been known to reach 148
325 dB re 1 μ Pa. The background noise has significant impact on the detection range of a
326 call to both intended recipient and observer (Urlick, 1983, Sprague and Luczkovich,
327 2004). For simple comparative purposes a maximum detection range of the
328 regression determined SL was calculated for each call category (Table III). This is the
329 range at which the signal would have attenuated to background noise level using
330 signal processing based on the estimated transmission losses and also using spherical
331 spreading as the transmission loss. It does not use statistical analysis of the
332 probability of signal detection or account for fish hearing critical ratios and so could
333 not be used as an estimation of the ranges over which fish may detect calls. The ratio
334 of detection ranges of a call with and without the noise of a passing vessel, however,
335 is comparable and shows that, even under near ideal detection conditions,

336 anthropogenic activity can reduce detection of such calls from hundreds of meters, to
337 less than 10 m.

338

339 **IV DISCUSSION**

340

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

352

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

360

361 Due to the variability of the call structure Category 1 calls displayed comparatively
362 low correlation with the least squares regression transmission loss model, compared to
363 that of the other call categories. The difference in amplitude between the first two
364 pulses of a call varied significantly throughout all three call categories. This variation
365 had greater impact on SLs of short calls comprising fewer pulses. Therefore
366 determined confidence limits of 148 and 179 dB re 1 μ Pa at 1 m with a correlation of
367 $R^2 = 0.42$ for the best fit ($25.39\log_{10}(r)$) transmission losses were deemed a
368 reasonable estimate of SL range for Category 1 calls.

369

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

383

384 Source levels of each *A. japonicus* category of call were significantly greater than the
385 reported SLs of calls from other species. *In situ*, silver perch (*Bairdiella chrysoura*)

386 and oyster toadfish (*Opsanus tau*) reportedly have maximum SLs of 135 and 132 dB
387 re 1 μ Pa at 1 m, respectively (Sprague and Luczkovich, 2004; Barimo and Fine, 1998),
388 and typically grow to total lengths of 30 and 43.2 cm, respectively (Robins and Ray,
389 1986). As call SLs are related to fish size (Connaughton *et al.*, 2000) and these
390 species are considerably smaller than *A. japonicus* captured in the Swan River (greater
391 than 1 m; Farmer, 2008), the comparatively lower SLs are to be expected. Cato
392 (1980) and McCauley (2001) reported SLs of 148 (\pm 4) and 149 (\pm 2) dB re 1 μ Pa at 1
393 m, respectively, from sources speculated to be *Protonibea diacanthus*, a Sciaenidae of
394 similar sound production mechanism to *A. japonicus*. Both of these reports comprised
395 calls of similar spectral peak frequencies (250 - 400 Hz) to those of *A. japonicus*
396 (Parsons, 2010, Parsons *et al.*, 2006). *P. diacanthus* caught in a recent study around
397 the Northern Territory were of comparable length to the Swan River *A. japonicus*
398 (Phelan, 2008). However, sampling conducted in Cape York Peninsula waters in
399 1999 and 2000 yielded predominantly 750-799 and 600-649 mm specimens,
400 respectively (Phelan *et al.*, 2008). It is not known whether the sounds reported by
401 Cato (1980) and McCauley (2001) originated from similar sized fish.

402

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

409

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

412

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

421

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

432

433 This study has provided some observations of *in situ* fish call directivity. The
434 estimated SL of Category 3 calls recorded as the fish passed the hydrophone displayed

435 a 5 to 8.5 dB difference between orientations. If the assumption of forward motion is
436 correct, and the individual was not swimming against a current drifting backwards
437 past the hydrophone, calls were greater in front of the caller than behind. This finding
438 is in contrast with Barimo and Fine (1998), who hypothesized that directivity in sound
439 production of *O. tau* would be reduced in the direction of the fish ears and observed a
440 3 to 5 dB re 1 μ Pa decline in SL moving from the rear to the front of the fish. The
441 reason for this difference is unknown, though if the *A. japonicus* Category 3 caller
442 was swimming into, and drifting backwards with the current the directivity would
443 result in a reduced SPL in front of the fish. Although the sample size of different
444 Category 3 calls is small and the variance large (in part due to the small sample size),
445 the differences in SL between orientation is notable. This would not be expected
446 given that the wavelength of each call is large compared with the range to the
447 receiver, but is a phenomenon similar to that reported by Barimo and Fine (1998).

448

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

457

458 Source level relative to background noise is a significant factor in determining the
459 maximum range at which a call can be detected by its intended recipient. Table III

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

473

474 *A. japonicus* in Mosman Bay form aggregations of low density calling by comparison
475 with other reports (Sprague and Luczkovich, 2004). Thus individuals can often be
476 detected at comparatively long ranges (Parsons *et al.*, 2009). During periods of low
477 background noise, such as those reported here, regression models predict a signal
478 processing detection range of approximately 120, 400 and 110 m for calls of
479 Categories 1, 2 and 3 respectively. However, periods of high background vessel noise
480 were frequent at the study site. Vessel noise of water skiers passing directly above
481 calling fish has reportedly masked calls at distances of less than the water depth
482 (Parsons *et al.*, 2009) and received vessel noise greater than 150 dB re 1 μ Pa would
483 mask all calls at distances of near 1 m (assuming spherical spreading). The ratio of
484 detection ranges between those identified with and without the noise of a passing

485 vessel (Table III) are comparable and show that, even under near ideal detection
486 conditions, anthropogenic activity can significantly reduce detection ranges of such
487 calls. Anthropogenic noise therefore poses a significant impact which needs assessing
488 to determine what, if any, effect it has on spawning success.

489

490 **V CONCLUSIONS AND RECOMMENDATIONS**

491

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

502

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

510

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512

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521

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634

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

Call Category	Orientation	Number Calls	Source Level (dB re 1 μ Pa) (\pm 95% confidence limits)	Transmission Loss (log(r)) (\pm 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
	All	N/A	28	157 (152, 162)	-23.04 (-27, -19)	0.88
Category 3	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

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653 Table II. Values of source levels with standard deviation, based on recorded
 654 values. Source levels (dB re 1 μ Pa at 1 m) using $20\log_{(10)}(r)$ losses are shown. Data is
 655 also for 3 type of source level as they are often reported (SPL, SEL equivalent energy
 656 and peak-to-peak pressures). For each method and call category the calculated source
 657 level, transmission loss curve constant and correlation coefficient are shown. Mean
 658 call lengths for each category are also shown.
 659

		Call Category		
		1	2	3
Source level (dB re 1 μ Pa)		153 (6)	165 (2)	156 (4)
20log(r) transmission loss (s.d.)				
Sound	Source level (95% c.l.)	163 (148, 179)	172 (168, 176)	157 (152, 162)
pressure level	Transmission loss			
(dB re 1μPa at	(log ₍₁₀₎ (r)) (95% c.l.)	-25.4 (-34.6, -16.2)	-23.7 (-25.9, -21.6)	-23.0 (-26.6, -19.5)
1 m)	R^2	(0.42)	(0.82)	(0.88)
SEL	Source level (95% c.l.)	152 (138, 166)	165 (156, 173)	136 (132, 139)
(dB re 1μPa²s	Transmission loss			
at 1 m)	(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	Source level (95% c.l.)	183 (173, 195)	194 (189, 201)	167 (165, 170)
pressure	Transmission loss			
(dB re 1μPa at	(log ₍₁₀₎ (r)) (95% c.l.)	-25.2 (-31.7, -18.6)	-27.2 (-30.8, -23.6)	-16.1 (-18.8, -13.5)
1 m)	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)

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665 Table III. Maximum detection ranges (r) for all call categories (using basic signal
 666 processing) when emitted during two levels of background noise (110 and 150 dB re
 667 1µPa), calculated by assuming the regression calculated TL determined from the data
 668 and losses due only to spherical spreading. Call/vessel noise energy was computed
 669 over broadband spectra. As this calculation does not account for critical hearing
 670 ratios, frequency bandwidths used by *A. japonicus* to detect calls and no probability of
 671 signal detection has been applied, this is a simple calculation of the range at which the
 672 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
2	172	396	8	660	7
3	157	112	2	117	1

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

683

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

689

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

693

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

700

701 Figure 5. Detected sound pressure levels (dB re 1 μ Pa) with range (log scale) for
702 53 Category 1 calls. Continuous line illustrates linear regression model of
703 transmission losses with 95% confidence limits of source level shown (dotted lines).

704

705 Figure 6. Detected sound pressure levels (dB re 1 μ Pa) with range (log scale) for
706 Category 2 calls. Calls of a tracked individual fish (\circ) and those of all remaining fish
707 (\times) are shown. Continuous line marks the linear regression determined transmission
708 losses with 95% confidence limits (dotted lines).

709

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

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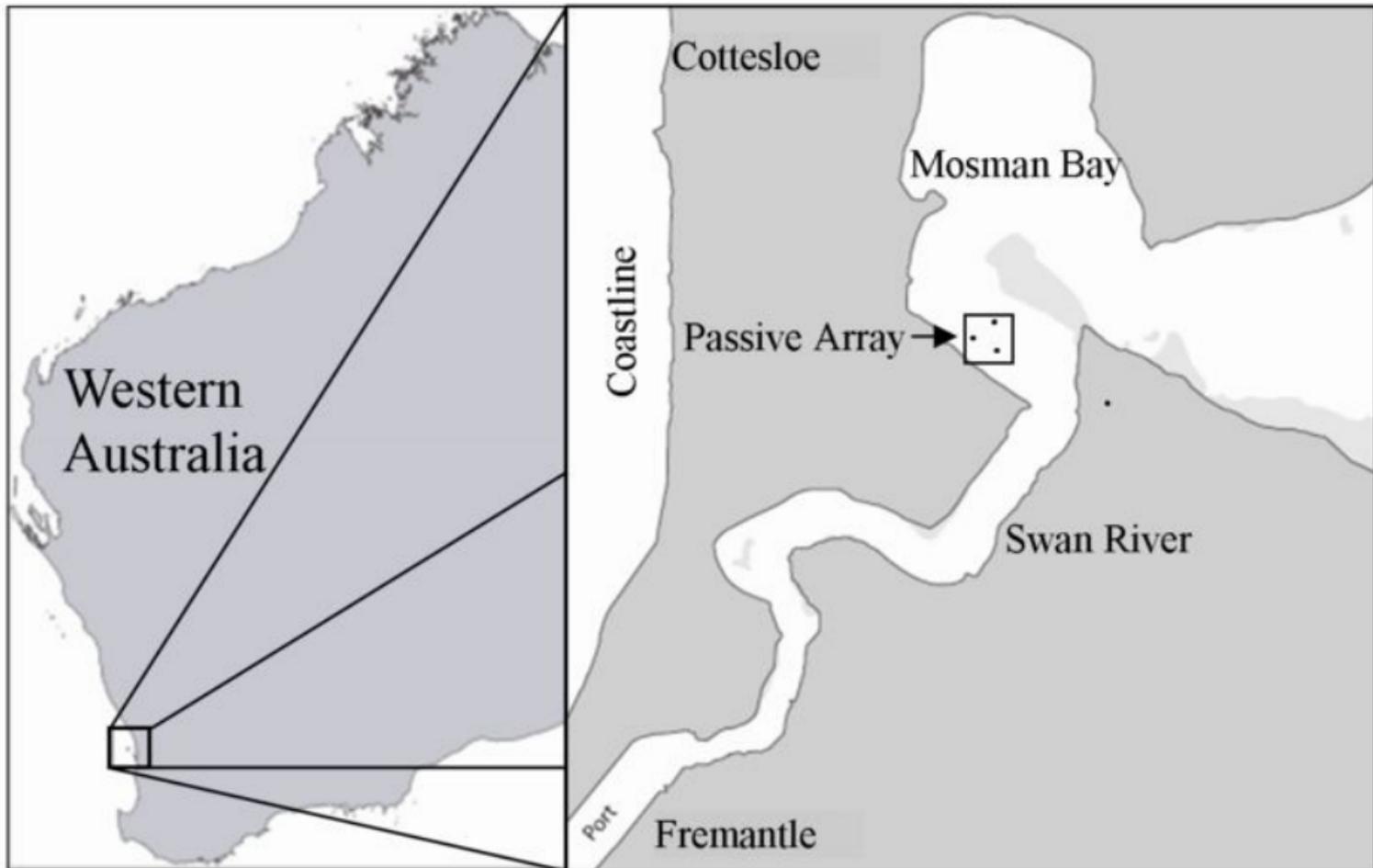
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722 Figure 8. Distribution of source levels (dB re 1 μ Pa at 1 m) from recorded sound
723 pressure levels for each *A. japonicus* call category based on the estimated
724 transmission losses only.

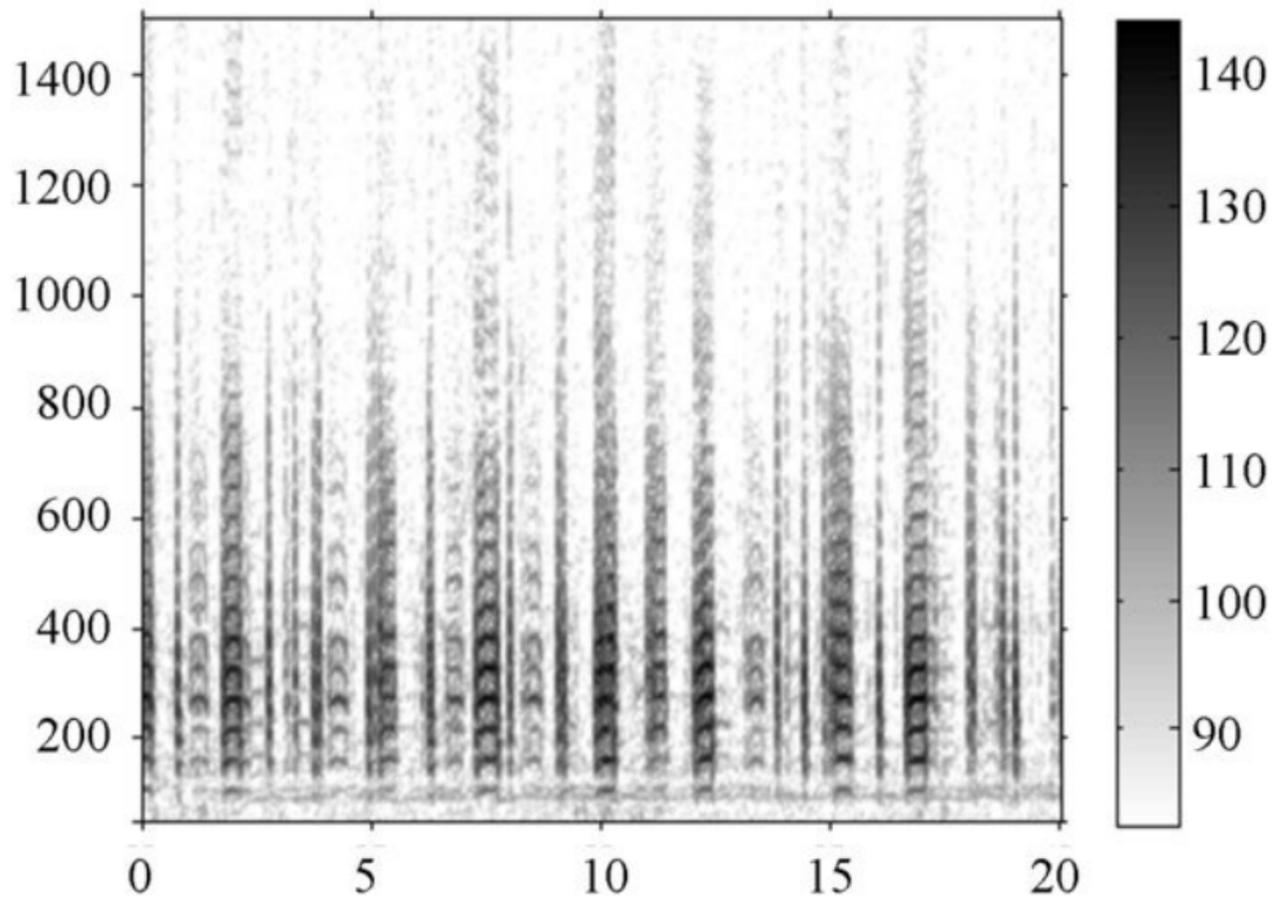
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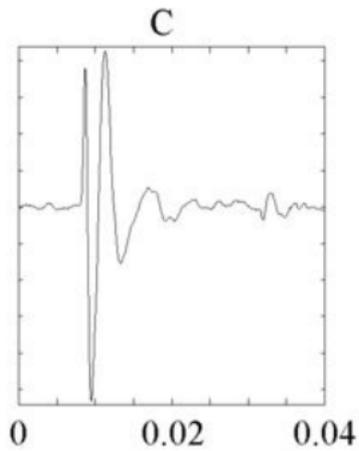
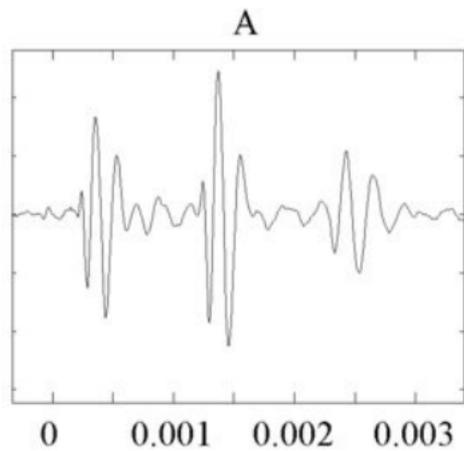
Frequency (Hz)



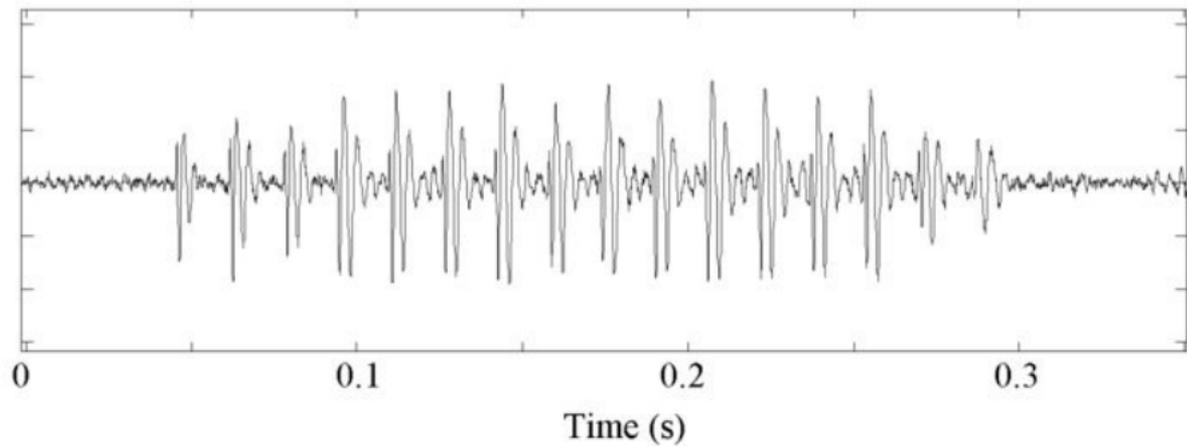
Time (s)

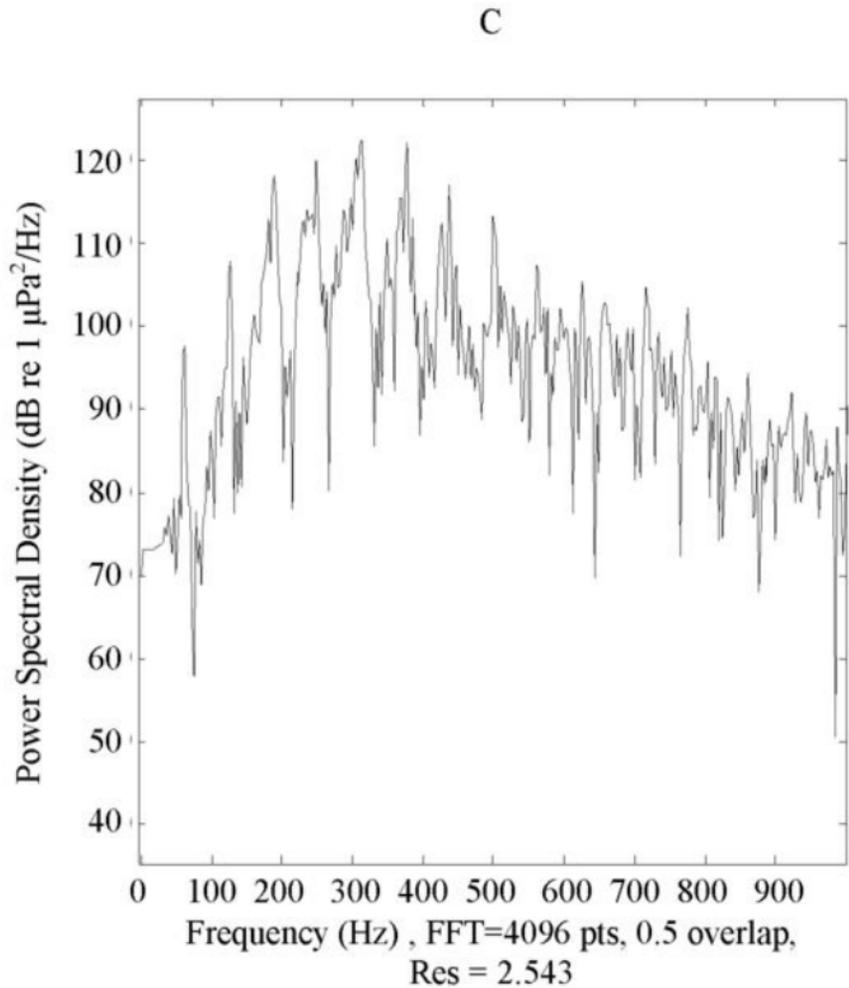
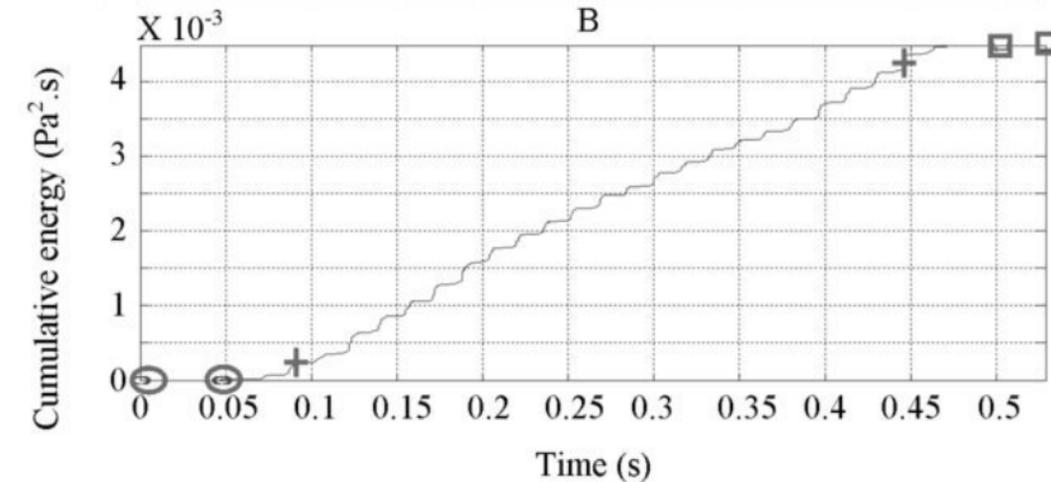
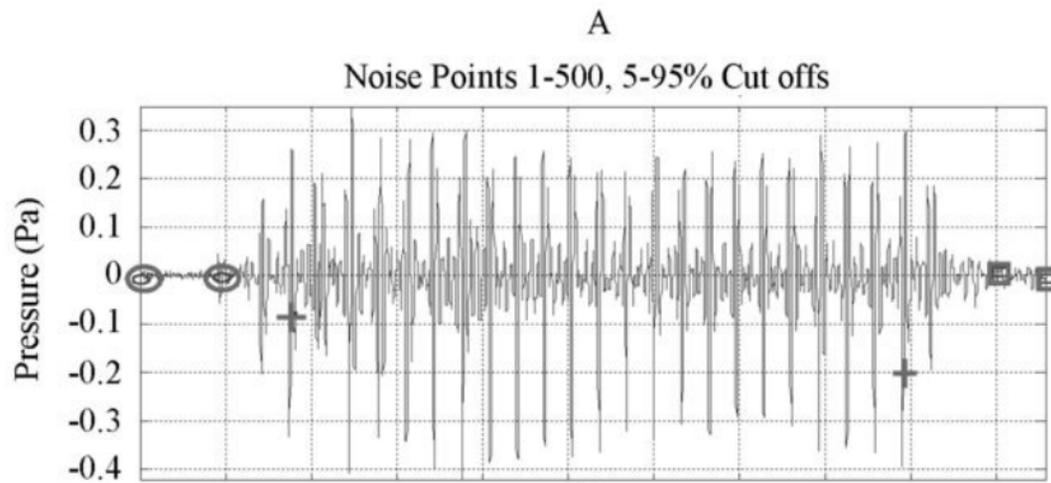
Power spectral density (dB re $1 \mu\text{Pa}^2/\text{Hz}$)

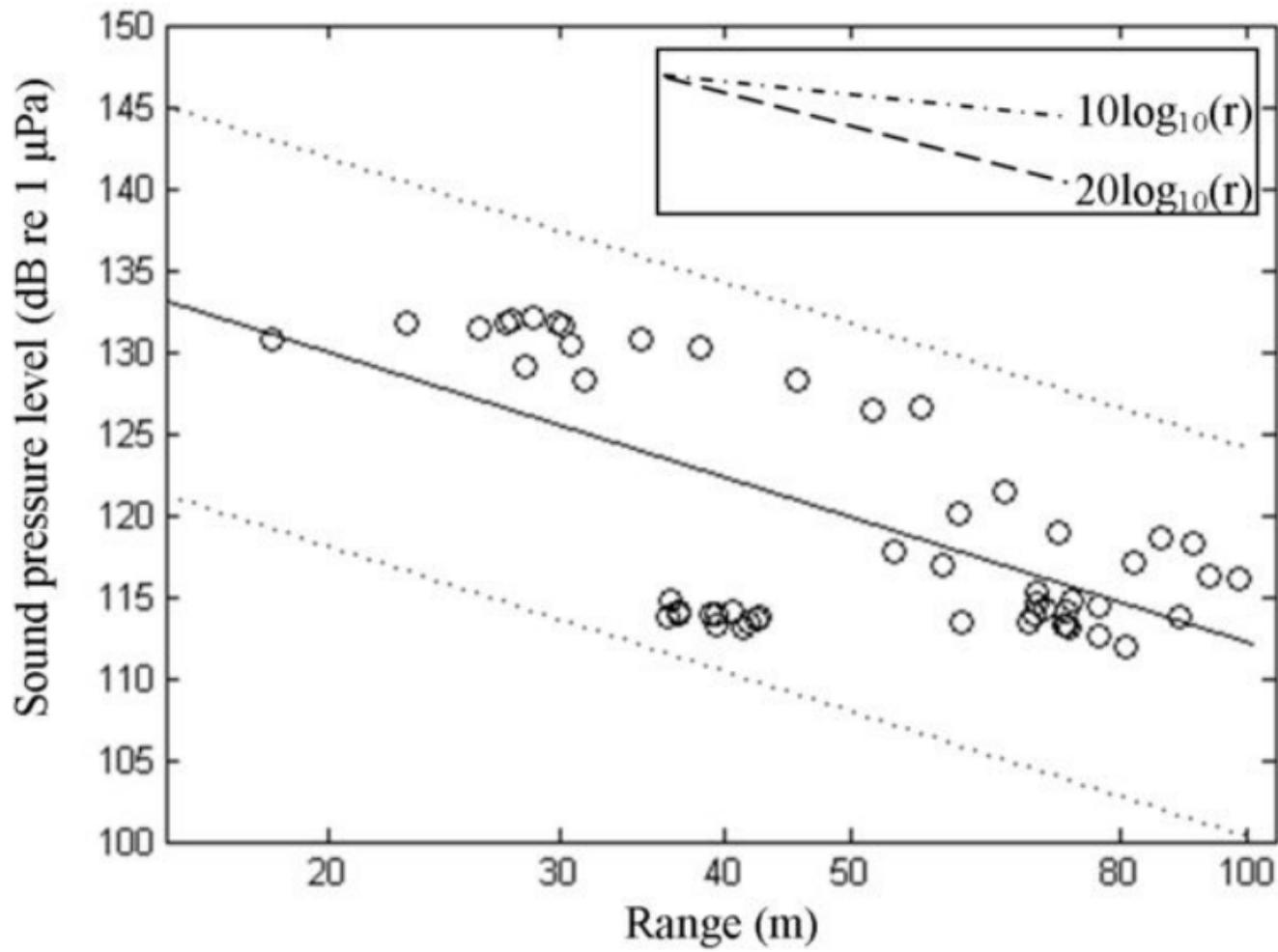
Relative voltage (V)



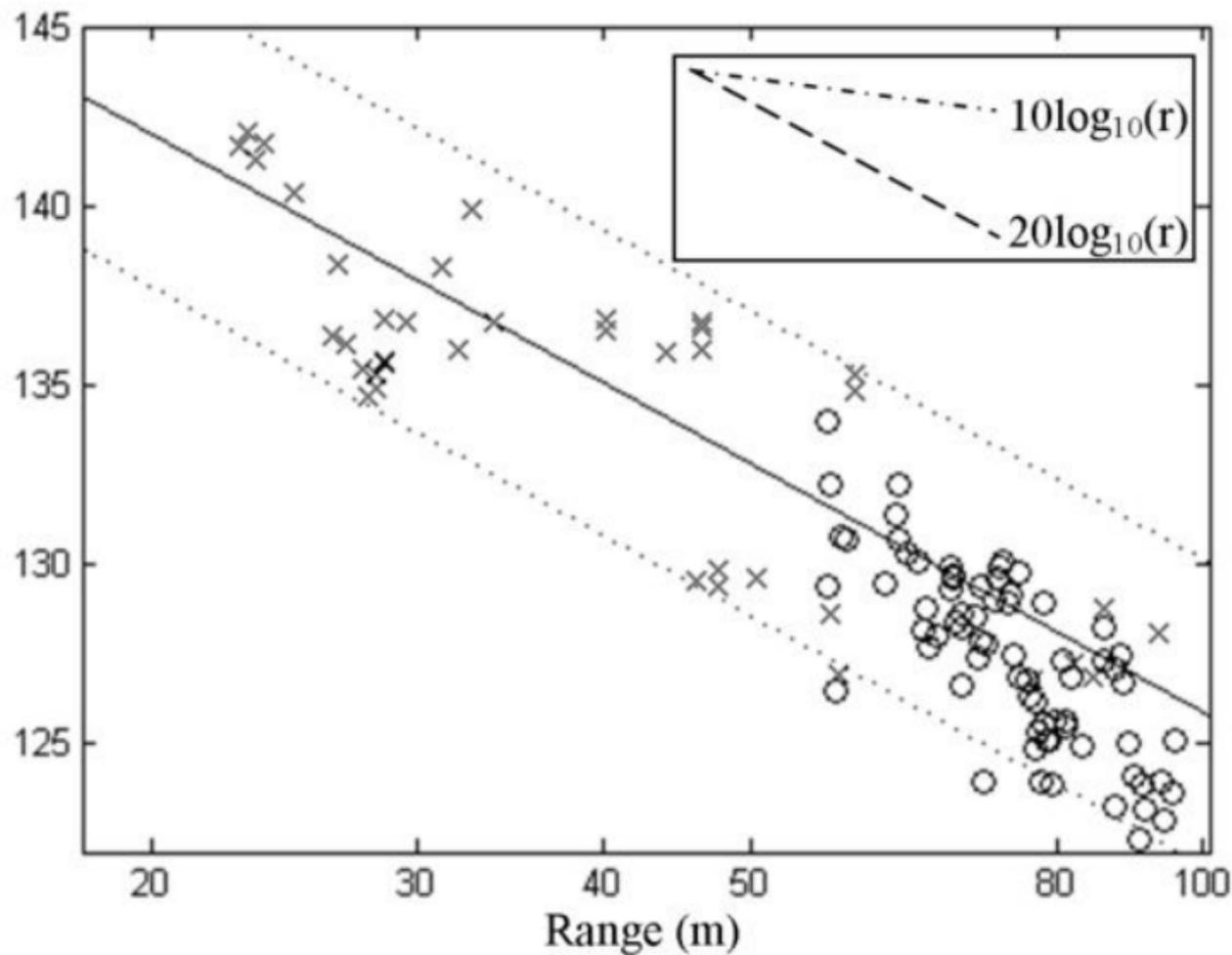
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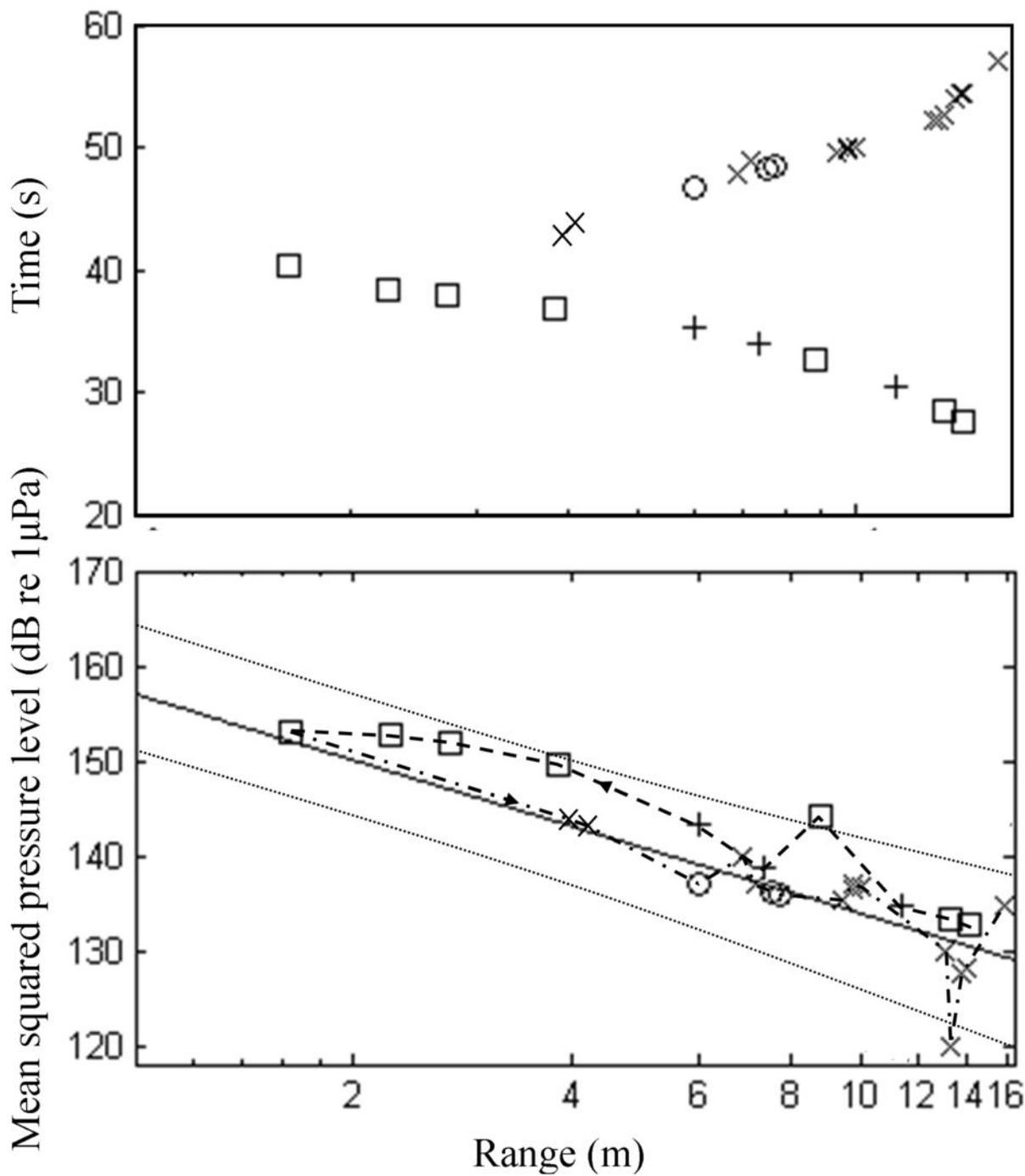




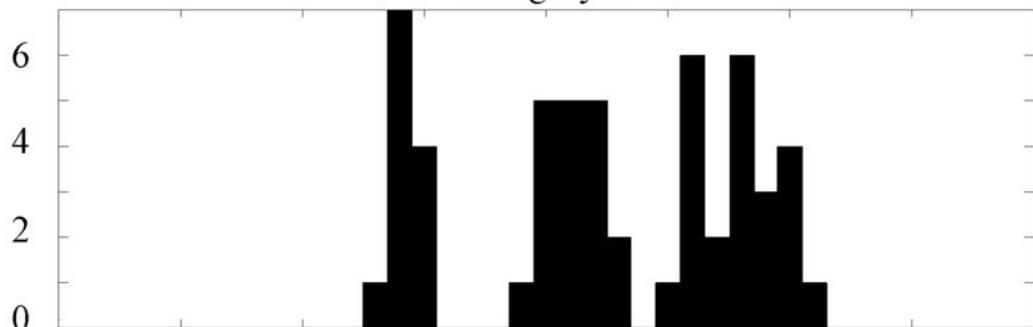


Sound pressure level (dB re 1 μ Pa)

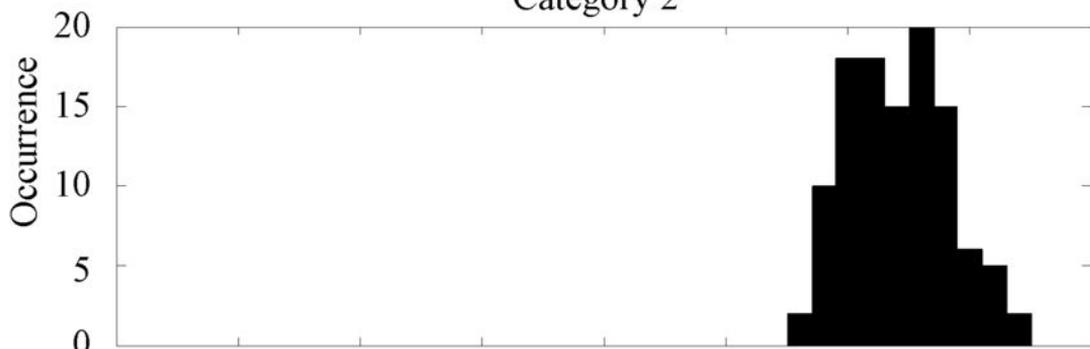




Category 1



Category 2



Category 3

