

1 **Clicks of Dwarf sperm whales (*Kogia sima*)**

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Abstract

The two species of the genus *Kogia* are widely distributed throughout the world's temperate and tropical oceans, but because they are small and highly cryptic, they are difficult to monitor. The acoustic signals of *K. breviceps* have been previously described (Madsen *et al.* 2005a), but the signals of *K. sima* have remained unknown. Here we present three recordings of *K. sima*, two from free-ranging animals and one from a captive setting, representing both the Atlantic Ocean and Pacific Ocean. The acoustic signals of *K. sima* are very similar to the signals of *K. breviceps* and other species that have narrow-band, high-frequency (NBHF) clicks. Free-ranging *K. sima* produce "usual" clicks (*sensu*: Weilgart and Whitehead 1988) that have mean peak and centroid frequencies of 127-129 kHz, mean -3 dB bandwidth of 10 kHz, mean -10 dB bandwidth of 16-17 kHz, and mean inter-click interval of 110-164 ms. Although *K. sima* clicks cannot yet be distinguished from those of *K. breviceps* or other NBHF clicking species, our detailed description of this species' signals reveals the similarities between the two *Kogia* species, and thus allows for passive acoustic monitoring of the genus *Kogia* in regions where other NBHF species are not present.

Keywords: *Kogia sima*, dwarf sperm whale, narrow-band high-frequency, echolocation, biosonar, click, The Bahamas, Florida, Atlantic, Guam, Pacific

82 **Introduction**

83 The genus *Kogia* comprises two species, the dwarf (*Kogia sima*) and the pygmy
84 sperm whale (*K. breviceps*). Both species are highly cryptic visually; they are small-
85 bodied (2-2.7 m as adults) and travel in small groups (1-12 animals) (Willis and Baird
86 1998, McAlpine 2002, Dunphy-Daly *et al.* 2008). They make deep (>250 m), long-
87 duration (~25 min) dives interspersed with short surfacings (Fitch and Brownell 1968,
88 Breese and Tershy 1993, Plön 2004, West *et al.* 2008). At the surface, they produce no
89 visible blow and are not known to raise their flukes or engage in other visible behavior
90 patterns (Willis and Baird 1998). Much of their distribution is known from records of
91 stranded individuals, which have been found on beaches throughout the world's
92 temperate and tropical oceans (summaries in Willis and Baird 1998, Taylor *et al.* 2012).

93 All odontocetes produce sounds to communicate and forage, and their sounds
94 are believed to be species specific. Having a clear description of the acoustic signals
95 made by any species is essential for fully understanding its foraging and social behavior
96 and to allow the use of passive acoustic monitoring (PAM) to record species
97 occurrence. PAM is particularly useful for species that are cryptic and/or inhabit
98 remote, hard-to-reach locations, such as the open ocean. By using PAM, we can monitor
99 the presence of *Kogia* spp. at off-shore locations that would otherwise be unavailable
100 for long-term monitoring of such cryptic species. PAM methods may also eventually
101 generate the information required for density and abundance estimation, which could
102 lead to more reliable estimates of population sizes than are currently possible, thereby
103 facilitating management directives (*e.g.*, Van Parijs *et al.* 2009, Marques *et al.* 2013).

104 Little information is available on the sound production of either *Kogia* species.
105 Early publications were limited because the instruments that were used did not record at
106 high enough frequencies to accurately capture *Kogia* spp. echolocation signals

107 (Caldwell *et al.* 1966, Caldwell and Caldwell 1987 in Marten 2000, Thomas *et al.*
108 1990). More recent efforts analyzed recordings of a stranded *K. breviceps* being held in
109 captivity for rehabilitation (Marten 2000, Ridgway and Carder 2001, Madsen *et al.*
110 2005a). The characteristics of the clicks included a high peak frequency (125-130 kHz),
111 moderate duration (100-600 μ s), and inter-click intervals (ICI) of 40-70 ms, as well as
112 high directionality (Table 1). Such narrow-band, high-frequency (NBHF) clicks appear
113 to be an adaptation to take advantage of low ambient noise levels at these frequencies
114 and to avoid predation by killer whales (*Orcinus orca*) by generating signals above the
115 predator's hearing range (Madsen *et al.* 2005a, Morisaka and Connor 2007).

116 This paper presents details about the echolocation clicks of *K. sima* from both
117 free-ranging and captive settings. These are the first confirmed recordings of the clicks
118 of this species.

119 **Methods**

120 ***Free-ranging Recording 1: The Bahamas***

121 An opportunistic encounter with a small group of *K. sima* during field research in The
122 Bahamas in the western North Atlantic Ocean provided the setting for a recording of
123 free-ranging animals. Visual observers searching for beaked whales aboard a 6.5 m
124 vessel saw a group of three *K. sima*, including two adults (sex unknown) and one sub-
125 adult (sex unknown), at 25.91 N, 77.18 W, southwest of Abaco Island, on 21 May 2005.
126 The water depth was approximately 600 m. The animals were observed and recorded
127 during 3.5 h of observation while they repeatedly dove and surfaced within 20-200 m of
128 the boat. No other cetaceans were seen in the area during this period, despite ongoing
129 visual observation, so it is unlikely that these clicks came from another species. A

130 BK8103 hydrophone (Brüel and Kjær Sound & Vibration Measurement A/S, Nærum,
131 Denmark, frequency range 0.1 Hz to 180 kHz +3.5/-12.5 dB, sensitivity -211±2 dB re:
132 1V/μPa) with a BK2635 charge amplifier was suspended approximately 2 m below the
133 surface. Recordings were made at 375 kHz sample rate on an Avisoft UltraSoundGate
134 416 connected to a Toshiba laptop computer. A low pass filter was not used in this
135 recording since the frequency response of the hydrophone fell off rapidly above the
136 Nyquist frequency.

137 *Free-ranging Recording 2: Guam*

138 The second data set from free-ranging animals was also obtained during a small-boat
139 survey and includes recordings of the same four individuals (two mother/calf pairs,
140 confirmed by photo-identification) from two one-hour encounters (28 May 2016 and 4
141 June 2016). The animals were found off the west side of Guam in the western North
142 Pacific Ocean at approximately 13.3 N, 144.6 E. No other cetaceans were seen in the
143 area during this period, despite ongoing visual observation, so it is unlikely that these
144 clicks came from another species. The water depth was approximately 650-800 m, and
145 the animals were roughly 3.5 km from shore. Recordings were made using a Compact
146 Acoustic Recording Buoy (CARB, Y. Barkley, pers. comm.¹), a free-floating
147 instrument deployed in the vicinity of the animals, that includes an HTI-96-MIN
148 hydrophone (High Tech, Inc., Long Beach, MS, sensitivity -180.7 dB re: 1V/μPa)
149 suspended around 30 m depth. The manufacturer specified frequency range for this
150 hydrophone is flat from 2 Hz to 30 kHz, but preliminary lab calibration has shown

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151 functionality out to at least 140 kHz (+3/-8 dB), with sensitivity of approximately -186
152 dB re: 1V/ μ Pa at 130 kHz. Field testing has confirmed successful recording of NBHF
153 porpoise clicks (J. Barlow, pers. comm.²). Please see below for further discussion of
154 potential issues arising from using this type of hydrophone for high frequency
155 recordings. Recordings were made at a sampling rate of 384 kHz on an SM2+ Song
156 Meter (Wildlife Acoustics, Concord, MA), which included pre-amplifier gain of +36 dB
157 and a 1 kHz high pass filter. There was no low-pass/anti-alias filter used at the time of
158 data collection.

159 *Captive Recording*

160 A female *K. sima* calf, weighing 28.5 kg, stranded at Cape Canaveral, Florida in July
161 2002, and was taken to the Mote Marine Lab's Dolphin and Whale Hospital in Sarasota,
162 Florida for care. She remained in captivity for over 15 months until October 2003,
163 during which time recordings were made. The cause of stranding was unknown,
164 however, later necropsy revealed an impacted colon and ink sac. The animal was
165 recorded while free-swimming in a 9.1 m circular, fiberglass tank approximately 1.5 m
166 deep. Unfortunately, due to loss of computer files only 4 s of data were saved for
167 analysis. A Reson TC4013 hydrophone (frequency range 1 Hz to 170 kHz +2/-4dB,
168 sensitivity -211 ± 3 dB re: 1V/ μ Pa; VP1000 preamplifier with 32 dB gain) was
169 suspended at approximately 0.75 m depth, and about 0.5 m away from the wall of the
170 tank. Recordings were digitized at 500 kHz using a Tucker-Davis Technologies AD2.
171 There was no low-pass/anti-alias filter used at the time of data collection.

² Jay Barlow, NOAA-SWFSC-MMTD, 8901 La Jolla Shores Dr., La Jolla CA, March 2017

172 ***Click Analysis***

173 Analysis of the *K. sima* recordings was performed using a trained analyst (KM) and
174 custom MATLAB subroutines (MathWorks, Natick, MA, USA). Although multiple
175 animals were present during the Bahamas and Guam recordings, it is not possible to
176 identify which clicks came from which individual; therefore, all clicks from within a
177 given region were combined for analysis. In each data set, a human analyst identified
178 periods of time with clicks present, and any unusual features were noted. In the Guam
179 recording, there were several burst-pulse click sequences with shorter inter-click
180 intervals, and a subset of clicks with visibly lower peak frequencies. Both subsets of
181 clicks were analyzed separately from the remainder of the signals. All sets of clicks
182 were analyzed using a two-stage automated detector based on Soldevilla *et al.* (2008),
183 Roch *et al.* (2011), and Baumann-Pickering *et al.* (2013). Archived code is available at:
184 <http://doi.org/10.5281/zenodo.164881>. Individual clicks were filtered using a 4-pole
185 Butterworth bandpass filter with a high pass threshold at 10 kHz and a low pass
186 threshold at 170 kHz. The captive recording was also filtered using Butterworth notch
187 filters at 81 and 160 kHz to remove tonal noise. After filtering, the clicks were retained
188 if they passed a peak-to-peak amplitude threshold for each click. This threshold was
189 adjusted independently for each data set based on ambient noise conditions to retain the
190 maximum number of clicks while excluding nonclick noise.

191 The retained clicks were used to calculate multiple parameters. The spectral
192 characteristics were computed using a 1200 μ s Fast Fourier Transform (FFT) on Hann-
193 windowed data centered on each click. The number of sample points and the frequency
194 bin size is slightly different for each recording because of the different sampling rates,
195 ranging from 460 points and approximately 418 Hz/bin in the Guam recording to 450
196 points and 416 Hz/bin in the recording from The Bahamas and 600 points and 416

197 Hz/bin for the recording of the captive animal. The mean frequency spectrum was
198 computed across all detected clicks within each recording. A mean noise spectrum was
199 also computed for each recording session based on periods of data preceding each click,
200 lasting an equal duration to each click, but separated from the click by approximately 5
201 ms. The mean and median of the following parameters were calculated for each click:
202 peak frequency, centroid frequency, -3 dB bandwidth, -10 dB bandwidth, rms
203 bandwidth, click duration, and ICI. The duration was calculated as the time spanned by
204 95% of the energy of the signal envelope (the absolute value of the analytical
205 waveform), following methods by Madsen *et al.* (2004). ICIs longer than 500 ms were
206 excluded as outliers based on examination of histograms of all ICIs. ICIs shorter than 2
207 ms were excluded because they were all caused by reflections. In the captive recording,
208 there were substantial echoes due to the nature of the tank; therefore, a lock-out period
209 of 50 ms after the initial click was used to remove all echoes from consideration.

210 **Results**

211 Recordings from both free-ranging and captive *K. sima* contained only NBHF
212 clicks, more similar to those of porpoise (*e.g.*, Villadsgaard *et al.* 2007, Kyhn *et al.*
213 2013) than those of other deep diving cetaceans such as beaked whales (family
214 Ziphiidae) and sperm whales (*Physeter macrocephalus*) (*e.g.*, Weilgart and Whitehead
215 1988, Goold and Jones 1995, Johnson *et al.* 2004). No whistle-like sounds were
216 recorded. Click parameters are summarized in Table 1. The majority of the clicks could
217 be described as “usual” clicks with a consistent ICI and received level throughout each
218 encounter (*sensu*: Weilgart and Whitehead 1988).

219 The parameters of the clicks from the two free-ranging recordings are assessed
220 here, while the results for the captive recording are reported below. Examples of the

221 mean spectra, waveform, and time series for all three recordings are shown in Figure 1.
222 The Bahamas recordings spanned 37 min and contained 328 “usual” clicks. The
223 recordings from Guam spanned 2 h and contained 938 clicks (including 759 “usual”
224 clicks and 179 clicks of two different types, described below). The characteristics of the
225 clicks in these two sets of recordings were similar, except for centroid frequency, rms
226 bandwidth and ICI. There was no notable frequency sweep, in contrast to the clicks of
227 most beaked whale species (*e.g.*, Baumann-Pickering *et al.* 2013).

228 The differences in the centroid frequencies were examined further, along with
229 the rms bandwidth, which is calculated using the centroid frequency. In the Bahamas
230 recording the centroid frequency was similar to the peak frequency and the rms
231 bandwidth was similar to the -3 dB bandwidth, which was expected based on previous
232 descriptions of the clicks of other NBHF species (*e.g.* Madsen *et al.* 2005a, Kyhn *et al.*
233 2009, Götz *et al.* 2010, Kyhn *et al.* 2010, Kyhn *et al.* 2013). In contrast, the centroid
234 frequency of the “usual” clicks from the Guam recording was lower than the peak
235 frequency by about 6 kHz and the rms bandwidth was wider than the -3 dB bandwidth
236 by about 10 kHz. These differences may have been caused by a large proportion of
237 clicks in the Guam recording with a low signal-to-noise ratio (SNR), so a subset of
238 clicks with SNR greater than 20 dB was examined separately. This subset of highest
239 SNR clicks had a peak frequency of 127 ± 0.8 kHz, centroid frequency of 127 ± 0.9
240 kHz, -3 dB bandwidth of 8.6 ± 1.0 kHz, -10 dB bandwidth of 13 ± 2.0 kHz, and an rms
241 bandwidth of 7 ± 1.3 kHz. These results are closer to what was expected for centroid
242 frequency and rms bandwidth given the values for peak frequency and -3 dB bandwidth,
243 and they are similar to the results for the Bahamas recording as well as those of NBHF
244 clicks from other species (*e.g.* Madsen *et al.* 2005a, Kyhn *et al.* 2009, Kyhn *et al.* 2010,

245 Kyhn *et al.* 2013), which reinforces the possibility that low SNR clicks were impacting
246 the summary results for the whole recording.

247 Two unique subsets of clicks in the recording from Guam were examined
248 separately (Fig. 2). Visual analysis of the spectrograms revealed the presence of four
249 burst-pulse click sequences, with notably shorter ICIs than the majority of “usual”
250 clicks (Fig. 2 A, B). There was a total of 81 clicks in these four burst-pulse sequences,
251 which were removed from the larger data set for exploration and are not included in the
252 description of “usual” clicks above. Three of the four sequences appeared to be terminal
253 to a chain of “usual” clicks that had a longer, stable ICI. The mean ICI of 37 ms for the
254 clicks in these sequences is longer than the standard definition of a “buzz” for porpoises
255 and delphinid species, which decreases from onset of approximately 8-15 ms to <2 ms
256 (e.g. deRuiter *et al.* 2009, Wisniewska *et al.* 2014), however there was a clear visual
257 difference between the sets of burst-pulse clicks and the remainder of the “usual” clicks.
258 In addition to having a shorter ICI, the burst-pulse clicks had a lower mean peak
259 frequency, lower centroid frequency, shorter click duration, wider bandwidths, and
260 larger Q-values compared to the “usual” clicks in the same recording. Statistical
261 analysis is not appropriate given the possibility that all of the clicks are from a single
262 individual, and are therefore not independent samples.

263 The second subset of signals that was separated included clicks with a lower
264 peak frequency (below 120 kHz) than the majority of “usual” clicks (Fig. 2 C, D).
265 These were present in short sequences of five to ten clicks that alternated with longer
266 sequences of higher peak frequency clicks. The lower peak frequency clicks were
267 removed from the larger data set and analyzed separately, and are not included in the
268 description of “usual” clicks above. Compared to the “usual” clicks, the mean peak
269 frequency for these 98 clicks was lower by about 10 kHz while the centroid frequency

270 was lower by about 8 kHz (Fig. 3). Additionally, the ICI was longer compared to the
271 rest of the “usual” clicks by about 90 ms. As with the burst-pulse clicks, statistical
272 analysis is not appropriate given the possibility that all of the clicks are from a single
273 individual, and are therefore not independent samples.

274 The characteristics of the clicks in the captive recording were different from
275 those in the free-ranging recordings. Although recordings of the captive animal were
276 made on multiple occasions, loss of computer files resulted in only 4 s of data being
277 available for analysis. From this small sample there were 49 clicks. These clicks had a
278 mean peak frequency that was about 15 kHz lower than the free-ranging recordings,
279 while the centroid frequency was 15-20 kHz lower. The bandwidths were more than
280 twice as wide as in the other recordings, while both the duration and the ICI were
281 shorter in comparison by approximately 100 μ s and 25-80 ms, respectively. The ICI was
282 closest to the ICI values from the clicks of the captive *K. breviceps* described by
283 Madsen *et al.* (2005a), which may indicate that a shorter ICI is an effect of being in a
284 pool where walls present a close target for echolocation. The Q values of the clicks in
285 the captive recording were lower than for those in the Bahamas recording, but compared
286 to the “usual” clicks from the Guam recording the Q_{-3dB} was similar while the Q_{rms} was
287 lower in the captive data.

288 **Discussion**

289 Here we present the first confirmed records of acoustic signals generated by the
290 dwarf sperm whale (*K. sima*). The more than 1,000 clicks in this data set are sufficient
291 to provide initial characterization for the species (*e.g.*, Madsen *et al.* 2005a, Baumann-
292 Pickering *et al.* 2013). The production of NBHF clicks places *K. sima* in a group with a
293 handful of other species, including its congener, *K. breviceps* (Marten 2000, Ridgway

294 and Carder 2001, Madsen *et al.* 2005a, Villadsgaard *et al.* 2007, Kyhn *et al.* 2009, Kyhn
295 *et al.* 2010, Kyhn *et al.* 2013, Reyes *et al.* 2016). With known click characteristics of *K.*
296 *sima*, it is now possible to conduct PAM for the genus *Kogia*. This may be particularly
297 important for this genus given the difficulty of visual monitoring due to typically cryptic
298 surface behavior and small group sizes. The main difference between our field sites was
299 found in the ICI. This most likely reflects differences in the distances to the targets that
300 the animals were investigating or behavior at the time of recording (*e.g.*, Miller *et al.*
301 1995, Johnson *et al.* 2004, Madsen *et al.* 2005b). Thus, it seems that clicks of *K. sima*
302 are similar in different ocean basins.

303 The characteristics of the clicks presented here are generally similar to the clicks
304 produced by the single captive *K. breviceps* (Marten 2000, Ridgway and Carder 2001,
305 Madsen *et al.* 2005a), as well as a few species of delphinids (*e.g.*, hourglass dolphins
306 (*Lagenorhynchus cruciger*) and Hector's dolphins (*Cephalorhynchus hectori*) (Kyhn *et*
307 *al.* 2009), the Chilean dolphin (*Cephalorhynchus eutropia*) (Götz *et al.* 2010), the
308 Commerson's dolphin (*Cephalorhynchus commersonii*) (Kyhn *et al.* 2010, Reyes *et al.*
309 2016)) and porpoises (*e.g.*, harbor porpoise (*Phocoena phocoena*) and Dall's porpoise
310 (*Phocoenoides dalli*) (Villadsgaard *et al.* 2007, Kyhn *et al.* 2013)). Given the data
311 presented here and what is available in the literature, it is still not possible to distinguish
312 the two *Kogia* species from each other (Table 1). This is particularly true given the
313 potential and unknown effects of recording an animal in captivity, which was the case
314 for the only confirmed recording of *K. breviceps* (Madsen *et al.* 2005a). With the
315 addition of field recordings for *K. breviceps*, differences in their click characteristics
316 may yet emerge to allow their separation in PAM data. The clicks of *K. sima* are easily
317 distinguished from non-NBHF odontocetes based simply on peak frequency, which is
318 higher than that of many other species, and also on Q-value, which, generally being >10

319 in NBHF species, is higher than many other odontocetes. Distinguishing between
320 *Kogia* spp. and the other species that produce NBHF clicks may be possible,
321 particularly based on subtle differences between peak frequencies, signal duration, ICI,
322 and bandwidth. For example, the range and habitat of *Kogia* spp. overlap with Dall's
323 porpoise in the northeast Pacific Ocean. The peak frequencies of the porpoise are above
324 130 kHz (Kyhn *et al.* 2013) compared to the *Kogia* spp. clicks, which are mostly below
325 130 kHz.

326 All clicks analyzed here are conservatively presumed to be off-axis, even though
327 in the Bahamas clicks were only recorded when the animals were facing the
328 hydrophone. Although we do not know the beam width of *K. sima* signals, other species
329 that generate NBHF signals are known to have a narrow beam width (Kyhn *et al.* 2013),
330 so capturing on-axis clicks during free-ranging recordings is difficult. Additionally, the
331 exact orientation of the animals to the hydrophone is not known in any of the current
332 recordings, and they cannot be localized with a single hydrophone. Madsen *et al.*
333 (2005a) found that the temporal and spectral characteristics of *K. breviceps* clicks did
334 not change notably in an off-axis recording, and similar results have been found for
335 harbor porpoise (Hansen *et al.* 2008, Koblitiz *et al.* 2012). This is in contrast to the
336 broadband clicks of delphinids and sperm whales, which show strong off-axis effects
337 (e.g. Zimmer *et al.* 2005, Lammers and Castellote 2009, Schulz *et al.* 2009, Au *et al.*
338 2012). Our data support a similar conclusion for *K. sima*, with the peak and centroid
339 frequencies being comparable across data sets despite animals being recorded in a
340 variety of orientations.

341 One parameter that was different in both free-ranging data sets from previously
342 recorded NBHF species was the click duration. For most other NBHF species the mean
343 click duration is in the range of 50-120 μ s (Madsen *et al.* 2005a , Villadsgaard *et al.*

344 2007, Kyhn *et al.* 2009, Götz *et al.* 2010, Kyhn *et al.* 2010, Kyhn *et al.* 2013, Reyes *et*
345 *al.* 2016), while the mean duration of the “usual” clicks from free-ranging animals
346 recorded in The Bahamas and Guam is $199 (\pm 54)$ and $186 (\pm 62)$, respectively. While it
347 is possible that the clicks of *K. sima* are indeed longer than other NBHF clicks, it is also
348 possible that the arrangement of the recording instruments, with a shallow hydrophone
349 and deeper animals, allows the production of surface reflections that artificially elongate
350 each click. Examination of histograms of the click durations of “usual” clicks from the
351 data sets revealed a strongly bimodal pattern in the Bahamas clicks (Fig. 4). It is likely
352 that the first mode represents single clicks with little or no effect from surface
353 reflections, while the second mode represents clicks plus reflections. To examine the
354 characteristics of the clicks that comprise the first mode, we set a threshold of $235 \mu\text{s}$,
355 which is the approximate location of the minimum between the two modes. The
356 duration of the clicks from the first mode alone (*i.e.* those with duration less than 235
357 μs) was found to be $161 \pm 22 \mu\text{s}$ (mean \pm standard deviation) (median $157 \mu\text{s}$) while the
358 duration of the clicks in the second mode was $264 \pm 21 \mu\text{s}$ and the mean of the entire
359 data set (both modes combined) was $199 \pm 54 \mu\text{s}$. This serves as a good reminder that
360 simple summary statistics, like mean and median, may not provide the details to reveal
361 a complete description of the situation. Additionally, despite this closer analysis of the
362 different modes of click durations in the Bahamas data, the click durations from this
363 subset are still longer than the published values for most other NBHF clicking species.

364 The majority of clicks in the recordings presented here can be considered
365 “usual” clicks, having a consistent ICI throughout each recording. In the data set from
366 Guam, however, we recorded at least four sequences of burst-pulse clicks, which had a
367 much shorter ICI for a short period of time (each sequence lasting <2 s). These burst-
368 pulse clicks were spread out in the recordings, with one in the first day and three in the

369 second. Across species, burst-pulses have been shown to have slightly different
370 temporal and spectral characteristics than “usual” clicks, commonly being shorter in
371 duration and wider in bandwidth (*e.g.*, Johnson *et al.* 2006, Jaquet *et al.* 2001, Götz *et*
372 *al.* 2010, Fais *et al.* 2016). In some species, the peak or centroid frequency is higher
373 than in the “usual” clicks (*e.g.*, sperm whale (Fais *et al.* 2016) and Blainville’s beaked
374 whale, *Mesoplodon densirostris*, (Johnson *et al.* 2006)), while in other species the peak
375 or centroid frequency is lower than in the “usual” clicks (*e.g.*, Chilean dolphin, (Götz *et*
376 *al.* 2010) and harbor porpoise, (Wisniewska *et al.* 2015)). Like the Chilean dolphin and
377 the harbor porpoise, which both produce NBHF clicks, the burst-pulse clicks of *K. sima*
378 have a shorter duration, wider bandwidth, and lower peak and centroid frequencies
379 compared to the “usual” clicks. The abrupt change observed in ICI between regular and
380 burst-pulse clicks in three out of four observations was similar to what was described
381 for echolocation behavior for some nondelphinid species (*e.g.*, Miller *et al.* 1995,
382 Madsen *et al.* 2005b).

383 Burst-pulse sequences are seen in the acoustic repertoire of most odontocete
384 species, and are assumed to be primarily a method of close-range echolocation with the
385 goal of prey capture (*e.g.*, Miller *et al.* 1995, Johnson *et al.* 2004, Madsen *et al.* 2005b,
386 deRuiter *et al.* 2009, Wisniewska *et al.* 2014). Buzz sequences, with ICIs below 8-13
387 ms, are generally assumed to indicate an attempt at prey capture in other cetaceans. If
388 future studies can confirm an association of burst-pulse clicks with prey-capture
389 attempts, our confirmation of the production of buzz-like clicks by *K. sima* could
390 facilitate the monitoring of feeding behavior, which has heretofore been prevented by
391 their deep-diving, deep-feeding behavior. However, in the current study the ICIs were
392 higher (37 ± 10 ms) and visual observations provided no indication of feeding activity,
393 which suggests these burst-pulses were intended for some other purpose than feeding.

394 Furthermore, most odontocete species use burst-pulses for communication, (e.g.
395 bottlenose dolphins (*Tursiops truncatus*) (Caldwell & Caldwell 1967), Risso's dolphins
396 (*Grampus griseus*) (Arranz *et al.* 2016) and short-finned pilot whales (*Globicephala*
397 *macrorhynchus*) (Perez *et al.* 2017)). They also occur in animals that do not produce
398 whistles, as is the case for *Kogia* spp. This variability in behavior serves as a reminder
399 to carefully consider the species and the habitat being monitored with PAM devices as
400 well as exploring a range of possible explanations for signals detected without
401 corroborating visual observation, particularly for deep-diving species.

402 Another variant click type in the recording of free-ranging *K. sima* from Guam
403 was characterized by lower peak frequencies compared to the majority of the “usual”
404 clicks (mean \pm standard deviation 117 \pm 3 kHz vs. 127 \pm 2 kHz). These lower peak
405 frequency clicks were present during a period of 6 min at the end of the recording, and
406 were present in short sequences of 5-10 clicks that were interspersed with longer
407 sequences of “usual” clicks with the more typical, higher peak frequency. The lower
408 peak frequency clicks appear to belong to a separate click type, visibly different in 5 or
409 10 s spectrograms (*e.g.* Fig. 2), and also apparent as a secondary peak in the histogram
410 of peak frequencies for the entire Guam data set (Fig. 3A), as well as the histograms of
411 the peak frequencies and centroid frequencies of a subset of clicks with SNR >20 dB
412 from the same data set (Fig. 3B&C). It is possible that surface reverberation may have
413 caused interference in the spectral characteristics of some clicks, causing them to have
414 lower peak frequencies; however, the correspondingly lower centroid frequencies
415 suggest that these are in fact a variant click type. The bandwidths and click duration
416 were similar between the lower peak frequency clicks and more abundant “usual”
417 clicks; however, peak frequency and centroid frequency were both lower and ICI was
418 longer. The source of these lower peak frequency clicks cannot be confirmed; however,

419 we can speculate that they were generated by the adult animals for a different purpose
420 than the majority of the “usual” clicks, or perhaps they were made by one of the calves,
421 also observed during this period. It is known from other odontocete species that the
422 signals generated by calves can be different from the more common clicks of adults
423 (*e.g.*, Madsen *et al.* 2003, Li *et al.* 2007, Harder *et al.* 2016). However, very little is
424 known about juvenile or calf sound production in the majority of species of cetaceans,
425 including the members of the genus *Kogia*.

426 There are some potential problems in the data analyzed here. For example, there
427 are notable differences between the characteristics of the “usual” clicks in the captive
428 and free-ranging recordings. In particular, the signals from the captive setting have
429 lower peak and centroid frequencies, shorter duration, wider bandwidths smaller Q-
430 values, and a shorter ICI. These differences could be a result of the acoustic
431 environment in the tank and/or unknown effects of captivity on a previously free-
432 ranging animal (Au 1993). Additionally, the captive animal was a calf, and was ill. We
433 do not know if or how the animal may have altered its acoustic signals because of being
434 in captivity or experiencing compromised health. Also, although we only selected one
435 click from each set of echoes in the captive recording, it is likely that some of the clicks
436 analyzed were actually echoes or were distorted due to reverberation, which may have
437 increased variability in the mean signal characteristics. Madsen *et al.* (2004) showed
438 notable differences between clicks of captive and free-ranging animals for two species
439 of delphinids (False killer whales (*Pseudorca crassidens*) and Risso’s dolphins),
440 particularly a lower peak frequency and source level in the captive setting. Therefore,
441 using only the captive signals to develop tools for PAM may lead to incorrect species
442 identification and/or missing signals from healthy, free-ranging animals. Additionally,

443 we only had 4 s of data to analyze from the captive animal, due to loss of computer
444 files, and these could have come from a context not represented in the wild recordings.

445 Issues may also have arisen from the recording equipment used in The Bahamas
446 and Guam. Specifically, the lack of an anti-alias filter in either recording may be
447 problematic because the Nyquist frequency is relatively close to the peak energy of the
448 signal, which may have resulted in aliased energy present in our recordings.
449 Additionally, the use of the HTI-MIN-96 hydrophone in the Guam recording should be
450 treated with great caution because this hydrophone has not been formally calibrated
451 above 50 kHz. The effect of decreasing sensitivity based on preliminary calibration was
452 tested, producing no notable effect on the mean peak frequency of the clicks in the
453 Guam data set, however the results presented here should not be considered to be
454 officially calibrated. Simultaneously, this type of hydrophone will be highly directional
455 at high frequencies like the peak frequencies of *Kogia* spp., which may produce
456 variability in sensitivity that depends on recording angle, and is otherwise
457 unpredictable. Results from such instrumentation, while highly informative for
458 preliminary exploration of sounds, should be treated with care and not assumed to be as
459 reliable as those from hydrophones specifically designed for high frequency data
460 collection.

461 The recordings presented here were made from a small number of individuals,
462 and the amount of individual variability in this species is unknown. However, based on
463 the similarities among the free-ranging recordings, we can conclude that some of the
464 signals produced by this species are fairly stereotyped. However, the identification of
465 unique click types within the Guam recordings does suggest that *K. sima* signals may
466 vary based on behavioral state, group size, or group composition, as has been shown for
467 other NBHF clicking species (Dawson and Thorpe 1990, Reyes *et al.* 2016). However,

468 advances in characterizing the signals of *K. sima* may also facilitate distinguishing the
469 signals of Kogiids from other NBHF clicking species, which will help to enhance
470 management and protection of this “data deficient”, cryptic species (Taylor *et al.* 2012).

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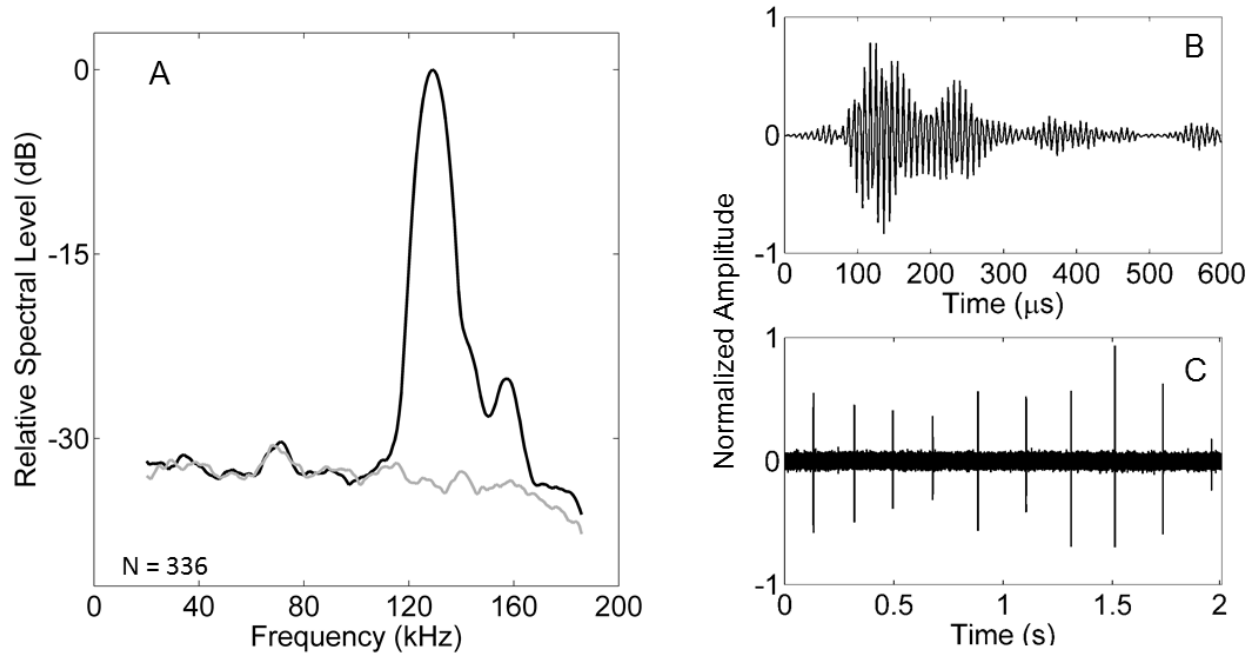
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Table 1. Click parameters for captive and free-ranging recordings of *K. sima* based on recordings from 2002 (captive), 2005 (The Bahamas) and 2016 (Guam) (\pm standard deviation). Also shown are parameters from recordings of captive *K. breviceps* for comparison (Madsen *et al.* 2005a). Peak frequency, centroid frequency, duration, -3 dB bandwidth, -10 dB bandwidth, rms bandwidth, Q_{-3dB} , Q_{rms} , and inter-click interval are show as Mean/Median (\pm Standard Deviation). Note: possible issues with the captive recording are detailed near the end of the article. na = “not available”

Species	Recording Setting	Sample Size (# clicks)	Peak Frequency (kHz)	Centroid Frequency (kHz)	Duration (μ s)	-3 dB Bandwidth (kHz)	-10 dB Bandwidth (kHz)	rms Bandwidth (kHz)	Q_{-3dB}	Q_{rms}	Inter-click Interval (ms)
<i>K. sima</i> (calf)	captive	49	112/110 (\pm 9)	108/105 (\pm 9)	91/52 (\pm 85)	21/16 (\pm 11)	43/43 (\pm 20)	18/17 (\pm 19)	6/6 (\pm 2)	7/7 (\pm 5)	83/79 (\pm 24)
<i>K. sima</i> (2 adults + 1 sub-adult)	free-ranging The Bahamas	328	129/129 (\pm 2)	129/129 (\pm 2)	199/179 (\pm 54)	10/10 (\pm 2)	16/17 (\pm 3)	9/9 (\pm 2)	15/15 (\pm 4)	14/13 (\pm 3)	164/135 (\pm 79)
<i>K. sima</i> (adult + calf)	free-ranging Guam	759	127/127 (\pm 2)	121/122 (\pm 5)	186/192 (\pm 62)	10/10 (\pm 3)	17/16 (\pm 7)	20/20 (\pm 7)	7/6 (\pm 3)	13/13 (\pm 3)	110/93 (\pm 73)
<i>K. sima</i> – burst pulse clicks	free-ranging Guam	81	124/124 (\pm 2)	117/118 (\pm 6)	138/130 (\pm 46)	14/14 (\pm 4)	25/26 (\pm 7)	23/22 (\pm 7)	6/5 (\pm 2)	10/9 (\pm 4)	37/37 (\pm 10)
<i>K. sima</i> – Lower frequency clicks	free-ranging Guam	98	117/117 (\pm 3)	113/115 (\pm 6)	189/191 (\pm 75)	11/10 (\pm 7)	19/16 (\pm 12)	17/16 (\pm 7)	8/7 (\pm 4)	12/12 (\pm 3)	198/216 (\pm 120)
<i>K. breviceps</i>	captive	820	130/na (\pm 1)	129/na (\pm 1)	119/na (\pm 19)	8/na (\pm 2)	15/na (\pm 3)	na	16/na (\pm 1)	na	40-70/na

Figure 1. Example clicks from the Bahamas (A,B,C), Guam (D,E,F) and captive (G, H, I), recordings, including (A, D,G) the mean spectrum of extracted usual clicks (black line) and mean noise before each click (light grey line), (B,E,H) an example waveform of a single click and (C,F,I) an example time series of 2 seconds of data.



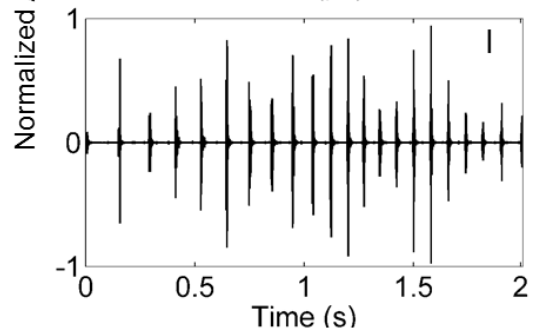
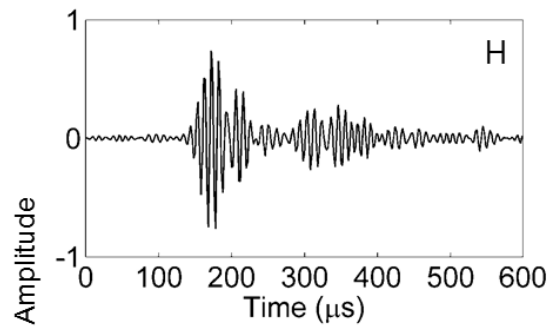
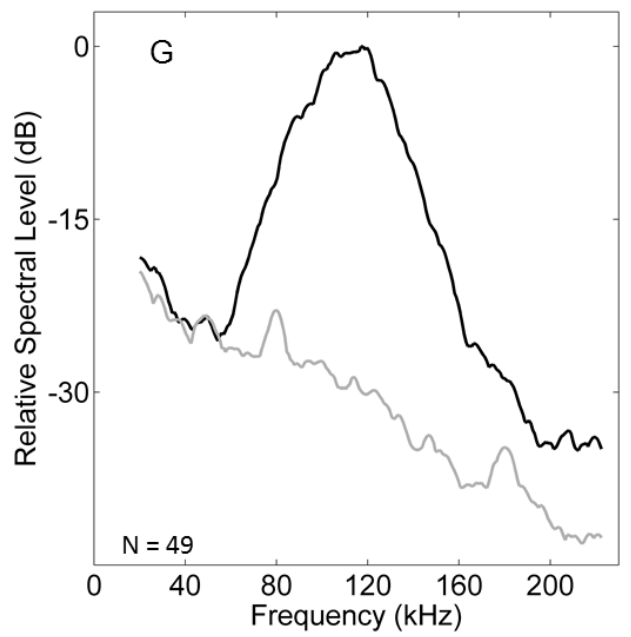
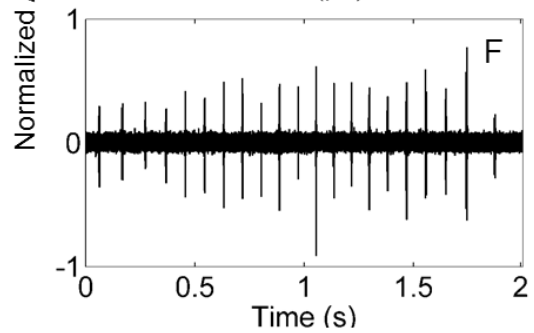
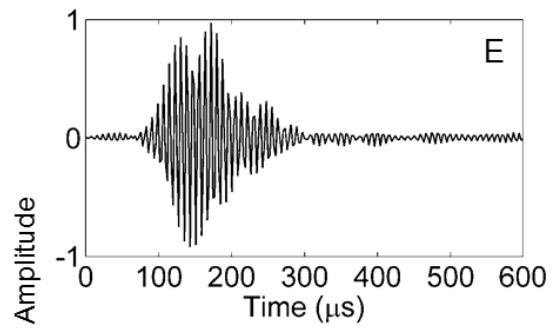
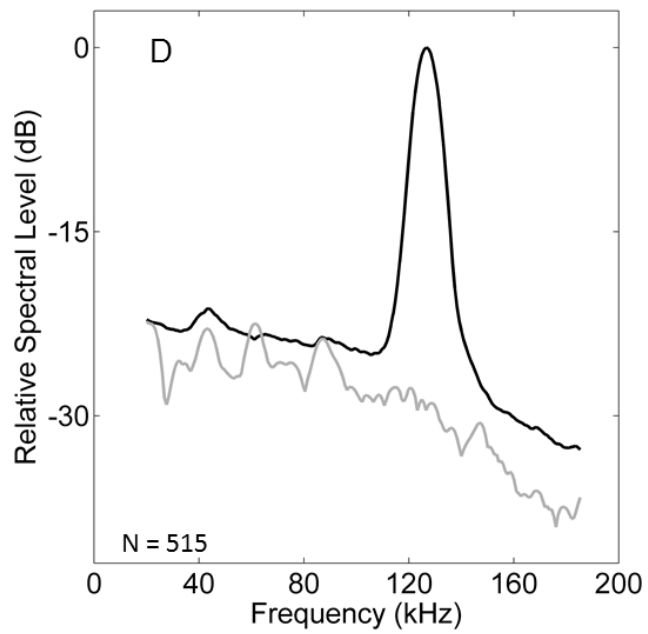


Figure 3. Histograms of peak and centroid frequencies for clicks in the Guam data set, highlighting the usual and lower peak frequency click types. A) Peak frequencies of all clicks, with a primary peak at 127 kHz and a secondary peak at 117 kHz. B) Peak frequencies and C) centroid frequencies of the clicks with $\text{SNR} \geq 20$ dB, with a primary peak at 127-128 kHz and a secondary peak at 116-117 kHz.

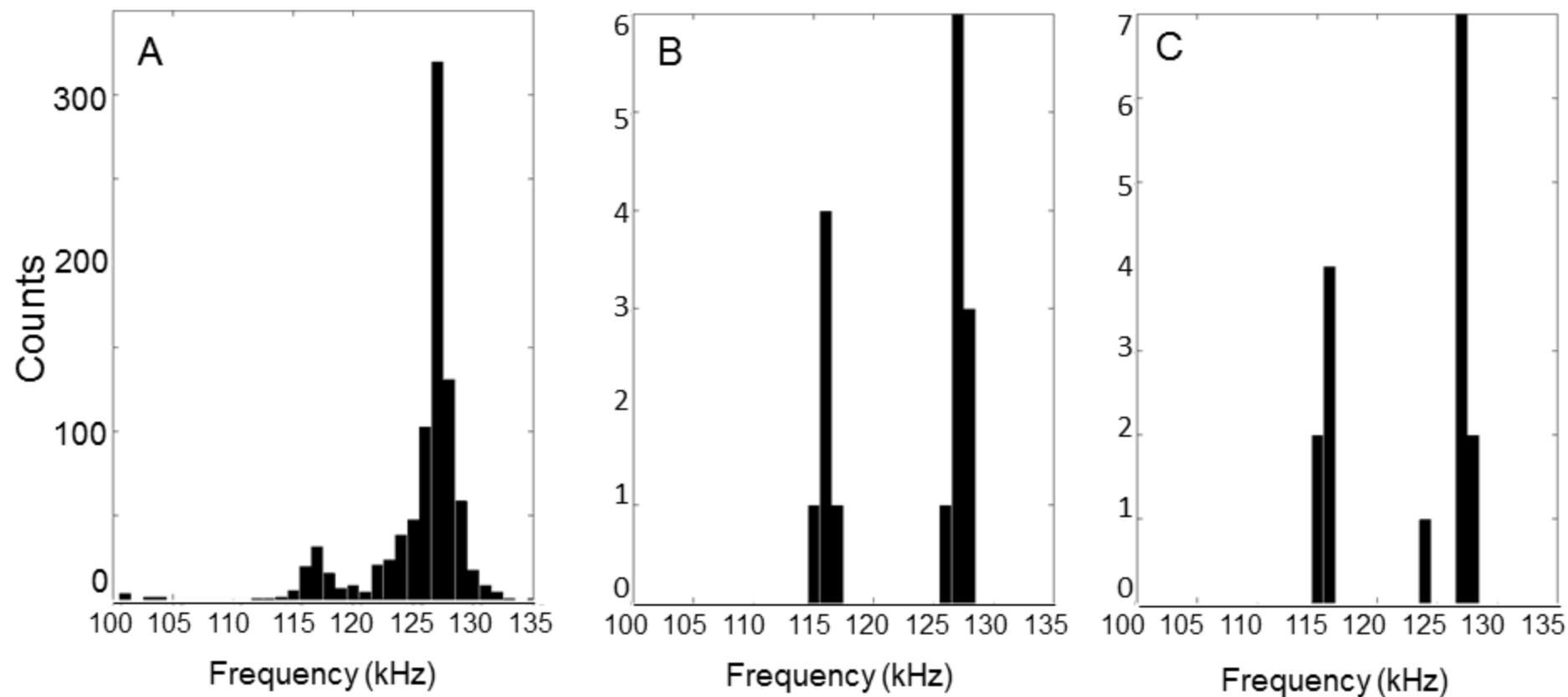


Figure 2. Examples of the burst-pulse clicks (A,B) and the lower frequency clicks (C, D) from Guam, including an example spectrogram (A) and time series (B) of the burst-pulse clicks and an example spectrogram (C) and waveform (D) of the lower frequency clicks. The burst-pulse is visible in A and B between 1.6 and 2.4 seconds. Lower frequency clicks are visible in C between 0 and 1.5 seconds, followed by usual clicks from 2.5 to 5 seconds.

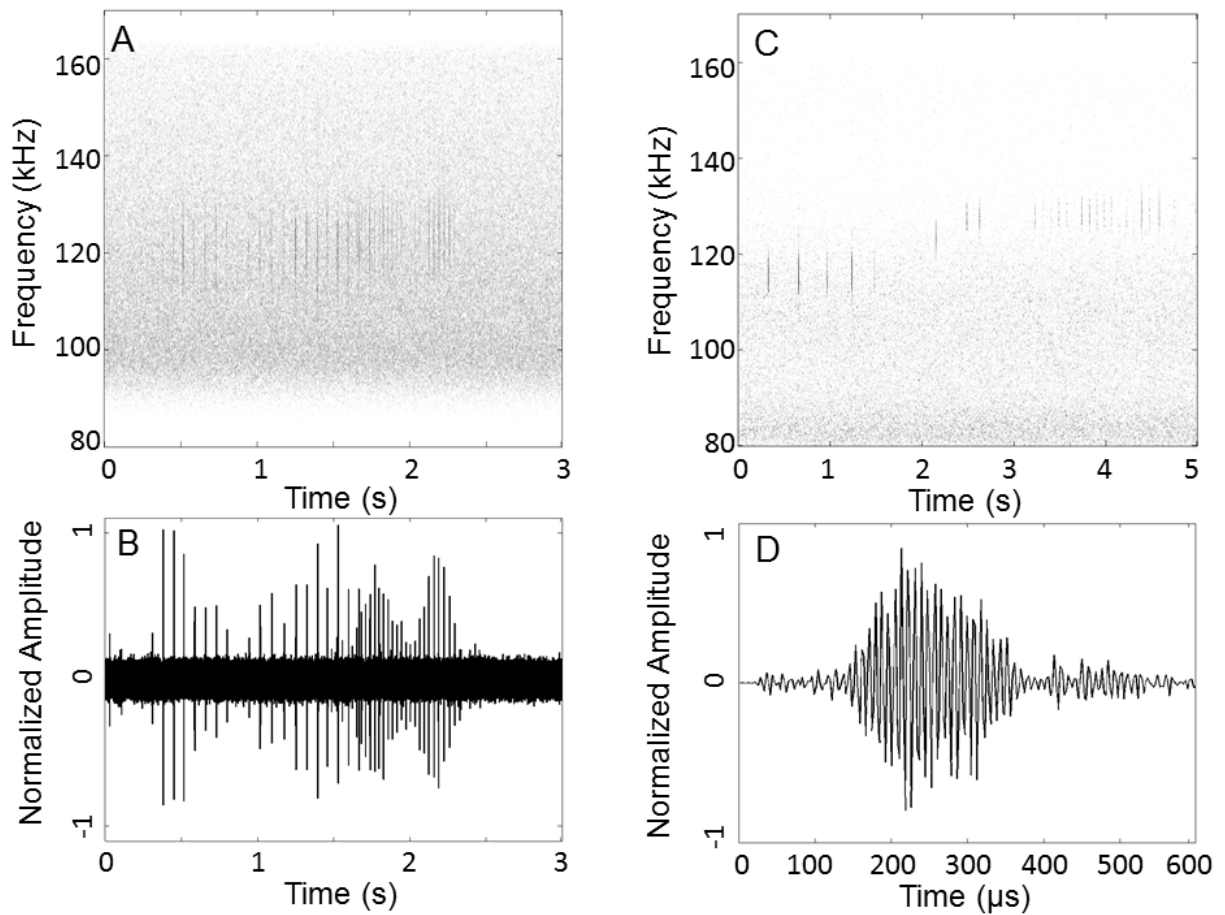


Figure 4. Histogram of click duration in the recording of free-ranging *K. sima* from The Bahamas. Grey bars indicate first mode (duration $< 235 \mu\text{s}$), likely comprised of single clicks. Black bars indicate second mode (duration $> 235 \mu\text{s}$), likely comprised of clicks-plus-reverberations. Dashed black lines indicate (a) median ($157 \mu\text{s}$) and (b) mean ($161 \mu\text{s}$) of the first mode (gray bars only). Solid black lines indicate (c) median ($179 \mu\text{s}$) and (d) mean ($199 \mu\text{s}$) of the complete data set (gray bars and black bars), which is reflected in the summary data, Table 1.

