<u>Methods & Techniques</u>: Journal of Experimental Biology

<u>Title</u>: Using accelerometers to determine the calling behavior of tagged baleen whales

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ABSTRACT

Low-frequency acoustic signals generated by baleen whales can propagate over vast distances, making the assignment of calls to specific individuals problematic. Here we report the novel use of acoustic recording tags equipped with high-resolution accelerometers to detect vibrations on the surface of two tagged fin whales that directly match the timing of recorded acoustic signals. A tag deployed on a buoy in the vicinity of calling fin whales, and a recording from a tag that had just fallen off of a whale, were able to detect calls acoustically but did not record corresponding accelerometer signals that were measured on calling individuals. Across the hundreds of calls measured on two tagged fin whales, the accelerometer response was generally anisotropic across all three axes, appeared to depend on tag placement, and increased with the level of received sound. These data demonstrate that high-sample-rate accelerometry can provide important insights into the acoustic behavior of baleen whales that communicate at low frequencies. This method helps identify vocalizing whales, which in turn enables the quantification of call rates, a fundamental component of models used to estimate baleen whale abundance and distribution from passive acoustic monitoring.

INTRODUCTION

A major challenge in studying acoustic behavior and its ecological context is determining the source of an acoustic signal and assigning the emitted sound to an individual. These data are critically needed to relate movements and physiology to call production, and also to quantify individual call rates for acoustic monitoring. Discerning sender and potential receivers is also important for a wide range of communication and behavioral ecology studies, including the effects of anthropogenic sounds. Identifying call-producers is particularly challenging for whales because they are rarely in view and often vocalize without any visual cue, such as opening the mouth, or releasing bubbles. Passive acoustic monitoring using hydrophone or seismometer arrays can localize the location of sound-producing whales over relatively large spatial scales (Soule and Wilcock, 2013; Stanistreet et al., 2013; Weirathmueller et al., 2013; Wilcock, 2012). At finer scales, animal-borne tags equipped with hydrophones provide acoustic information with simultaneous information on orientation, depth, and acceleration (Johnson et al., 2009; Johnson and Tyack, 2003). Sounds recorded by these multi-sensor tags have been assigned to either the tagged whale itself or nearby conspecifics based on the angle of arrival (Johnson et al., 2009; Johnson et al., 2006; Madsen et al., 2013; Oliveira et al., 2013) or a combination of consistent received level, high signal-to-noise ratio, and apparent isolation of the tagged animal (Janik, 2000; Jensen et al., 2012; Oleson et al., 2007; Parks et al., 2011). Most of these methods are problematic for analyzing baleen whale sound production when conspecifics are present because tagged whale sounds cannot be easily distinguished from those of nearby animals given the typical long-range propagation of low frequency calls. Another potentially complicating factor is that individuals may vary the source level of generated sounds (Au et al., 2006; Parks et al., 2011), making received level an unreliable indicator of range to the caller. However, recent increases in the sampling capacity of digital recording tags provide new opportunities to assess the calling behavior of individual whales. In particular, the low frequency signals of large baleen whales could be detected using high-resolution accelerometry from tags attached to vocalizing individuals. Here we tested this hypothesis in fin whales because they generate some of the lowest frequency calls (~30-20 Hz downsweeps) among aquatic animals (Watkins et al., 1987), making them an ideal model system to study calling behavior with high-resolution, multi-sensor acoustic tags.

RESULTS AND DISCUSSION

For two tagged fin whales, calls as low as 20 Hz were simultaneously recorded on both accelerometers and hydrophones (Fig 1, 2). The acoustic signals exhibited durations of 1.00±0.27 s, and the corresponding accelerometer signals had similar features with respect to duration (0.99±0.03 s). The accelerometer responses that coincided with acoustic signals were largely anisotropic (Fig. 3), exhibiting differences in magnitude among the three-accelerometer axes within each deployment. This variation could be related to differences in tag location on each whale, given the inconsistent directionality of the anisotropic accelerometer responses between deployments, but we were unable to resolve this relationship conclusively due to our limited sample size. Nevertheless, the magnitude of accelerometer signals increased with the received sound pressure level of calls recorded on the tag during both tag deployments acoustic received levels for bp12_294a acoustic calls (mean ± 1 standard deviation): 184±6 dB re 1µPa pkpk, 170±7 dB re 1µPa rms, and for bp13_258b acoustic calls: 177±5 dB re 1µPa pkpk, 162±5 dB re 1µPa rms; Fig. 4). We also note that we recorded acoustic signals that had no corresponding accelerometer signals for both tag deployments. This may be due to masking of accelerometer signals by greater body movements during these times. RMS noise levels on the accelerometer data in a 1-second window preceding each detected acoustic call supported this hypothesis, with levels higher near calls that were not detected on the accelerometers than near those detected (grand means of 0.21±0.18 and 0.13±0.10 m s^{-2} respectively).

To test the hypothesis that coincident pressure and accelerometer signals represent the calls of the tagged whale, we attached a DTAG to a drifting buoy deployed at 30m depth, within 1000m of calling fin whales. We recorded fin whale calls on the DTAG hydrophone, but no evidence of calls on the accelerometers were resolvable on that associated data stream (Figure 2D). An opportunistic test also occurred with deployment bp12_294a, when the tag fell off the whale and recorded a call 3 seconds after detachment. At an estimated distance of less than 10 m from the whale, assuming fin whale steady swimming speed of less than 3 m s^{-1} (Goldbogen et al., 2006), there were no concomitant accelerometer signals when the call was recorded acoustically on the tag (Figure 2B). Our measurements of clear accelerometer signals for tags attached to calling animals and the absence of such signals on tags close to calling whales suggest that the body vibrations associated with calling played a substantial role in generating the coincident accelerometer signals.

However, most acoustic signals do consist of particle acceleration as well as pressure. In the far-field of a sound source, sound pressure and the associated particle acceleration are related by known physics, expressed by the linearized conservation of the momentum equation. We tested the null hypothesis that the tag accelerometer signals could represent the particle accelerations associated with incoming calls of fin whales in the far field of the tagged whale by applying these models to each data stream (see supplement). The magnitude and phase of pressure and accelerometer data did not conform to these predicted far-field relationships, suggesting that calls were recorded in the near-field. In addition, acceleration and pressure magnitudes in the far field are proportional to each other with the constant equal to $2\pi f/\rho c$, with f = frequency (Hz), ρ = seawater density (g cm^{-3}), and c = speed of sound in water (m s^{-1}). Given the sound pressure levels of the calls on the tag (Figure 4), accelerometer magnitudes on our tag recordings were much higher than expected. For example, the ~1000 Pa peak-to-peak pressure signal recorded in Figure 1A should produce an acceleration magnitude of approximately 0.08 m s^{-2}. The levels we recorded on tags coupled to calling animals were close to an order of magnitude higher than this prediction. This evidence further supports the hypothesis that tagged animal body vibrations were contributing to these surprisingly high accelerometer values. It is important to note that because the details of the fin whale sound production mechanism are unknown, the boundary that defines the transition from near-field to far-field is also unknown, and could be anywhere from 15 m to 150 m, or less than a whale length to approximately eight whale lengths away (see supplement). Thus, although the modeling described above suggests that calls were recorded in the near-field, there remains a small chance they were produced by a whale closely and consistently associated with the tagged whale. However, considering the clear results of our opportunistic experiments, the most likely explanation for our observations is that the acoustic and accelerometry signals originate from each call produced by the tagged whale.

Using high resolution accelerometry to detect low frequency call production will significantly increase our ability to study baleen whale communication systems, including the contexts in which a particular sender signals, and how individuals acoustically respond to other animals or anthropogenic sound. The method we propose here offers a breakthrough in identifying when a tagged whale produces a sound. Although acoustic tags equipped with high-resolution accelerometry may make it possible to confirm caller identity in other species, the applicability of this method will be limited by sensor capacity and resolution. For these reasons, our approach may be limited to large baleen whales that generate low frequency signals, or toothed whales that exhibit lower frequency body movements associated with emission of sounds (Johnson et al., 2009). This method also enables the quantification of individual calling rates, a fundamental input parameter for models that use passive acoustic monitoring to estimate the abundance and distribution of animals (Marques et al., 2013). Lastly, characteristics of these accelerometer signals may prove useful in future investigations of baleen sound production (Adam et al., 2013).

MATERIALS AND METHODS

We attached multi-sensor acoustic recording tags, or DTAGs (Johnson et al., 2009; Johnson and Tyack, 2003), to fin whales off the coast of southern California in the summer months of 2012 and 2013. These tagging operations took place in the context of a behavioral response study, where tagged whales were exposed to controlled sounds (DeRuiter et al., 2013; Goldbogen et al., 2013; Southall et al., 2012). The tags contained a pressure transducer, stereo hydrophones sampling at 240 kHz, and tri-axial accelerometers and magnetometers sampling at 200 Hz for bp12_294a and at 500 Hz for bp13_258b. DTAGs were equipped with flotation, four small suction cups for attachment, and a VHF transmitter for tag retrieval.

The tag acoustic record was manually audited by visual inspection of a spectrogram (Hamming window, FFT size 512, 75% overlap). The auxiliary sensor data (accelerometers, magnetometers, pressure) were separately visually inspected for corresponding signals and the time, duration, and peak-to-peak magnitude of those signals was recorded over a manually determined window. Acoustic call start-times were marked by an analyst, and received levels were automatically calculated in Matlab using these user-defined time cues as a starting point. Calls were low pass filtered (6th order Butterworth filter at 100 Hz) before level measurement, and both the waveforms and reported levels have been adjusted for measured tag sensitivity (based on laboratory calibration at 10 Hz - 20 kHz) to account for reduced hydrophone response at low frequency and the effects of the tag's analog high-pass filter). Reported peak-to-peak and RMS received levels for acoustic calls were calculated over the full reported signal duration based on a 97% energy criterion for signal duration (Madsen et al., 2004). These levels are not source levels, and cannot be compared directly to fin whale call levels measured using other methods.

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AUTHOR CONTRIBUTIONS

JAG, AKS, and SLD analyzed data and wrote the paper. All authors contributed with fieldwork, experimental design, manuscript editing, and/or theory.

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FIGURE LEGENDS

Figure 1. Detection of fin whale calls from tag data. (A) Acoustic detection of 20 Hz signals were simultaneous with all three orthogonal axes (x,y,z) of the accelerometer. Signal has been adjusted for the tag's analog high pass filter, filtered (2nd order Butterworth bandpass filter between 10 and 60 Hz), and downsampled (1200 Hz sampling rate). Spectrogram FFT size 512, 98% overlap. Accelerometer data were mean-subtracted and the linear trend removed, but data were not filtered. (B) Time series of acoustic and accelerometer signal detections (bp12_294a). The cessation and resumption of calling in bp12_294a demonstrated the reliability of this method to assess calling behavior in the context of a controlled exposure experiment (see methods).

Figure 2. Different tag deployment scenarios and their effect on accelerometer signal detection (spectrogram parameters, acoustic signal processing, and accelerometer processing as in Figure 1). (A) Tag attached to whale bp12_294a. (B) Tag just moments after detachment from whale bp12_294a. (C) Tag attached to whale bp13_258b. (D) Tag attached to floating buoy in vicinity of calling fin whales. Impulsive spikes in the acoustic record are interference from the tag's VHF radio transmissions.

Figure 3. Accelerometer response during fin whale calls. The acceleration measurements along each axis represent peak-to-peak magnitudes for each tag deployment (bp12_294a, left panels; bp13_258b, right panels). Ordinary least-squares linear regressions (solid thick lines) and 95% confidence intervals (solid thin lines) for each pairwise comparison were used to illustrate a

general departure from isometry (dashed lines) for bp12_294a (x-y, r^2=0.26; x-z, r^2=0.15; y-z, r^2=0.64) and bp13_258 (x-y, r^2=0.32; x-z, r^2=0.56; y-z, r^2=0.42).

Figure 4. Relationship between accelerometer magnitude and the received level of sound. Received levels of sound (peak-to-peak sound pressure levels) were correlated with peak-to-peak accelerations for both bp12_294a (r_s=0.614; $p<0.005$) and bp13_258a (r_s=0.654; $p<0.005$). Right panels show distributions for bp12_294a (C) and bp13_258a (D) of received sound levels with (light bars) and without (shaded bars) concomitant acceleration signals.

REFERENCES

Uncategorized References

Adam, O., Cazau, D., Gandilhon, N., Fabre, B., Laitman, J. T. and Reidenberg, J. S. (2013). New acoustic model for humpback whale sound production. *Applied Acoustics* **74**, 1182-1190.

Au, W. W. L., Pack, A. A., Lammers, M. O., Herman, L. M., Deakos, M. H. and Andrews, K. (2006). Acoustic properties of humpback whale songs. *Journal of the Acoustical Society of America* **120**, 1103-1110.

DeRuiter, S. L., Southall, B. L., Calambokidis, J., Zimmer, W. M. X., Sadykova, D., Falcone, E. A., Friedlaender, A. S., Joseph, J. E., Moretti, D., Schorr, G. S. et al. (2013). First direct measurements of behavioural responses by Cuvier's beaked whales to mid-frequency active sonar. *Biology Letters* **9**.

Goldbogen, J. A., Calambokidis, J., Shadwick, R. E., Oleson, E. M., McDonald, M. A. and Hildebrand, J. A. (2006). Kinematics of foraging dives and lunge-feeding in fin whales. *Journal of Experimental Biology* **209**, 1231-1244.

Goldbogen, J. A., Southall, B. L., DeRuiter, S. L., Calambokidis, J., Friedlaender, A. S., Hazen, E. L., Falcone, E. A., Schorr, G. S., Douglas, A., Moretti, D. J. et al. (2013). Blue whales respond to simulated mid-frequency military sonar. *Proceedings of the Royal Society B-Biological Sciences* **280**.

Janik, V. M. (2000). Source levels and the estimated active space of bottlenose dolphin (Tursiops truncatus) whistles in the Moray Firth, Scotland. *Journal of Comparative Physiology A* **186**, 673-680.

Jensen, F. H., Beedholm, K., Wahlberg, M., Bejder, L. and Madsen, P. T. (2012). Estimated communication range and energetic cost of bottlenose dolphin whistles in a tropical habitat. *The Journal of the Acoustical Society of America* **131**, 582-592.

Johnson, M., Aguilar de Soto, N. and Madsen, P. T. (2009). Studying the behaviour and sensory ecology of marine mammals using acoustic recording tags: a review. *Marine Ecology-Progress Series* **395**, 55-73.

Johnson, M., Madsen, P. T., Zimmer, W. M. X., de Soto, N. A. and Tyack, P. L. (2006). Foraging Blainville's beaked whales (Mesoplodon densirostris) produce distinct click types matched to different phases of echolocation. *Journal of Experimental Biology* **209**, 5038-5050.

Johnson, M. and Tyack, P. L. (2003). A digital acoustic recording tag for measuring the response of wild marine mammals to sound. *Ieee Journal of Oceanic Engineering* **28**, 3-12.

Madsen, P. T., de Soto, N. A., Arranz, P. and Johnson, M. (2013). Echolocation in Blainville's beaked whales (Mesoplodon densirostris). *Journal of Comparative Physiology a-Neuroethology Sensory Neural and Behavioral Physiology* **199**, 451-469.

Madsen, P. T., Kerr, I. and Payne, R. (2004). Echolocation clicks of two free-ranging, oceanic delphinids with different food preferences: false killer whales *Pseudorca crassidens* and Risso's dolphins *Grampus griseus*. *Journal of Experimental Biology* **207**, 1811-1823.

Marques, T. A., Thomas, L., Martin, S. W., Mellinger, D. K., Ward, J. A., Moretti, D. J., Harris, D. and Tyack, P. L. (2013). Estimating animal population density using passive acoustics. *Biological Reviews* **88**, 287-309.

Oleson, E. M., Calambokidis, J., Burgess, W. C., McDonald, M. A., LeDuc, C. A. and Hildebrand, J. A. (2007). Behavioral context of call production by eastern North Pacific blue whales. *Marine Ecology-Progress Series* **330**, 269-284.

Oliveira, C., Wahlberg, M., Johnson, M., Miller, P. J. O. and Madsen, P. T. (2013). The function of male sperm whale slow clicks in a high latitude habitat: Communication, echolocation, or prey debilitation? *The Journal of the Acoustical Society of America* **133**, 3135-3144.

Parks, S. E., Johnson, M., Nowacek, D. and Tyack, P. L. (2011). Individual right whales call louder in increased environmental noise. *Biology Letters* **7**, 33-35.

Soule, D. C. and Wilcock, W. S. D. (2013). Fin whale tracks recorded by a seismic network on the Juan de Fuca Ridge, Northeast Pacific Ocean. *Journal of the Acoustical Society of America* **133**, 1751-1761.

Southall, B. L., Moretti, D., Abraham, B., Calambokidis, J. and Tyack, P. (2012). Marine mammal behavioral response studies in Southern California: advances in technology and experimental methods. . *Marine Technology Society Journal* **46**, 46-59.

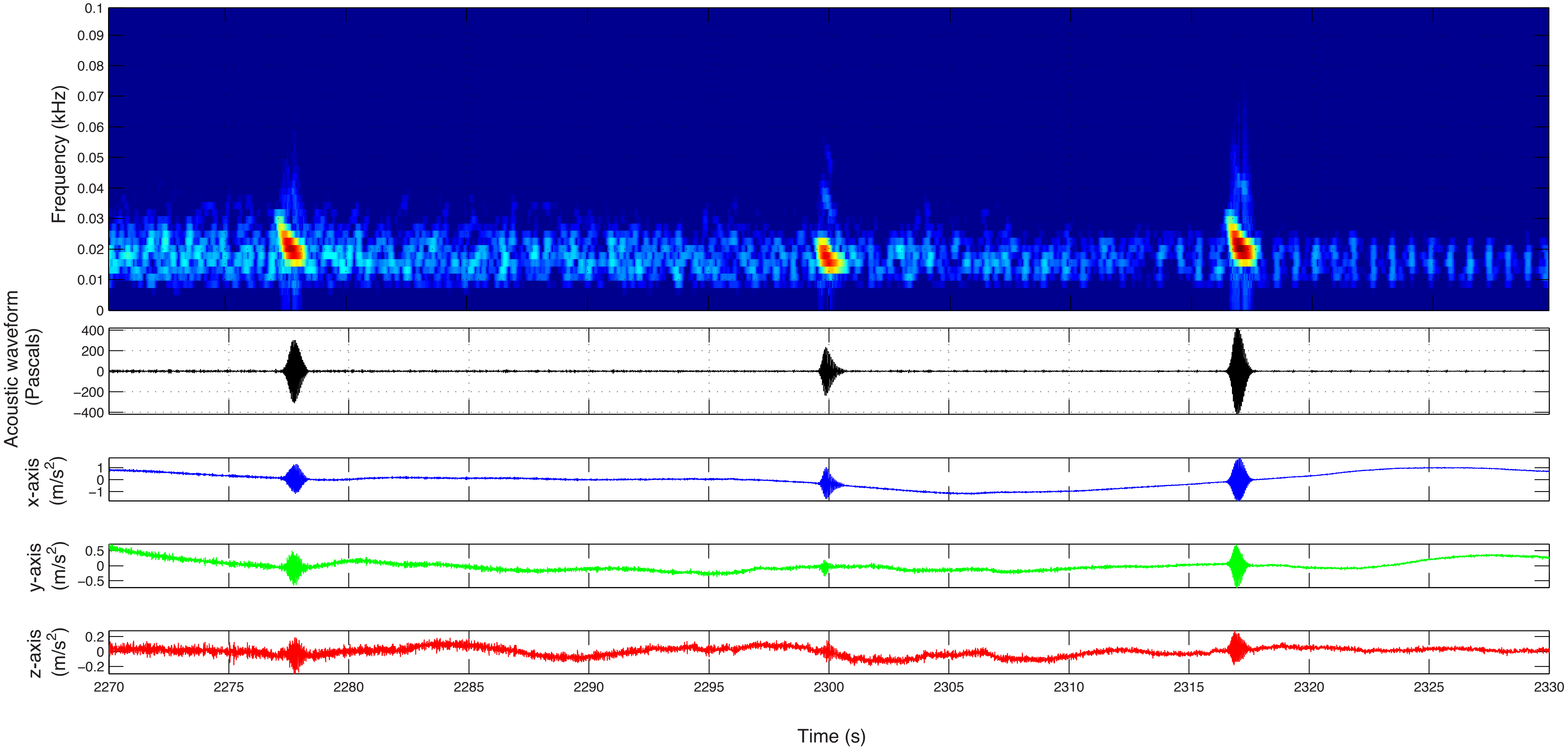
Stanistreet, J. E., Risch, D. and Van Parijs, S. M. (2013). Passive acoustic tracking of singing humpback whales (*Megaptera novaeangliae*) on a Northwest Atlantic feeding ground. *Plos One* **8**, e61263.

Watkins, W. A., Tyack, P., Moore, K. E. and Bird, J. E. (1987). The 20-Hz signals of finback whales (Balaenopteraphysalus). *The Journal of the Acoustical Society of America* **82**, 1901-1912.

Weirathmueller, M. J., Wilcock, W. S. D. and Soule, D. C. (2013). Source levels of fin whale 20 Hz pulses measured in the Northeast Pacific Ocean. *Journal of the Acoustical Society of America* **133**, 741-749.

Wilcock, W. S. D. (2012). Tracking fin whales in the northeast Pacific Ocean with a seafloor seismic network. *Journal of the Acoustical Society of America* **132**, 2408-2419.

Figure 1A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0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
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Acoustic waveform (Pascals)
400
200
0
−200
−400
x-axis (m/s^2)
1
0
−1
y-axis (m/s^2)
0.5
0
−0.5
z-axis (m/s^2)
0.2
0
−0.2
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2275
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2290
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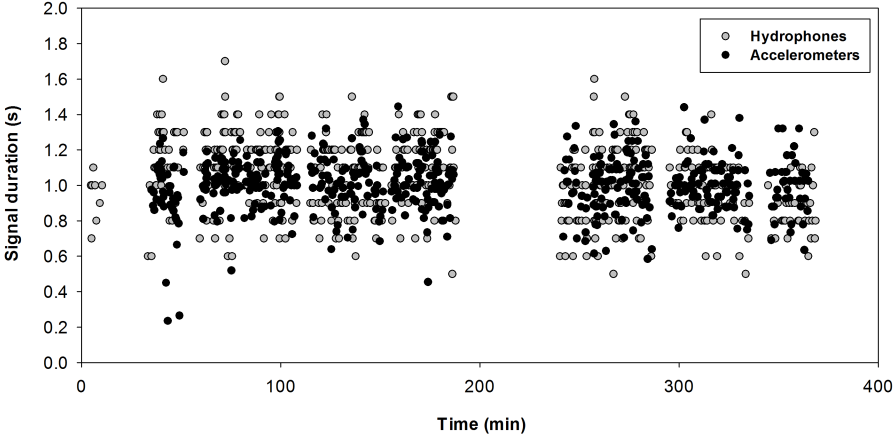
2315
2320
2325
2330
Time (s)

Figure 1B



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1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
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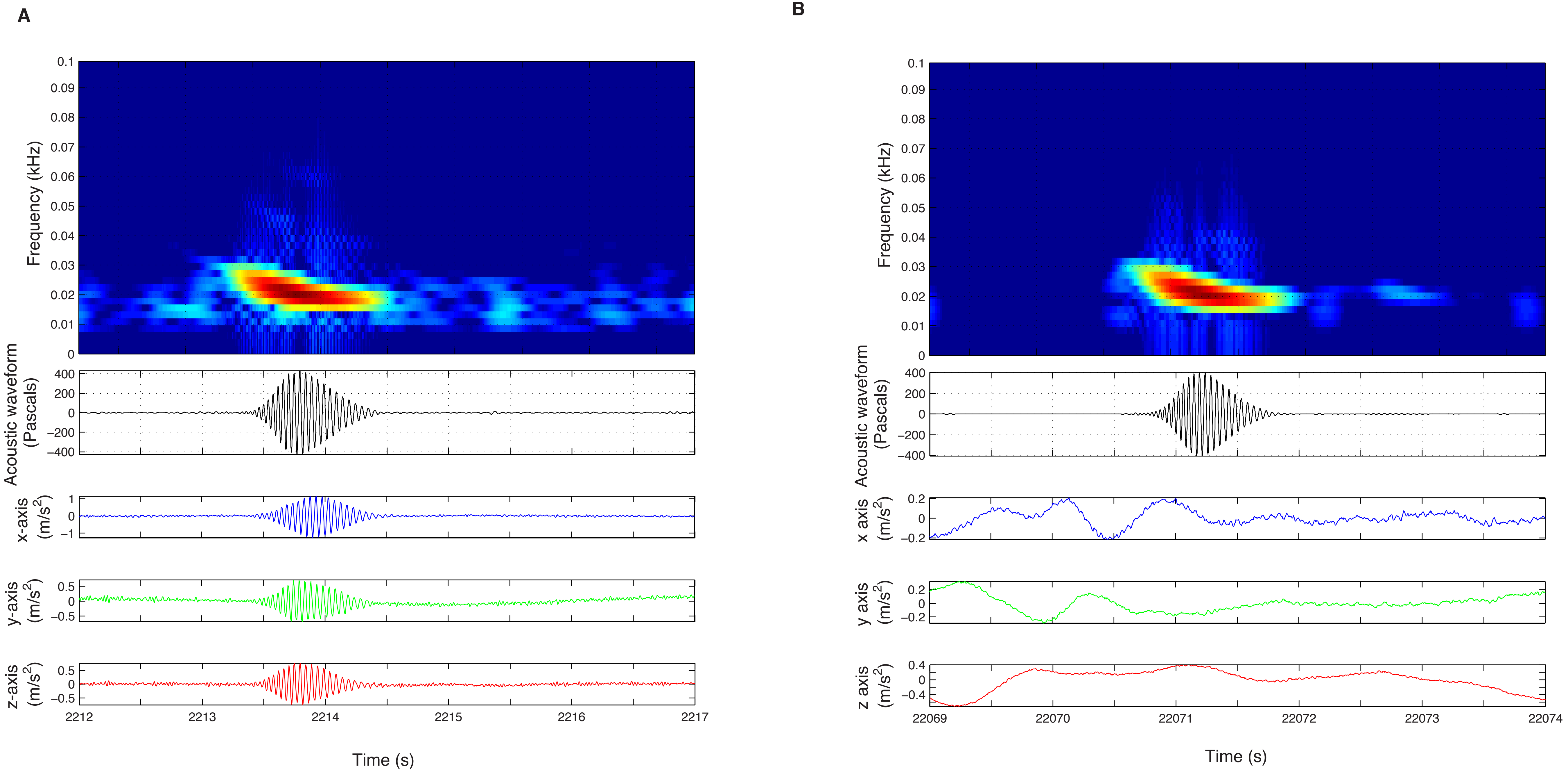
100
200
300
400
Time (min)
Hydrophones
Accelerometers

Figure 2


A
B
Frequency (kHz)
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0.01
0
Acoustic waveform (Pascals)
400
200
0
−200
−400
x-axis (m/s^2)
1
0
−1
y-axis (m/s^2)
0.5
0
−0.5
z-axis (m/s^2)
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0
−0.5
2212
2213
2214
2215
2216
2217
Time (s)
x axis (m/s^2)
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0
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y axis (m/s^2)
0.2
0
−0.2
z axis (m/s^2)
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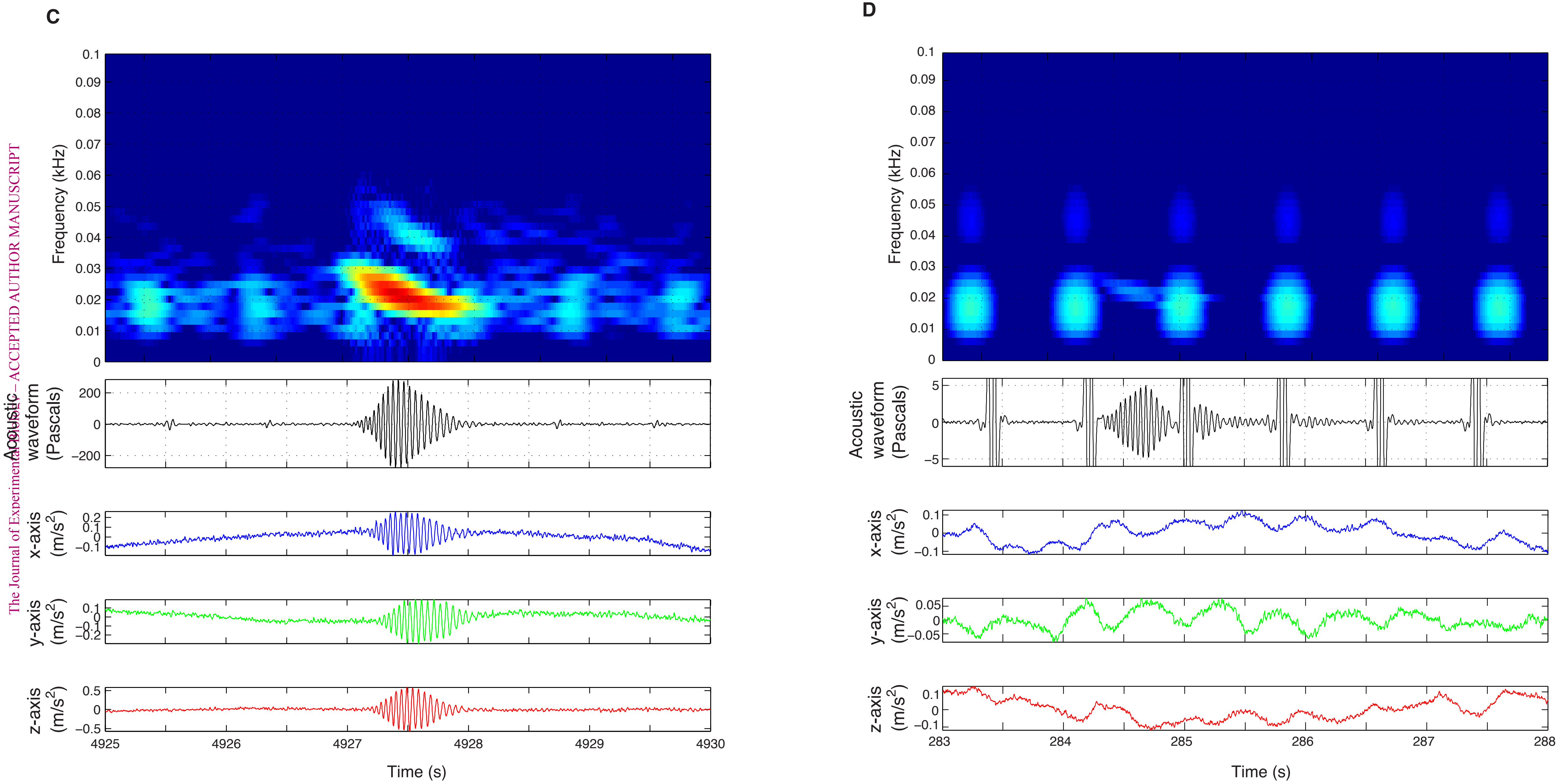
22072
22073
22074
Time (s)

Figure 2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Frequency (kHz)
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0.07
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0.04
0.03
0.02
0.01
0
Acoustic waveform (Pascals)
200
0
−200
5
−5
x-axis (m/s^2)
0.2
0.1
0
−0.1
y-axis (m/s^2)
0.1
0
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−0.2
0.05
−0.05
z-axis (m/s^2)
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0
−0.5
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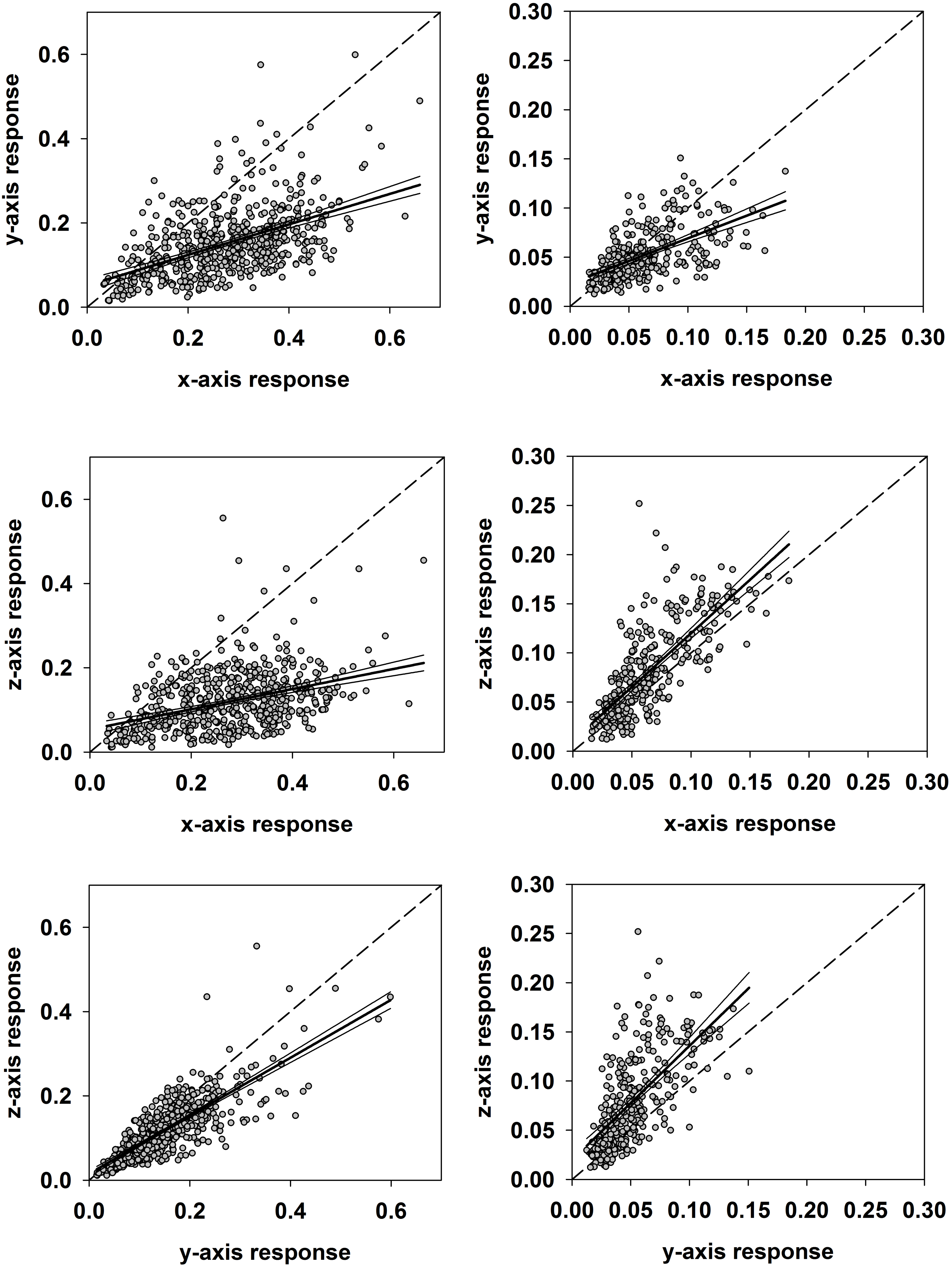
286
287
288
Time (s)

Figure 3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0.10
0.15
0.20
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0.30
x-axis response
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x-axis response
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0.05
0.10
0.15
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0.25
0.30
z-axis response
0.0
0.2
0.4
0.6
y-axis response
0.0
0.2
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0.6
z-axis response
0.00
0.05
0.10
0.15
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y-axis response
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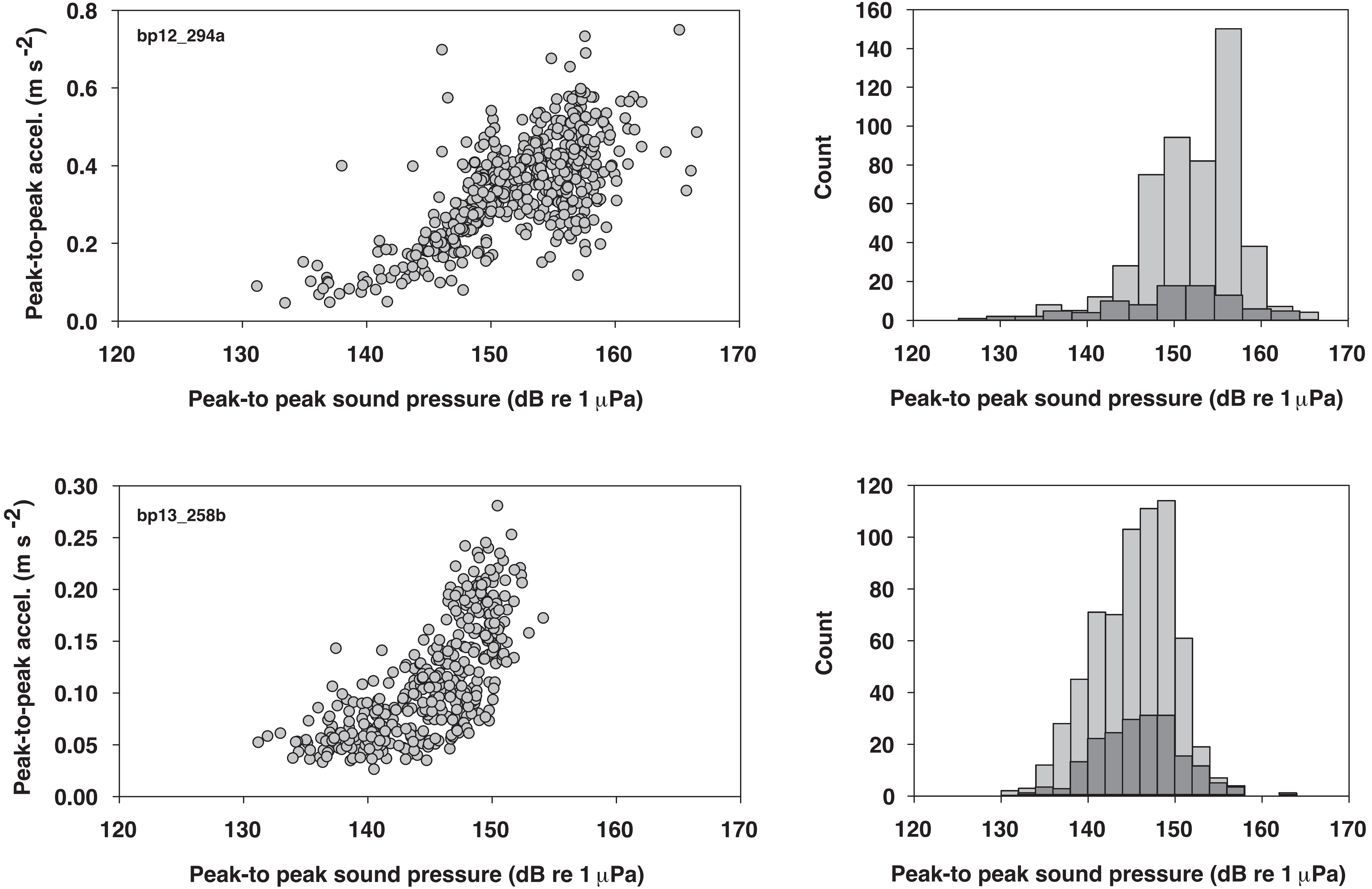
Figure 4


bp12_294a
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0.0
0.2
0.4
0.6
0.8
120
130
140
150
160
170
Peak-to peak sound pressure (dB re 1 μPa)
Count
0
20
40
60
80
100
120
140
160
bp13_258b
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0
20
40
60
80
100
120