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NAVAL POSTGRADUATE SCHOOL

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Characterization of Marine Mammal Recordings from the Hawaii Range Complex

by

Simone Baumann-Pickering, Lisa K. Baldwin, Anne E. Simonis, Marie A. Roche, Mariana L. Melcon, John A. Hildebrand, Erin M. Oleson, Robin W. Baird, Gregory S. Schorr, Daniel L. Webster, and Daniel J. McSweeney

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Monterey, California 93943-5000

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14. ABSTRACT
This report summarizes work conducted in FY2009-FY2010 to characterize marine mammal sounds related to passive acoustic monitoring in the Hawaii Range Complex. Existing acoustic data from the Complex were analyzed to provide better descriptions of acoustic signals by species. Recordings were from a boat-based hydrophone or an autonomous bottom-moored High-frequency Acoustic Recording Package (HARP). Recordings were made of pygmy killer whales, melon-headed whales, Risso's dolphins, and rough-toothed dolphins. Echolocation click parameters were calculated for single species recordings during visual and acoustic surveys by boat-based hydrophones, and by using sightings from small boat surveys and locations of satellite tagged individuals near the HARP. Automatic classification of echolocation clicks of false killer whales and short-finned pilot whales was performed using a Gaussian mixture model.

An analyst manually screened the HARP data collected off the west coast of Hawaii during the period ii/10/2009-iii/9/2009. Distinct call types were found for: beaked whales with frequency modulated upsweep echolocation pulses; sperm whales; high frequency clicks of unknown origin; low frequency banded echolocation clicks; and a large number of unidentified echolocation clicks. Odontocetes were acoustically active every day. Beaked whales were detected on 41% of recording days, but only briefly each day.

15. SUBJECT TERMS
Marine mammals, sound, acoustics, Hawaii Range Complex, HARP, passive acoustic monitoring, odontocetes, beaked whales, pygmy killer whales, melon-headed whales, Risso's dolphins, rough-toothed dolphins, echolocation clicks, sperm whales.

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Characterization of Marine Mammal Recordings from the Hawaii Range Complex

Principal Investigator: John Hildebrand
Marine Physical Laboratory
Scripps Institution of Oceanography

Contract Number: 28H-1087365
Project Title: Marine Mammal Monitoring for the Hawaii Range Complex (HRC)
Project Duration: June 17, 2009 – May 31, 2010

Executive Summary

This report summarizes work conducted in FY2009-FY2010 with Navy support to characterize marine mammal sounds related to passive acoustic monitoring in the Hawaii Range Complex (HRC). Existing acoustic data from the Hawaii Range Complex area were analyzed to provide better descriptions of acoustic signals by species. Recordings were either from a boat-based hydrophone during small boat-based surveys, or from an autonomous bottom-moored High-frequency Acoustic Recording Package (HARP). Recordings were made of pygmy killer whales (*Feresa attenuata*) during four encounters, melon-headed whales (*Peponocephala electra*) during three encounters, Risso's dolphins (*Grampus griseus*) during one encounter, and rough-toothed dolphins (*Steno bredanensis*) during one encounter. Echolocation click parameters were calculated for single species recordings during visual and acoustic surveys by boat-based hydrophones, as well as by using sightings from small boat surveys and locations of satellite tagged individuals in the vicinity of the HARP. False killer whales and short-finned pilot whales had the lowest peak frequencies (15-21 kHz) in comparison to the other species. Pygmy killer whale echolocation clicks showed a bimodal distribution of peak frequencies (in the range of 35 to 50 kHz or 75 to 100 kHz). Melon-headed whales had peak frequency in the range of 31 to 35 kHz. Risso's dolphins showed a distinct peak/notch frequency structure in their echolocation clicks. (Peaks appear at 24.5, 26.7, 34.6 and 40.3 kHz.) Automatic classification of echolocation clicks of false killer whales and short-finned pilot whales was performed using a Gaussian mixture model. This method resulted in a mean misclassification of 10.7 ± 0.7%. Two unknown but distinct echolocation click types were observed in the HARP data. One was a high frequency click that had its minimum frequency around 70 kHz and extended beyond the frequency range of the recorder (100 kHz). The other click type was a low frequency click that had a distinct banding pattern with peak structure at 12.2, 16.4 and 23.8 kHz, close to the peaks seen for short-finned pilot whales.

An acoustic analyst manually screened the HARP data collected off the west coast of the island of Hawaii during the time period of February 10, 2009, until March 9, 2009. Distinct call types were found for: beaked whales with frequency modulated upsweep echolocation pulses (particularly those previously noted at Cross Seamount); sperm whales; high frequency clicks of unknown origin; low frequency banded echolocation clicks; and a large number of unidentified echolocation clicks. Odontocetes were acoustically active every day of the recording period. (65% of total hours had echolocation clicks.) Beaked whales were detected on 41% of the recording days, but only during short periods per day (4% of total hours). Events of anthropogenic noise were logged and categorized as ship noise or echosounder.

Characterization of Marine Mammal Recordings from the Hawaii Range Complex

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I) Descriptions of acoustic signals by species

Acoustic recordings of cetaceans were obtained either with an autonomous bottom-moored High-frequency Acoustic Recording Package (HARP) deployed off the island of Hawaii (Wiggins and Hildebrand 2007) or with a boat-based hydrophone during several small boat-based field projects undertaken off the island of Hawaii (see Baird *et al.* 2008a). The boat-based hydrophone system (sampling frequency of 192 kHz) was deployed opportunistically when in the presence of a single species of cetacean, typically at distances of less than 100 m from the animals and positioned such that the animals were likely to pass within 50 m of the hydrophone. Species present were confirmed both visually and with photographs. The HARP was deployed in approximately 620 m of water (19° 34.8 N 156° 00.9 W, figure 1) in an area that has been regularly surveyed during small boat field projects since 2002 and is known to be an area where a wide diversity of odontocetes is found (Baird *et al.* 2008a, 2008b, 2009, 2010; McSweeney *et al.* 2007, 2009; Schorr *et al.* 2009a, 2009b). The HARP was recording either continuously or on an intermittent schedule with five minutes of recordings in 8 or 15 minute intervals (Table 1). Information on cetacean presence in the vicinity of the HARP, to confirm species recorded acoustically, was obtained in one of two ways. During small boat-based field efforts the area around the HARP was surveyed periodically, typically with the vessel stopping at the location and making 360^{o} scans with binoculars, to assess whether any cetaceans were at the survey in the area. In addition, individuals of a number of species were tagged with location-only satellite tags (see Schorr *et al.* 2009a, 2009b; Baird *et al.* 2010) and tracked with the ARGOS satellite system. The distance from all filtered locations (see Schorr *et al.* 2009a) to the HARP location was measured using the Posdist[1] function in Excel, and consecutive satellite locations that spanned the HARP site (indicating an animal passing the HARP location) or were within 2 km of the HARP were used to assess acoustic detection from the HARP recordings.

[1]Available from http://www.afsc.noaa.gov/nmml/software/excelgeo.php.

Table 1: **HARP deployment cycles off the west coast of the island of Hawaii. Duty cycle: cont. = continuous, recording time/recording interval in minutes.**

	Start	End	Duty cycle	# hour bins	# daily bins
Hawaii 01	08/ 11/2007, 0000 hours	10/04/2007, 0616 hours	cont.	1302	55
Hawaii 02	04/19/2008, 0600 hours	07/04/2008, 1419 hours	5/8	1832	77
Hawaii 03	07/ 08/2008, 0000 hours	10/15/2008, 2048 hours	5/15	2396	100
Hawaii 05	02/10/2009, 0000 hours	03/09/2009, 0615 hours	cont.	654	28
Hawaii 06	04/23/2009, 1000 hours	8/18/2009, 1748 hours	5/15	2815	118

Recordings with the boat-based hydrophone were obtained from pygmy killer whales (*Feresa attenuata*) during four encounters, melon-headed whales (*Peponocephala electra*) during four encounters (two from the Hawaii resident population and two from the Main Hawaiian Islands population; see Aschettino 2010), Risso's dolphins (*Grampus griseus*) during one encounter, and rough-toothed dolphins (*Steno bredanensis*) during one encounter (Table 2).

Three visual sightings of short-finned pilot whales (*Globicephala macrorhynchus*) and one sighting of rough-toothed dolphins occurred in close proximity to the recording HARP (figure 2). Three satellite tagged false killer whales (*Pseudorca crassidens*) from the Hawaii insular population were repeatedly in the area around the HARP. Seven satellite positions were close enough to the HARP that acoustic detections during that time period were likely corresponding with vocalizations of these animals (figure 3), which resulted in four time periods with false killer whale echolocation click periods on HARP recordings.

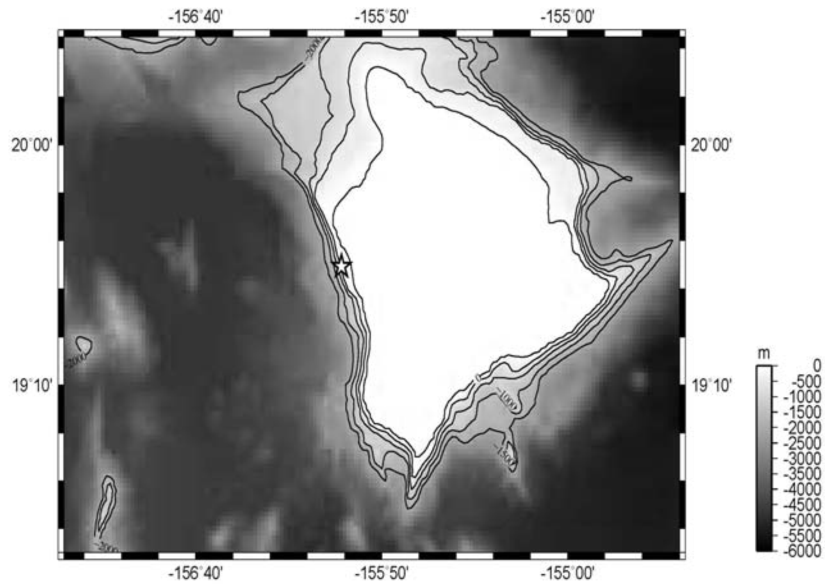


Figure 1: **Location of the High-frequency Acoustic Recording Package (HARP) indicated with a star on the west coast of the island of Hawaii, position 19° 34.8 N, 156° 00.9 W.**

1) *Echolocation click parameters of confirmed species*

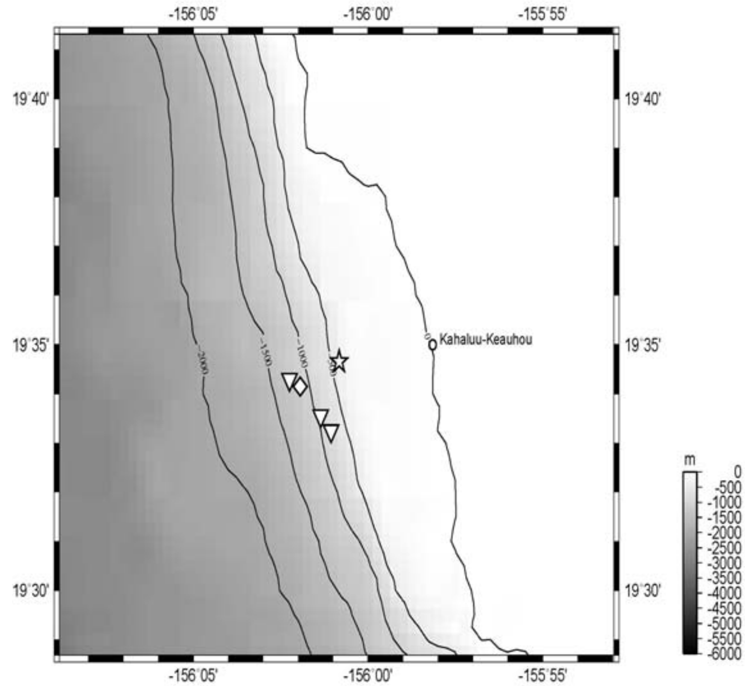
Echolocation clicks were analyzed and described in detail for future species classification by their acoustic signals. Echolocation click parameters have been calculated for all single species recorded during boat-based surveys as well as when satellite tagged or visually sighted species were in the vicinity of the HARP and recordings were made (Table 2).

False killer whales and short-finned pilot whales had the lowest peak and center frequencies in comparison to the other species (Table 2, figure 4). Their overall appearances of all clicks (figure 4/I+IIB) as well as their mean spectra of all clicks (figure 4/I+IIC) were very similar. Possible features for discrimination were a slightly broader distribution of peak frequencies for short-finned pilot whales (figure 4/I+IIA) and their potentially species-specific peaks at 12.6, 18.8 and 28.2 kHz (figure 4/IIC). Whether these peaks are consistent for this species will have to be verified with further single species recordings. The only other species we know of so far which might produce echolocation clicks that are also in this frequency range would be killer whales and Baird's beaked whales. Killer whales are rare in Hawaiian waters (Baird *et al.* 2006), and Baird's beaked whales have not been documented in Hawaii. Both should be different in the spectral structure of their echolocation clicks. Therefore, sequences on the autonomous HARP data with peak frequencies in the range of 15-21 kHz are most often of false killer whale or short-finned pilot whale origin.

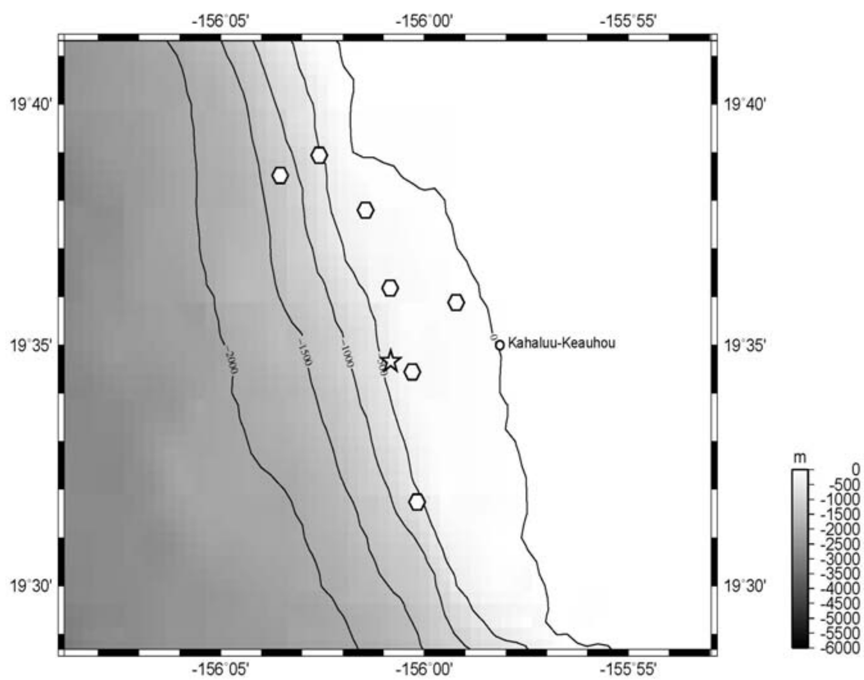
Pygmy killer whale echolocation clicks showed a bimodal distribution of peak frequencies (figure 4/IIIA-C). Clicks had their peak frequency either in the range of 35 to 50 kHz or 75 to 100 kHz. Clicks with low peak frequency also had low amplitude (figure 4/IIIB), which was either due to the distance or, more likely, the angle of the animal to the recording hydrophone. A similar correlation has previously been demonstrated by Madsen *et al.* (2004).

Melon-headed whales had their peak frequency in the range of 31 to 35 kHz (Table 2, figure 4/IV). This was higher than known from a previous study at Palmyra Atoll (Baumann-Pickering, 2009), where the peak frequency was around 25-29 kHz. Recordings in Hawaii were made from two different populations, one of which is resident to the island of Hawaii and the other that moves throughout the main Hawaiian Islands and into offshore waters (Aschettino 2010), and it is possible there may be population-level differences between them that will be investigated at a future date when more recordings are available. Rough-toothed dolphins and melon-headed whales are probably difficult to discriminate (Table 2, figure 4/V). No further efforts have been made to classify these signals automatically.

Risso's dolphins showed a very distinct peak/notch frequency structure in their echolocation clicks (figure 4/VI). The peaks appear in the mean spectra at 24.5, 26.7, 34.6 and 40.3 kHz (figure 4/VIC). These values differ from values reported for Risso's dolphins in Southern California, where the peaks lie at 22.1, 25.6, 30.3 and 39.0 kHz (Soldevilla *et al.*, 2008).



<u>Figure 2:</u> Location of visual sightings of short-finned pilot whales (triangles) and rough-toothed dolphins (diamond) near the HARP (star).



<u>Figure 3:</u> Location of satellite tagged false killer whales (hexagons) near the HARP (star). In most cases, tagged false killer whales were transiting alongshore and groups were typically spread inshore and offshore (Baird *et al.* 2010). Thus, whales in the group likely passed close to the HARP.

Table 2: Echolocation click parameters. Values are given as medians followed by first and third quartiles in brackets. n= number of clicks.

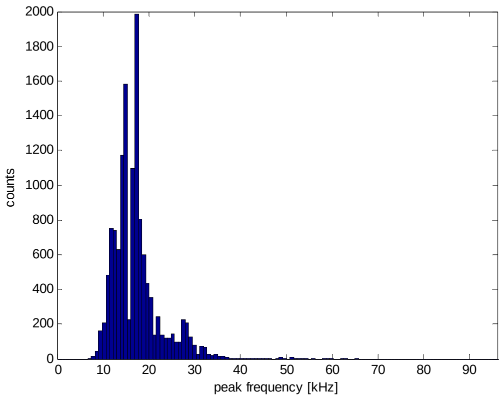
	Peak Frequency (kHz)	Center Frequency (kHz)	Duration (ms)	Inter-click Interval (ms)	Bandwidth -10dB (kHz)	Bandwidth -3dB (kHz)
I) False killer whale						
HARP Hawaii 7.26.08	15.2	18.5	0.21	198	18.3	8.5
(n=2,738)	[13.2 17.5]	[16.5 22.0]	[0.17 0.28]	[66 484]	[14.0 23.8]	[6.2 10.9]
HARP Hawaii 7.27.08	16.7	20	0.23	82	19.5	8.5
(n= 3,089)	[14.0 17.9]	[17.5 23.0]	[0.18 0.30]	[24 258]	[13.2 27.3]	[5.8 11.3]
HARP Hawaii 8.1.08	16.4	19.5	0.23	352	16.4	7.4
(n=3,010)	[14.0 19.1]	[17.2 23.7]	[0.17 0.32]	[121.3 853.5]	[11.3 22.2]	[5.4 10.5]
HARP Hawaii 8.16.08	17.1	20.2	0.24	150	18.3	8.2
(n=4,536)	[14.0 19.9]	[17.7 24.9]	[0.18 0.32]	[48.4 390.1]	[12.1 26.1]	[5.8 10.5]
II) Short-finned pilot whale						
HARP Hawaii 8.25.07	17.5	21.8	0.37	179	11.7	5
(n=1,374)	[13.2 19.9]	[14.5 28.9]	[0.23 0.56]	[52.3 245]	[7.4 18.7]	[3.9 7.8]
HARP Hawaii 5.01.08	19.1	22.8	0.32	184	11.3	5
(n=3,428)	[15.2 20.3]	[20.0 26.8]	[0.20 0.47]	[99.1 241.9]	[7.8 17.5]	[4.2 7.0]
HARP Hawaii 5.15.08	20.7	24.7	0.32	188.7	16.7	6.25
(n=4,863)	[15.2 27.7]	[21.1 28.5]	[0.22 0.45]	[97.3 244.8]	[10.1 23.8]	[4.6 8.9]
III) Pygmy killer whale						
array Hawaii 4.24.08	84	65	0.3	75.6	52.5	10.5
(n=534)	[73.1 88.1]	[59.0 69.2]	[0.23 0.63]	[37.2 137.9]	[22.5 64.5]	[5.5 16.5]
array Hawaii 12.06.08	82	65	0.2	55	52.5	12.7
(n=1263)	[48.3 87.3]	[58.0 69.3]	[0.17 0.25]	[39.0 102.0]	[34.5 63]	[7.8 17.6]
array Hawaii 12.09.08	36	38	0.2	404	36	14
(n=127)	[25.1 44.6]	[31.4 49.4]	[0.18 0.35]	[10.8.6 2734]	[19.8 45.7]	[6.7 18]
array Hawaii 4.20.09	47.2	56.4	0.2	99	62.6	17.6
(n=648)	[42.3 79.5]	[50.0 63.8]	[0.15 0.29]	[70.4 158.6]	[42.3 71.6]	[14.6 22.5]

<u>Table 2 continued:</u> Echolocation click parameters. Values are given as medians followed by first and third quartiles in brackets. n= number of clicks.

	Peak Frequency (kHz)	Center Frequency (kHz)	Duration (ms)	Inter-click Interval (ms)	Bandwidth -10dB (kHz)	Bandwidth -3dB (kHz)
IV) Melon-headed whale						
array Hawaii 4.25.08	34.5	43.9	0.29	173.3	24.7	9
(n=125)	[20.6 50.43]	[36.1 50.0]	[0.20 0.41]	[98.1 326.2]	[12.3 33.3]	[5.1 11.8]
***array Hawaii 12.10.08**	34.1	38.6	0.37	23	24.3	7.8
(n=6,985)	[25.5 43.8]	[33.9 47.9]	[0.26 0.54]	[11.8 53.6]	[13.1 33.3]	[4.8 12.3]
array Hawaii 12.15.08	31.1	36.2	0.32	24	25.1	9.37
(n=2,361)	[25.1 40.1]	[31.9 43.1]	[0.21 0.49]	[12.4 52.5]	[16.1 32.2]	[5.9 13.5]
V) Rough-toothed dolphin						
HARP Hawaii 7.12.08	25	30	0.18	130	37	13.2
(n=4013)	[21.8 33.9]	[26.3 33.5]	[0.14 0.23]	[72.1 241.4]	[26.1 44.1]	[8.2 20.7]
array Hawaii 5.01.09	34	37	0.27	155	28.1	11.2
(n=329)	[26.6 43.9]	[31.6 43.9]	[0.19 0.38]	[95.0 332.0]	[22.1 35.2]	[7.7 14.2]
VI) Risso's dolphin						
array Hawaii 4.27.09	43.8	56	0.32	209	21.7	5.6
(n=221)	[41.9 52.5]	[50.3 60.5]	[0.20 0.64]	[129.5 470.9]	[10.5 39.3]	[3.7 10.5]

* Two encounters from a single day are combined.

I) False killer whale (*Pseudorca crassidens*)
HARP



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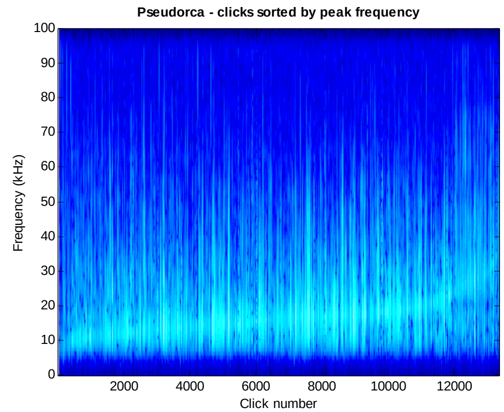

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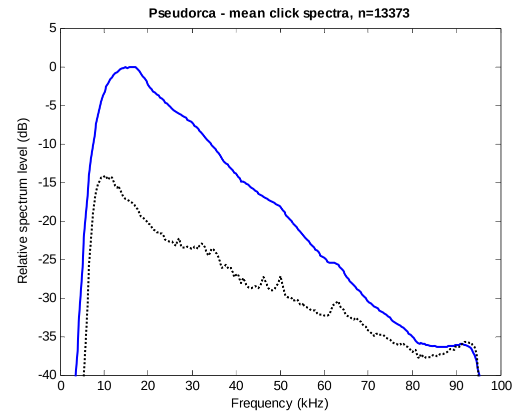

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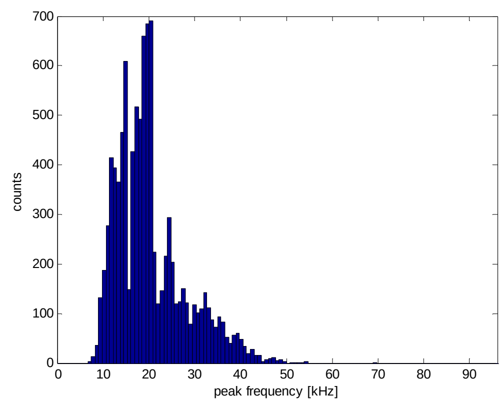
II) Short-finned pilot whale (*Globicephala macrorhynchus*)
HARP



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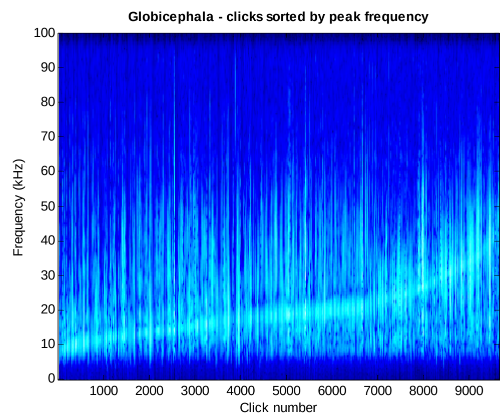

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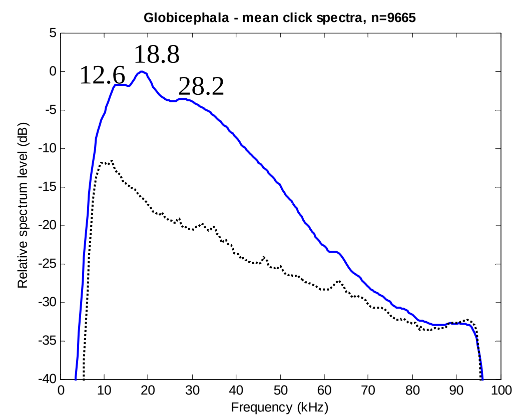

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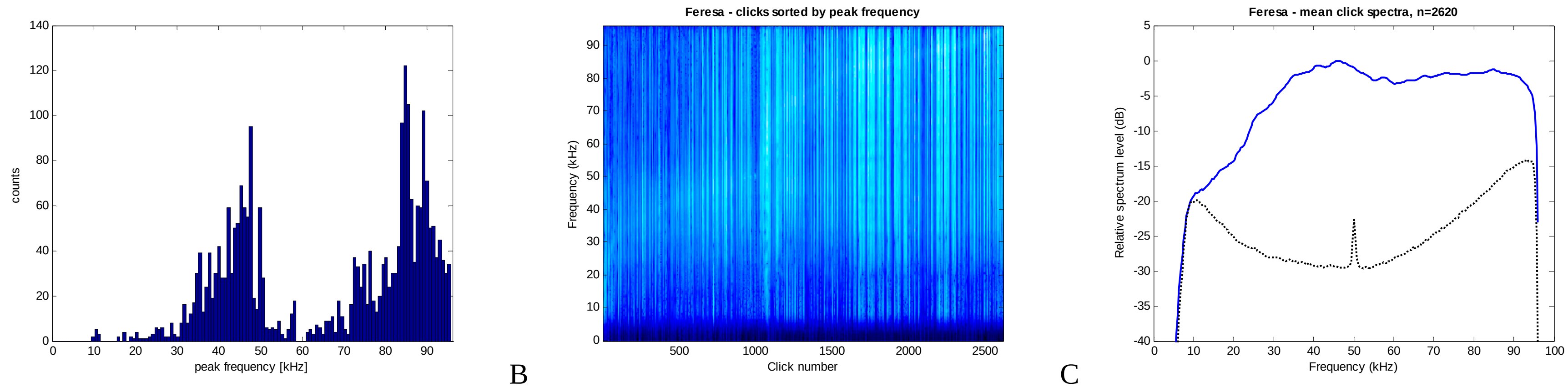
<u>Figure 4:</u> Echolocation clicks of I) false killer whales, II) short-finned pilot whales, III) pygmy killer whales, IV) melon-headed whales, V) rough-toothed dolphins, and VI) Risso's dolphins. A) Distribution of peak frequency, B) Concatenated spectrogram sorted by peak frequency with frequency over click number and spectrum level coded in color, C) Mean spectra (solid line) and mean noise (dashed line) with relative spectrum level over frequency.

III) Pygmy killer whale (*Feresa attenuata*)
Boat-based hydrophone



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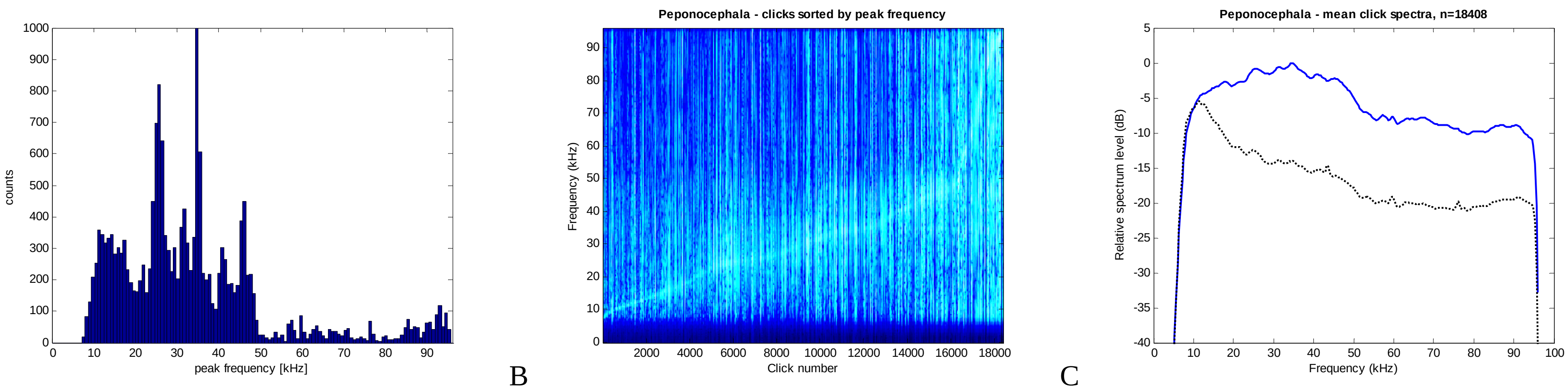
IV) Melon-headed whale (*Peponocephala electra*)
Boat-based hydrophone



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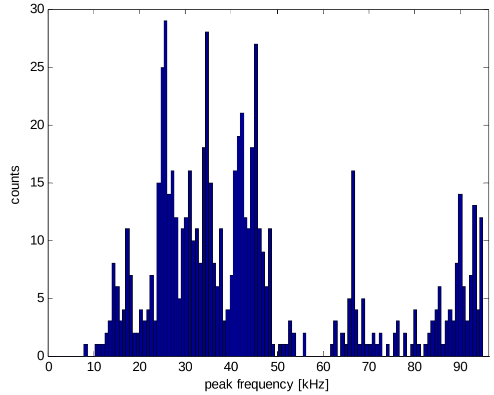
<u>Figure 4 continued:</u> Echolocation clicks of I) false killer whales, II) short-finned pilot whales, III) pygmy killer whales, IV) melon-headed whales, V) rough-toothed dolphins, and VI) Risso's dolphins. A) Distribution of peak frequency, B) Concatenated spectrogram sorted by peak frequency with frequency over click number and spectrum level coded in color, C) Mean spectra (solid line) and mean noise (dashed line) with relative spectrum level over frequency.

V) Rough-toothed dophin (*Steno bredanensis*)

Boat-based hydrophone



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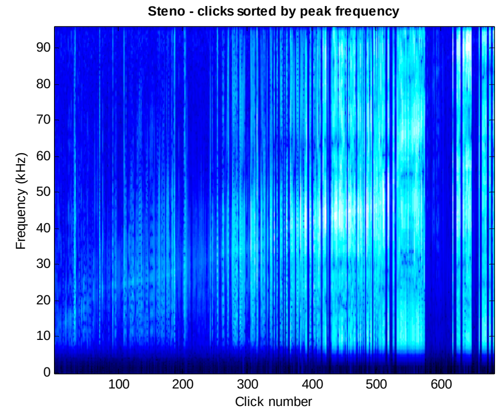

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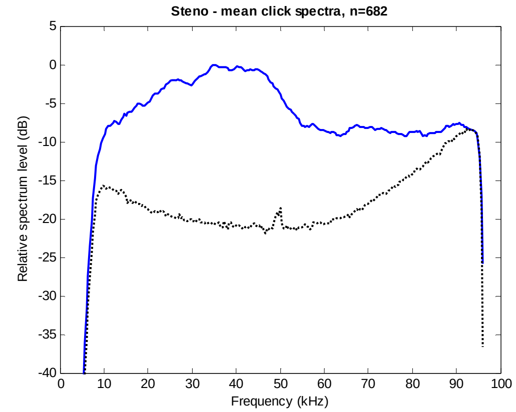

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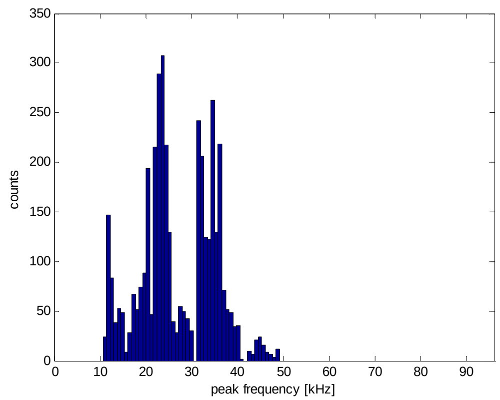
HARP



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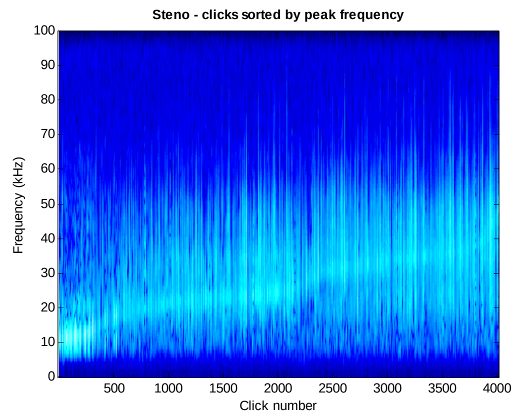

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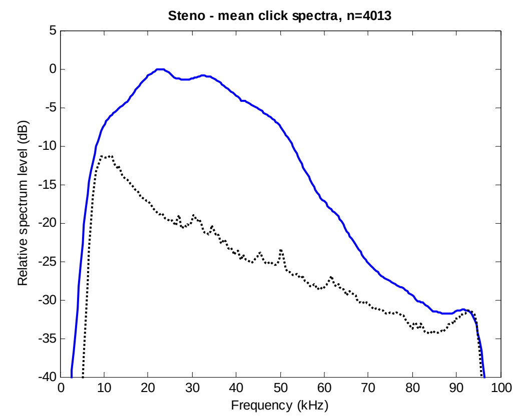
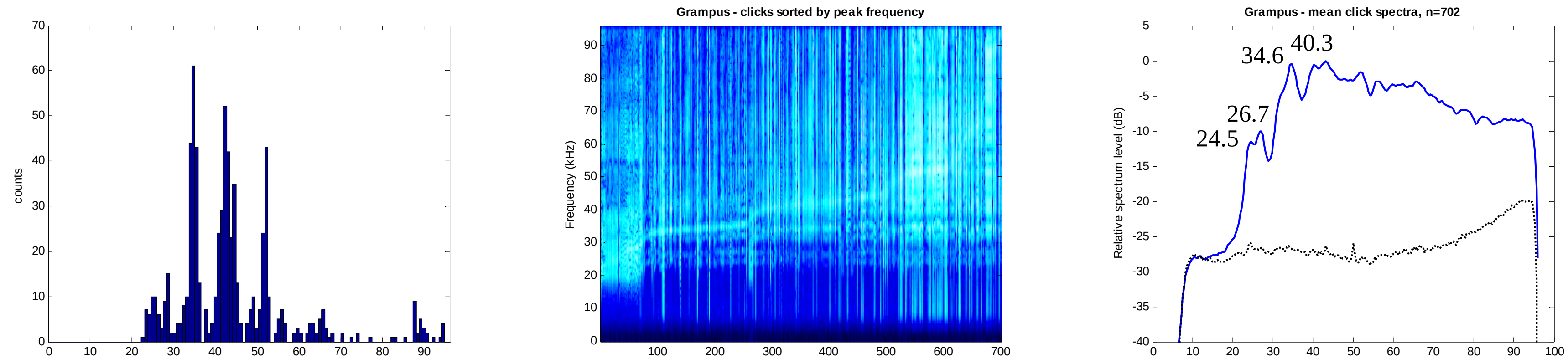


C

<u>Figure 4 continued:</u> Echolocation clicks of I) false killer whales, II) short-finned pilot whales, III) pygmy killer whales, IV) melon-headed whales, V) rough-toothed dolphins, and VI) Risso's dolphins. A) Distribution of peak frequency, B) Concatenated spectrogram sorted by peak frequency with frequency over click number and spectrum level coded in color, C) Mean spectra (solid line) and mean noise (dashed line) with relative spectrum level over frequency.

VI) Risso's dolphin (*Grampus griseus*)

Boat-based hydrophone



A B C

<u>Figure 4 continued:</u> **Echolocation clicks of I) false killer whales, II) short-finned pilot whales, III) pygmy killer whales, IV) melon-headed whales, V) rough-toothed dolphins, and VI) Risso's dolphins. A) Distribution of peak frequency, B) Concatenated spectrogram sorted by peak frequency with frequency over click number and spectrum level coded in color, C) Mean spectra (solid line) and mean noise (dashed line) with relative spectrum level over frequency.**

2) *Automatic classification of echolocation clicks of false killer whales and short-finned pilot whales*

Automatic classification of echolocation clicks of false killer whales and short-finned pilot whales was performed using a Gaussian mixture model (Roch *et al.*, 2008) with a 3-fold test, 100 experiments, 16 mixtures, and 200 consecutive clicks grouped as coming from the same species. This resulted in a mean error rate of misclassification of 10.7 ± 0.7%, and a median error rate of 9.3%. When looking at the falsely classified data more closely, there appeared to be one particular HARP recording of short-finned pilot whales (figure 5) that had more than 60% misclassifications in all experiments. We will have to increase our sample size to evaluate if this is an irregularity caused by recording a visually undetected species (e.g., false killer whales).

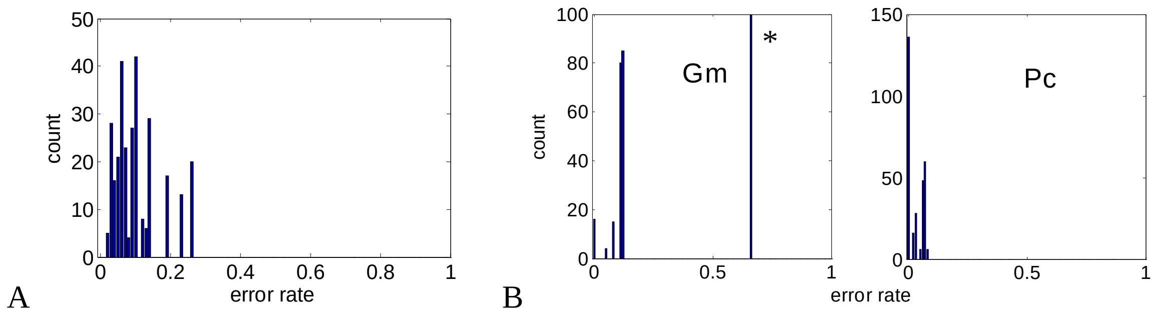
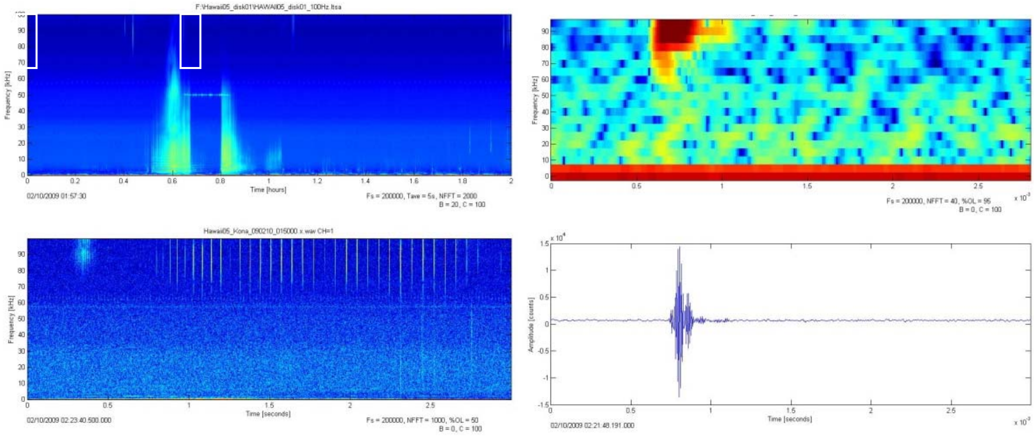


Figure 5: **Distribution of error rates for automatic classification of echolocation clicks of false killer whales (Pc) and short-finned pilot whales (Gm). A) Overall error rate, B) error rate detailed for Pc and Gm.**
*** indicates dataset with highest incorrect classification in all experiments.**

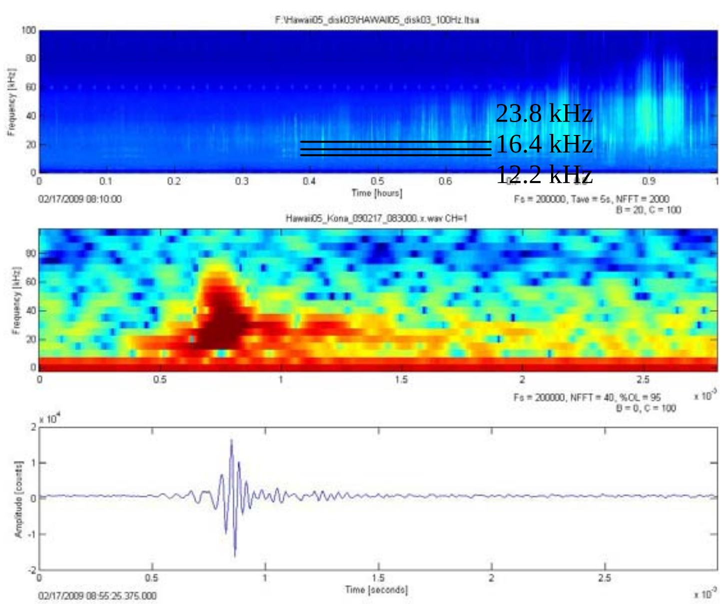
3) *Echolocation clicks of unknown origin*

Two distinct echolocation click types were notable in the long-term autonomous HARP data. One click type was a high frequency click that had its lowest frequency around 70 kHz and was extending beyond the frequency range of the recorder (figure 6). The example click has in its time series and spectrogram a hint of a sweep, indicating a possible beaked whale species of unknown kind. Data with a higher sampling rate would show this more clearly.

The other click type was a low frequency click that had a distinct banding pattern, with peak structure at 12.2, 16.4 and 23.8 kHz (figure 7). This banding appears to be very close to the peaks reported for short-finned pilot whales above (figure 4/IIC), with peaks at 12.6, 18.8 and 28.2 kHz. Further data need to be gathered of single species encounters or tagged animals to strengthen this hypothesis.



<u>Figure 6:</u> Example of high frequency clicks of unknown origin. Top left: Long-term spectral average of 2 hours of data. White boxes indicate areas of interest. Bottom left: spectrogram of 3 seconds. Right: Example click in detail, with top spectrogram and bottom time series.



<u>Figure 7:</u> Notable banding pattern in echolocation clicks. Top: Long-term spectral average of 1 hour. Banding pattern in echolocation clicks, frequencies indicated by horizontal lines. Center spectrogram and bottom time series of example echolocation click.

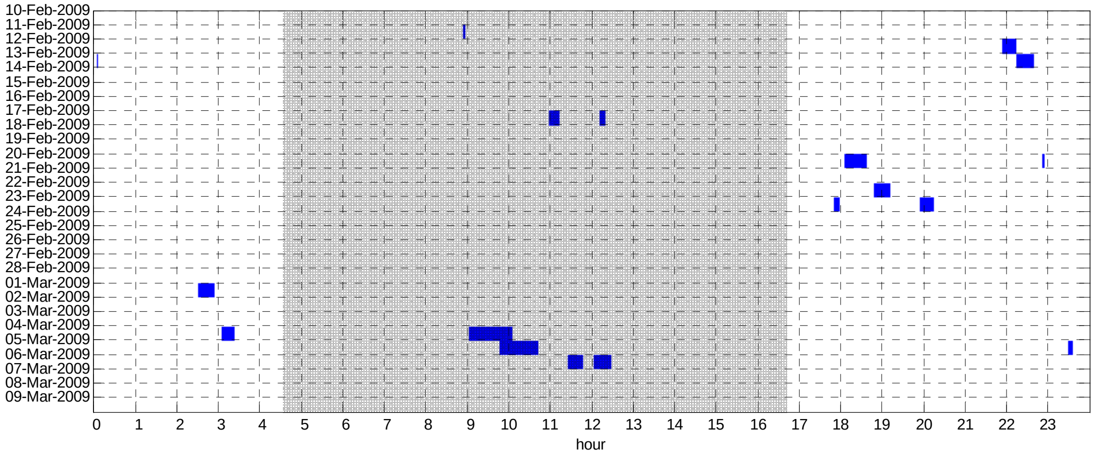
II) Acoustic detections of marine mammals from HARP

1) *Manual acoustic detections*

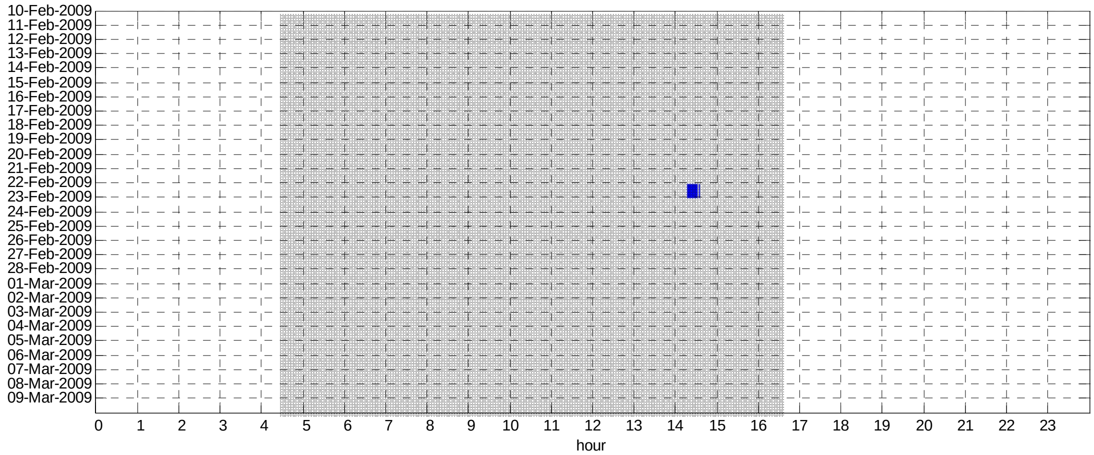
A trained analyst manually screened the HARP data collected off the west coast of the island of Hawaii (figure 1) during the time period of February 10, 2009, 0000 hours GMT, until March 9, 2009, 0615 hours GMT (deployment Hawaii 05, Table 1). A MATLAB based software package called *TRITON* was used for data display and event logging. Potential sound events detected in a one-hour or shorter spectrogram were investigated at finer temporal scales to identify the origin of the sound by species or type of anthropogenic sound. Start and end of a distinct vocalization period were marked.

Distinct call types were found for: beaked whales with their frequency modulated upsweep echolocation pulses (figure 8A), particularly those first noted at Cross Seamount (McDonald *et al.*, 2009) (figure 8B); sperm whales (figure 8C); high frequency clicks of unknown origin (figure 8D, described in figure 6); and low frequency, banded echolocation clicks (figure 8E, described in figure 7). Additionally, a large number of echolocation clicks originating from unidentified odontocetes were noted that could not be attributed to a certain species or a distinct call type (figure 8F).

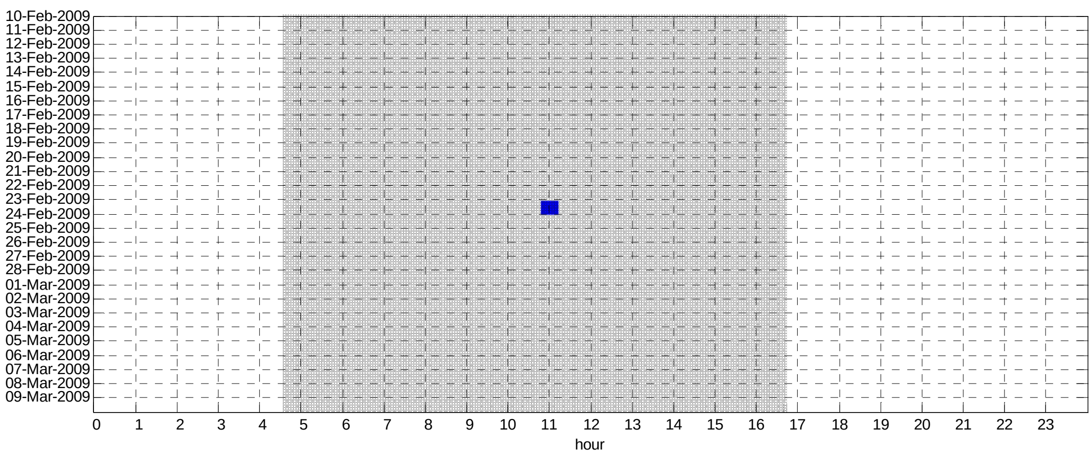
Odontocetes were acoustically active every day of the recording period, with approximately 65% of total hours with echolocation click activity (Table 3). Beaked whales were detected on 41% of the recording days, yet only during short periods per day, resulting in about 4% of total hours with beaked whale echolocation pulses (Table 3). Low frequency, banded clicks (figure 7) were noted with similar regularity.



A: Beaked Whale spp.

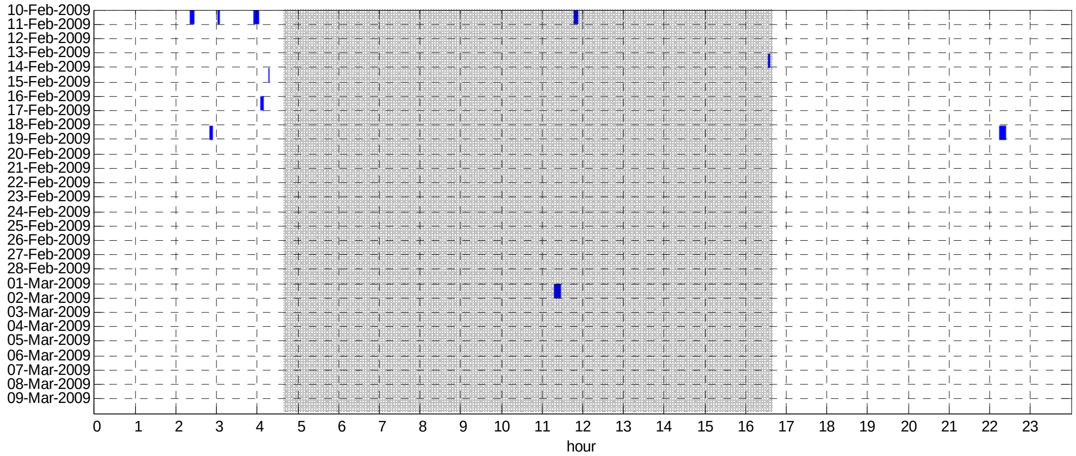


B: Frequency modulated upsweep, first reported from Cross Seamount, Hawaii (McDonald *et al.*, 2009).

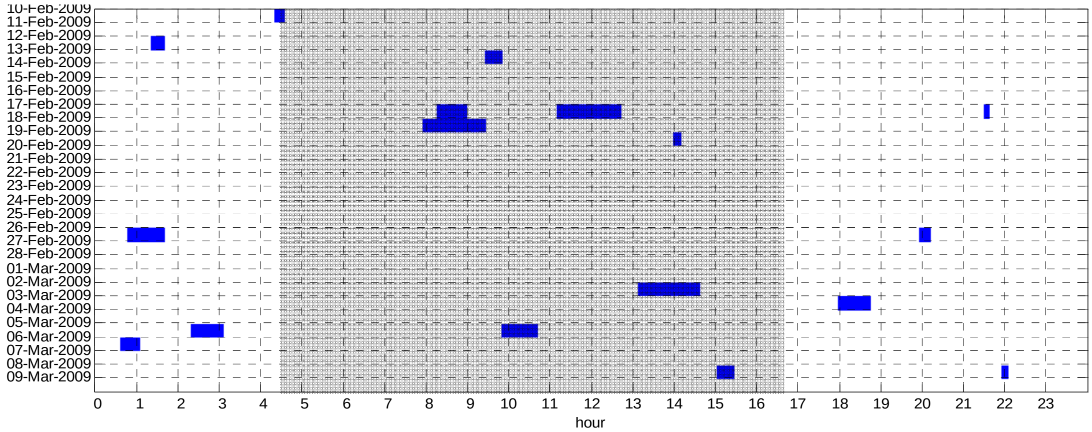


C: Sperm whale

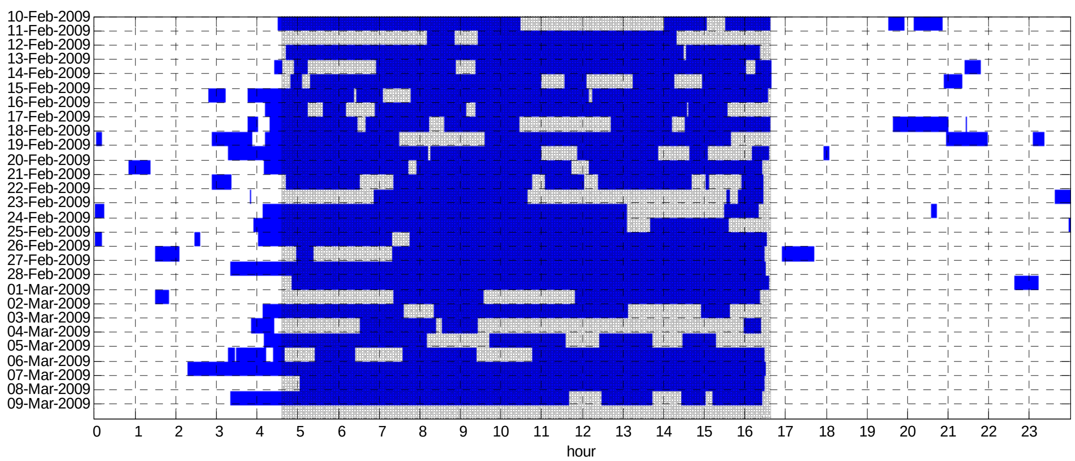
Figure 8: Manual detections of A) All beaked whale echolocation pulses with frequency modulated (FM) upsweep, B) FM pulses, known from Cross Seamount, Hawaii, C) Sperm whale echolocation clicks, D) High frequency clicks of unknown origin (figure 6), E) Low frequency, banded echolocation clicks (figure 7), and F) Unidentified odontocete echolocation clicks. Time is given in GMT, local approximate night time indicated with gray background.



D: High frequency echolocation clicks



E: Low frequency, banded echolocation clicks



F: Unidentified odontocete echolocation clicks

Figure 8 continued: Manual detections of A) All beaked whale echolocation pulses with frequency modulated (FM) upsweep, B) FM pulses, known from Cross Seamount, Hawaii, C) Sperm whale echolocation clicks, D) High frequency clicks of unknown origin (figure 6), E) Low frequency, banded echolocation clicks (figure 7), and F) Unidentified odontocete echolocation clicks. Time is given in GMT, local approximate night time indicated with gray background.

Table 3: **Manual detections of marine mammal species and anthropogenic sound sources during February 10, 2009, until March 9, 2009.**

	# hour bins	percent	# day bins	percent
Marine mammal sounds				
Beaked whale spp.	23	3.5%	11	40.7%
Cross Seamount beaked whale	1	0.2%	1	3.7%
Sperm whale	1	0.2%	1	3.7%
High frequency clicks (figure 6)	10	1.5%	6	22.2%
Low frequency clicks (figure 7)	26	4.0%	12	44.4%
Clicks of other odontocete spp.	361	55.2%	27	100.0%
Anthropogenic sounds				
25 kHz echosounder	5	0.8%	3	11.1%
28.8 kHz echosounder	39	6.0%	12	44.4%
30 kHz echosounder	83	12.7%	19	70.4%
33 kHz echosounder	4	0.6%	2	7.4%
43 kHz echosounder	1	0.2%	1	3.7%
50 kHz echosounder	362	55.4%	27	100.0%
80 kHz echosounder	5	0.8%	4	14.8%
ship engine noise	464	70.9%	27	100.0%

2) *Automatic acoustic detections*

An automatic routine in Matlab detected odontocete clicks (method described in Soldevilla *et al.*, 2008) and subsequently classified frequency modulated clicks as of beaked whale origin. The classifier was an expert system, which screened 75-s segments of data as a unit and evaluated the temporal and spectral parameters of detected clicks within each segment. A detailed description of the classification procedure is currently under preparation for publication.

The detector is capable of detecting all FM pulses currently known for beaked whales in the Pacific Islands region, namely Blainville's beaked whale (*Mesoplodon densirostris*), Cuvier's beaked whale (*Ziphius cavirostris*), signals known from an unknown species at Palmyra Atoll (possibly *Mesoplodon hotaula*, Baumann-Pickering *et al.*, 2010), and an unknown species at Cross Seamount (McDonald *et al.*, 2009). The detector was verified for missed and false detections for the manually screened time period described above (section II/1). It detected 51 segments with beaked whale vocalizations, out of which 6 segments were misclassified, resulting in a 12% false detection rate. There were a total of 28 beaked whale sequences detected. A sequence was defined as a series of echolocation activity of undefined length with gaps not longer than 10 minutes. The detector missed 6 of these sequences, resulting in a 21% missed detection rate, the analyst missed 9 of these, resulting in a 32% missed detection rate. From data collected in Southern California on which the classifier was tested in more detail, it is known that the number of false detections is fairly stable over time. This means that the percentage of false detections will decrease with an increase of beaked whale detections. The number of missed detections is dependent on overall activity. The missed detection rates are higher during periods of high acoustic activity, mostly due to mixed species recordings.

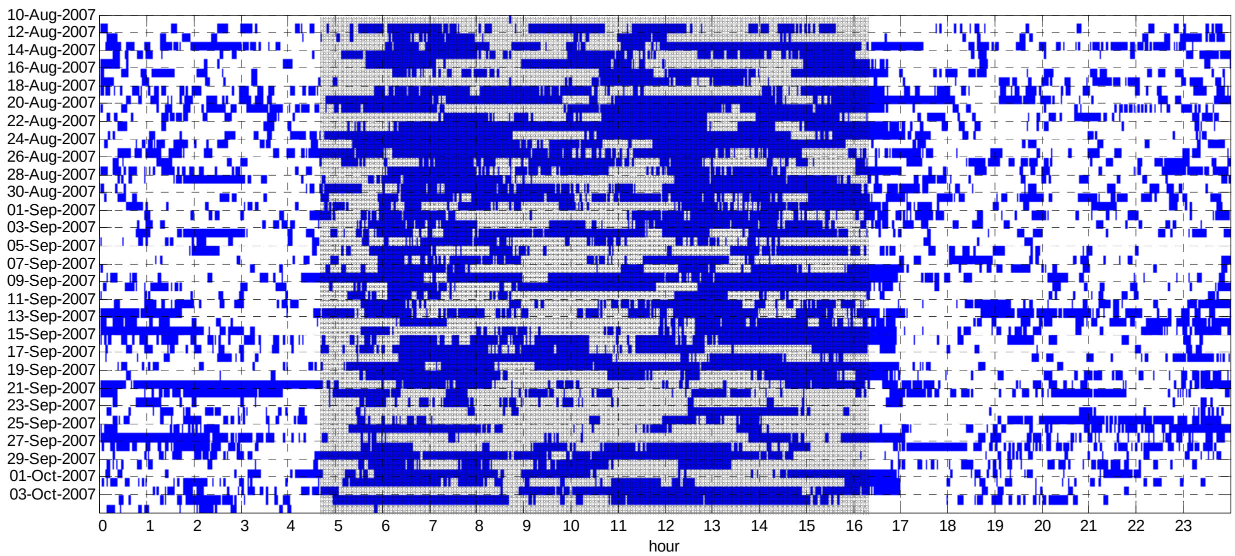
The data automatically analyzed were five deployments of the HARP off the island of Hawaii. The analysis is preliminary, and further evaluation of the outcome will be necessary.

Automatic detections of echolocation clicks of all odontocete species show a higher echolocation activity during nighttime (figure 9). This could be related to a higher foraging activity at night for the two most frequently encountered species of odontocetes in the area, pantropical spotted dolphins and short-finned pilot whales (e.g., Baird *et al.* 2001, 2003). There seems to be an irregularity in the output of the detector, with unexpectedly high numbers of detections starting in Hawaii 02, early June, and all through deployment Hawaii 03 (figure 9B). This irregularity will have to be investigated further. Overall, odontocete echolocation clicks were detected every day of the recording period and during 79 to 96% of hourly bins (Table 4). On average, only deployments Hawaii 01, 05 and 06 taken into account, there were 87% of all hours with detections of echolocation activity.

Beaked whale echolocation pulses were automatically detected throughout the entire recording period (figure 10). Detection rates ranged between 42 and 86% of days with detections and 3 to 9% of hours with detections (Table 4). On average, they were acoustically detectable during 55% of days and 5 % of hourly bins. In most cases beaked whales were detected on one day and not on the next (figure 11). On fewer occasions, between 2 and 19 days of consecutive detections were noted. There did not seem to be a dominant preferred time of the day for vocalizations (figure 12), not surprising, given the lack of diel pattern in deep foraging dives documented for both Cuvier's and Blainville's beaked whales in the area (Baird *et al.* 2008c), and the similar uses of water depths during the day and night by Blainville's beaked whales (Schorr *et al.* 2009a). Only during the very active beaked whale deployment Hawaii 01 was a preference for nighttime activity notable. Echolocation activity appears to be particularly low at the hours of dusk and dawn. In future analysis the beaked whale detections should be investigated more closely to species level. Possibly one species was dominating the detections in Hawaii 01 and showed a preference for vocal activity during a certain time of the day.

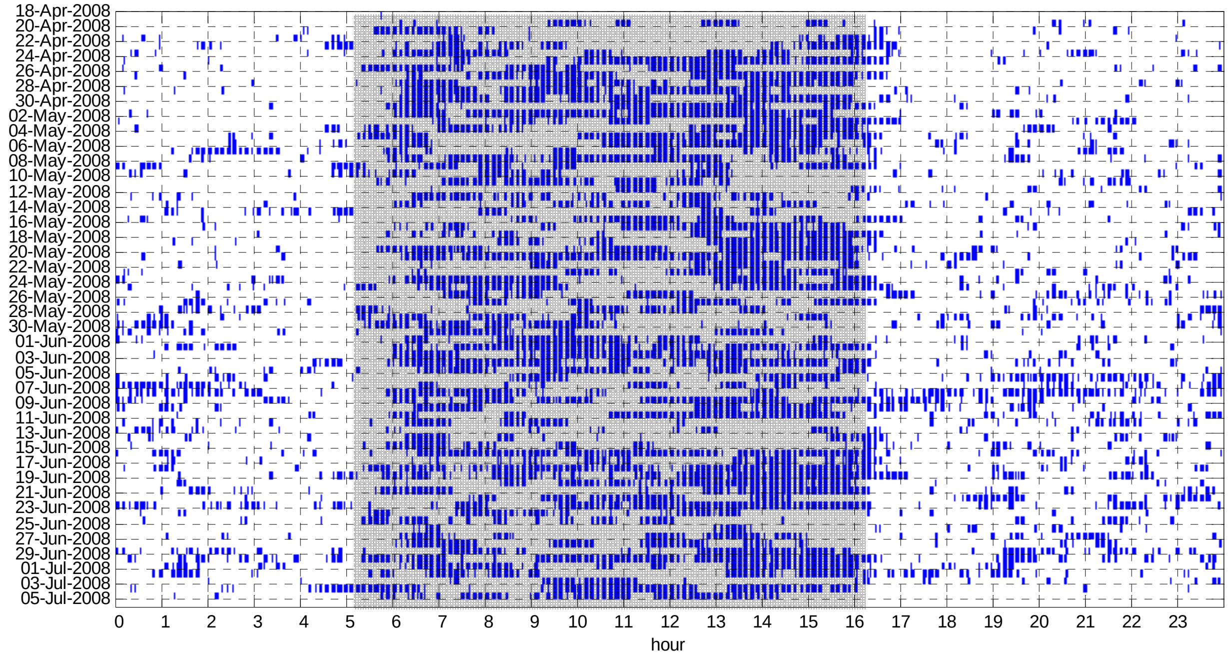
Table 4: **Automatic detections of echolocation clicks of all odontocetes and beaked whale pulses during five HARP deployments.**

	# hour bins	percent	# day bins	percent
Odontocete detections				
Hawaii 01	1139	87.5%	55	100.0%
Hawaii 02	1455	79.4%	77	100.0%
Hawaii 03	2396	100.0%	100	100.0%
Hawaii 05	628	96.0%	28	100.0%
Hawaii 06	2349	83.4%	118	100.0%
Total (only HI01+05+06)	4116	86.7%	201	100.0%
Beaked whale detections				
Hawaii 01	114	8.8%	47	85.5%
Hawaii 02	95	5.2%	48	62.3%
Hawaii 03	81	3.4%	42	42.0%
Hawaii 05	29	4.4%	15	53.6%
Hawaii 06	107	3.8%	54	45.8%
Total	426	4.7%	206	54.5%

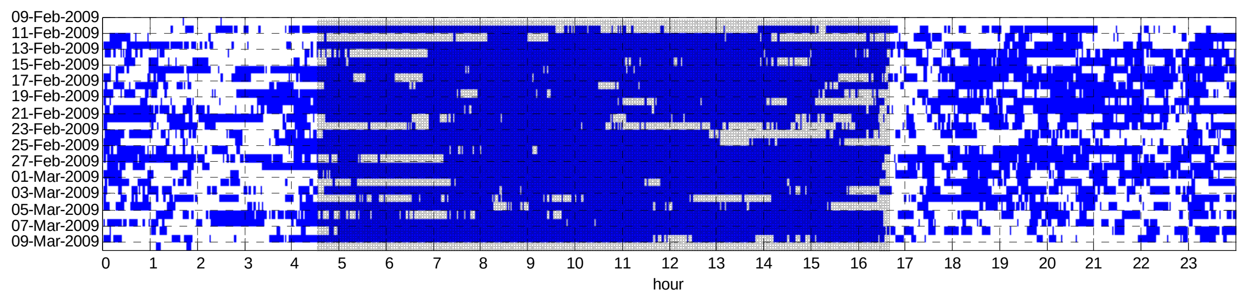


A: Odontocete spp. Hawaii 01, duty cycle continuous

Figure 9: **Automatic detections of echolocation clicks of all odontocete species during deployment A) Hawaii 01, B) Hawaii 02, C) Hawaii 05, and D) Hawaii 06. Time is given in GMT, local approximate nighttime indicated with gray background. Duty cycle is shown as recording time/recording interval in minutes.**

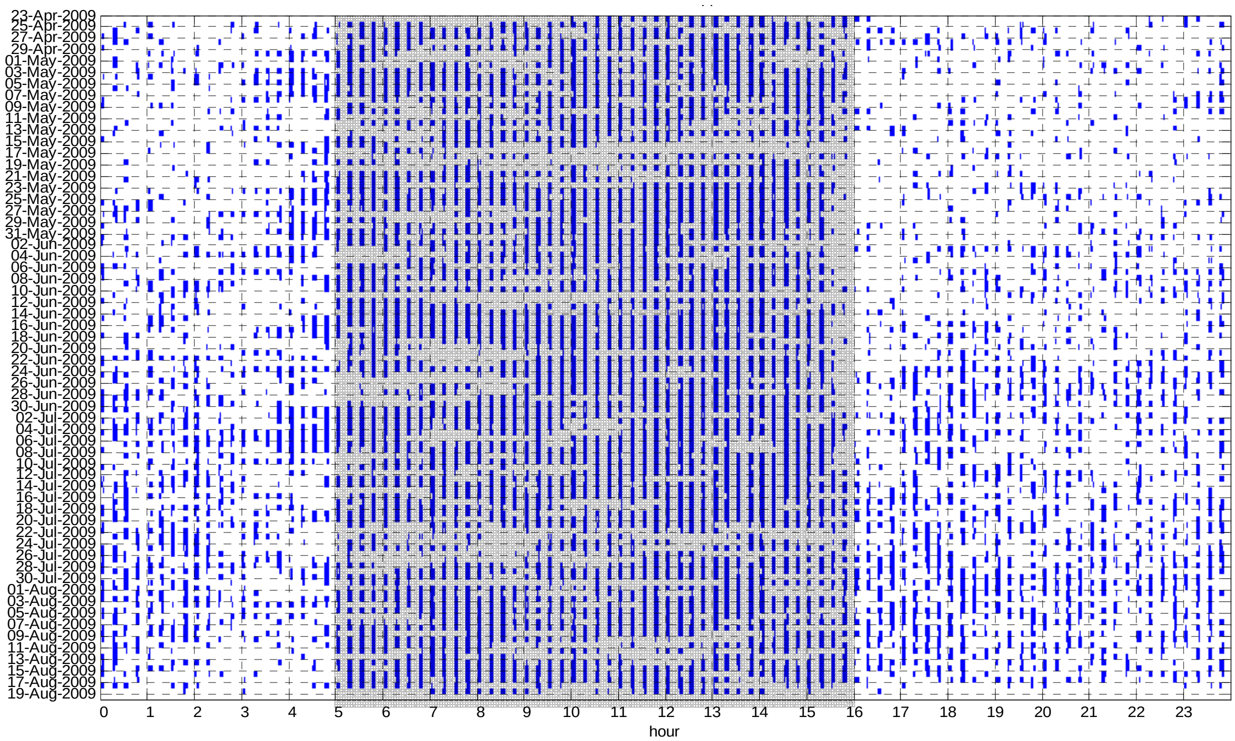


B: Odontocete spp. Hawaii 02, duty cycle 5/8



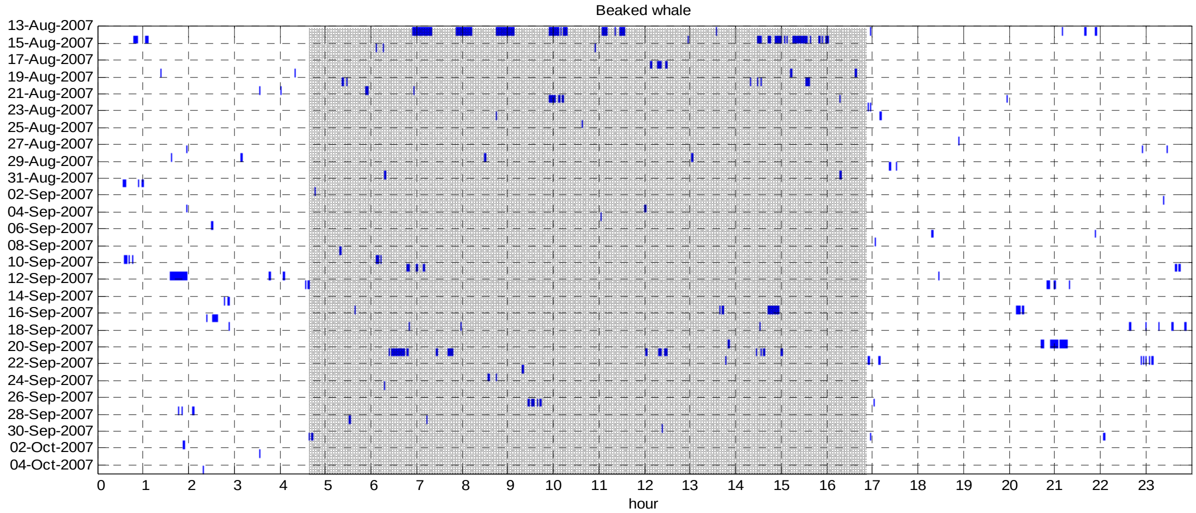
C: Odontocete spp. Hawaii 05, duty cycle continuous

Figure 9 continued: **Automatic detections of echolocation clicks of all odontocete species during deployment A) Hawaii 01, B) Hawaii 02, C) Hawaii 05, and D) Hawaii 06. Time is given in GMT, local approximate nighttime indicated with gray background. Duty cycle is shown as recording time/recording interval in minutes.**

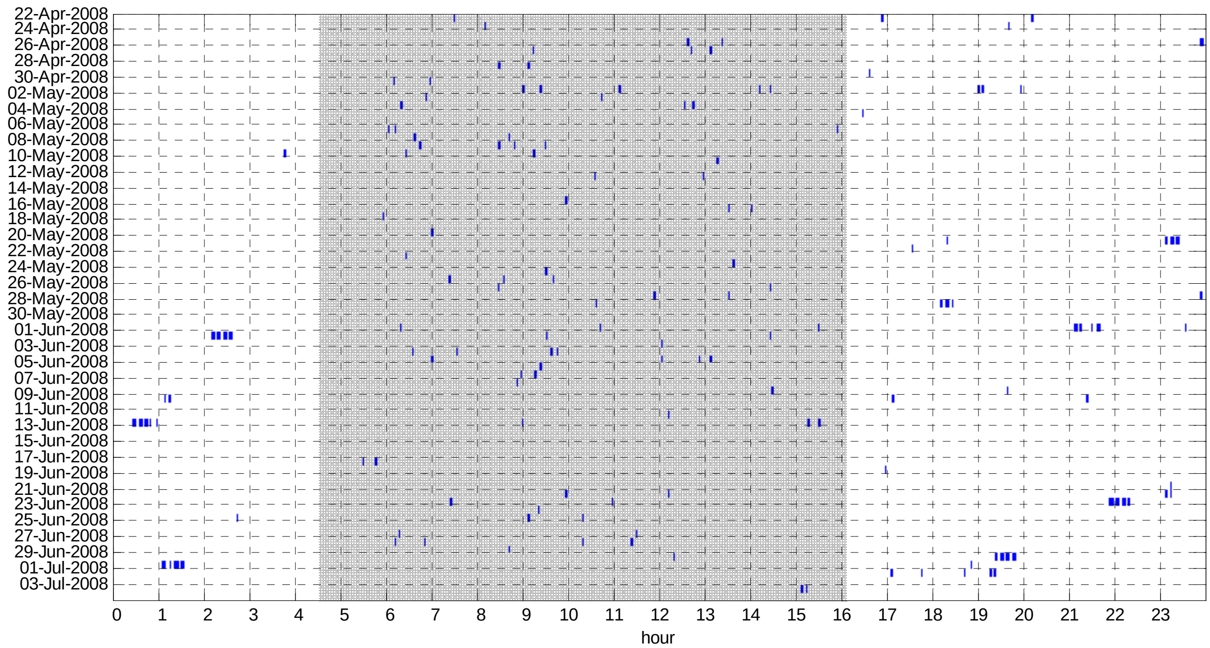


D: Odontocete spp. Hawaii 06, duty cycle 5/15

<u>Figure 9 continued:</u> Automatic detections of echolocation clicks of all odontocete species during deployment A) Hawaii 01, B) Hawaii 02, C) Hawaii 05, and D) Hawaii 06. Time is given in GMT, local approximate nighttime indicated with gray background. Duty cycle is shown as recording time/recording interval in minutes.

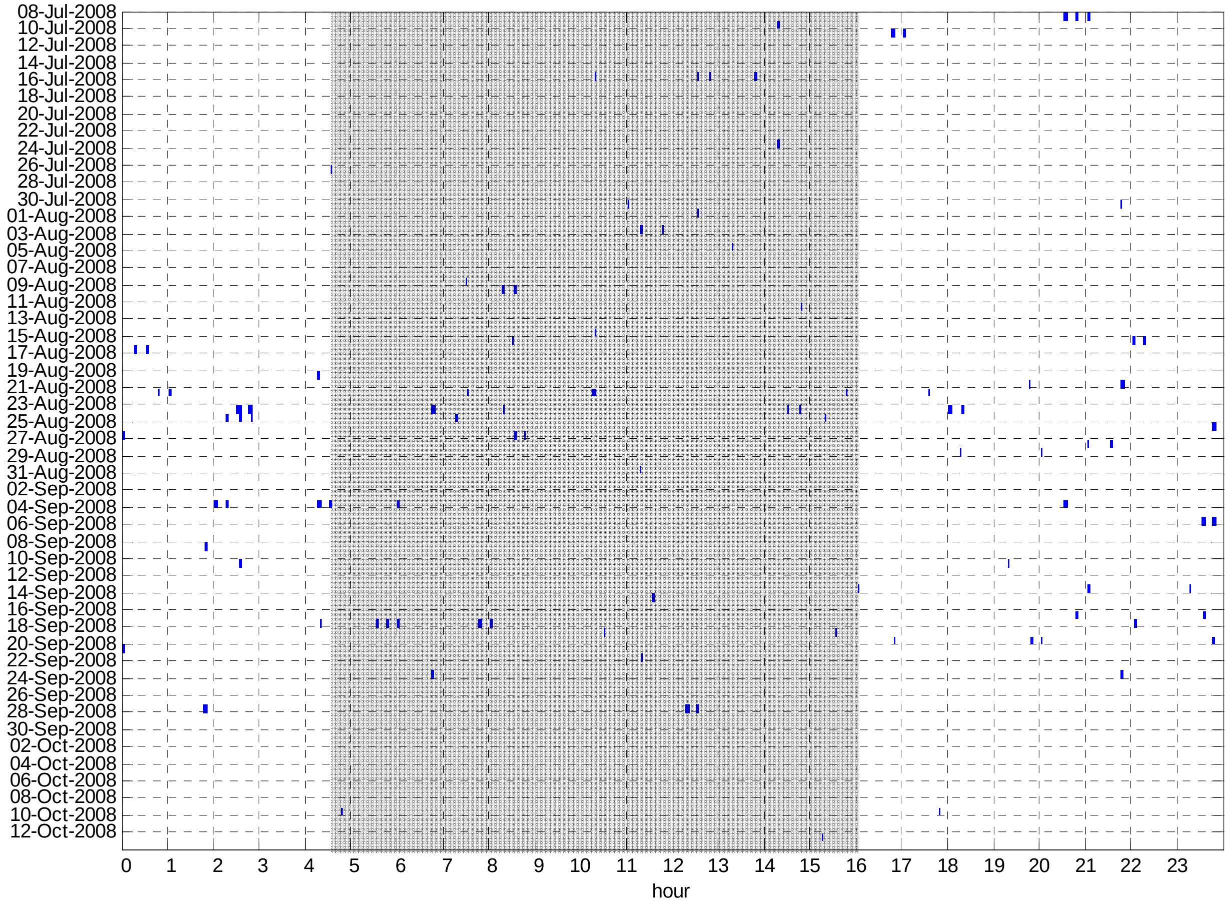


A: Beaked whale Hawaii 01, duty cycle continuous

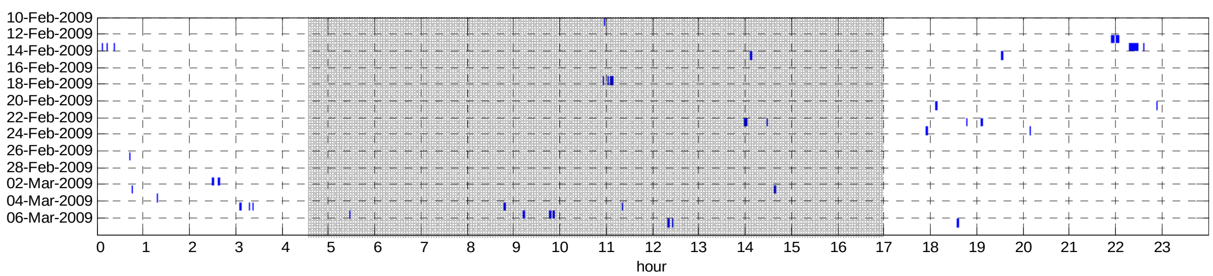


B: Beaked whale Hawaii 02, duty cycle 5/8

<u>Figure 10:</u> Automatic detections of beaked whale echolocation pulses during deployment A) Hawaii 01, B) Hawaii 02, C) Hawaii 03, D) Hawaii 05, and E) Hawaii 06. Time is given in GMT, local approximate nighttime indicated with gray background. Duty cycle is shown as recording time/recording interval in minutes.

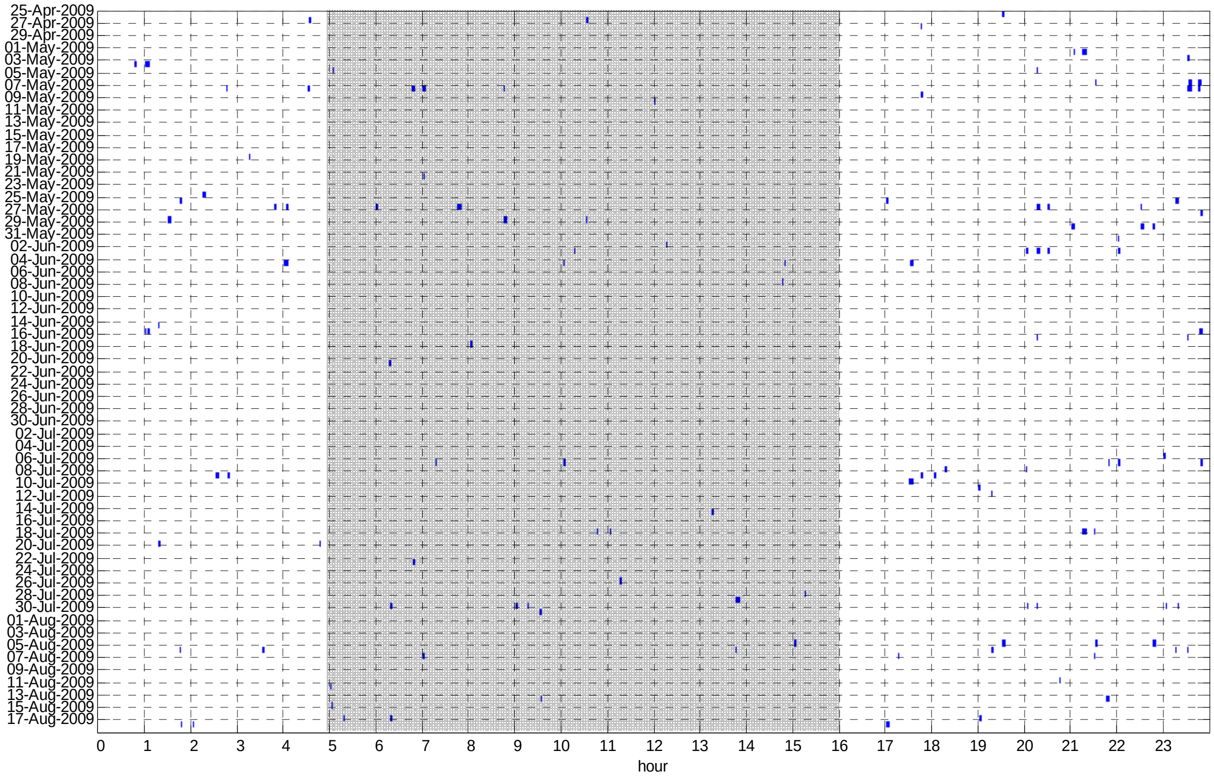


C: Beaked whale Hawaii 03, duty cycle 5/15



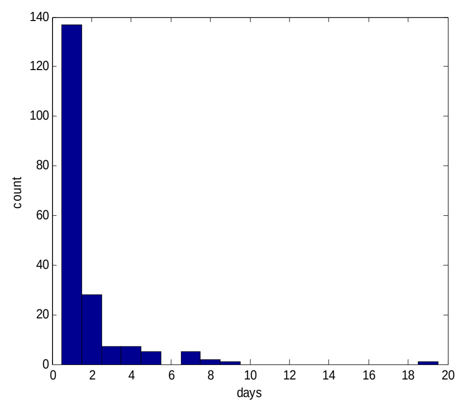
D: Beaked whale Hawaii 05, duty cycle continuous

<u>Figure 10 continued:</u> Automatic detections of beaked whale echolocation pulses during deployment A) Hawaii 01, B) Hawaii 02, C) Hawaii 03, D) Hawaii 05, and E) Hawaii 06. Time is given in GMT, local approximate nighttime indicated with gray background. Duty cycle is shown as recording time/recording interval in minutes.

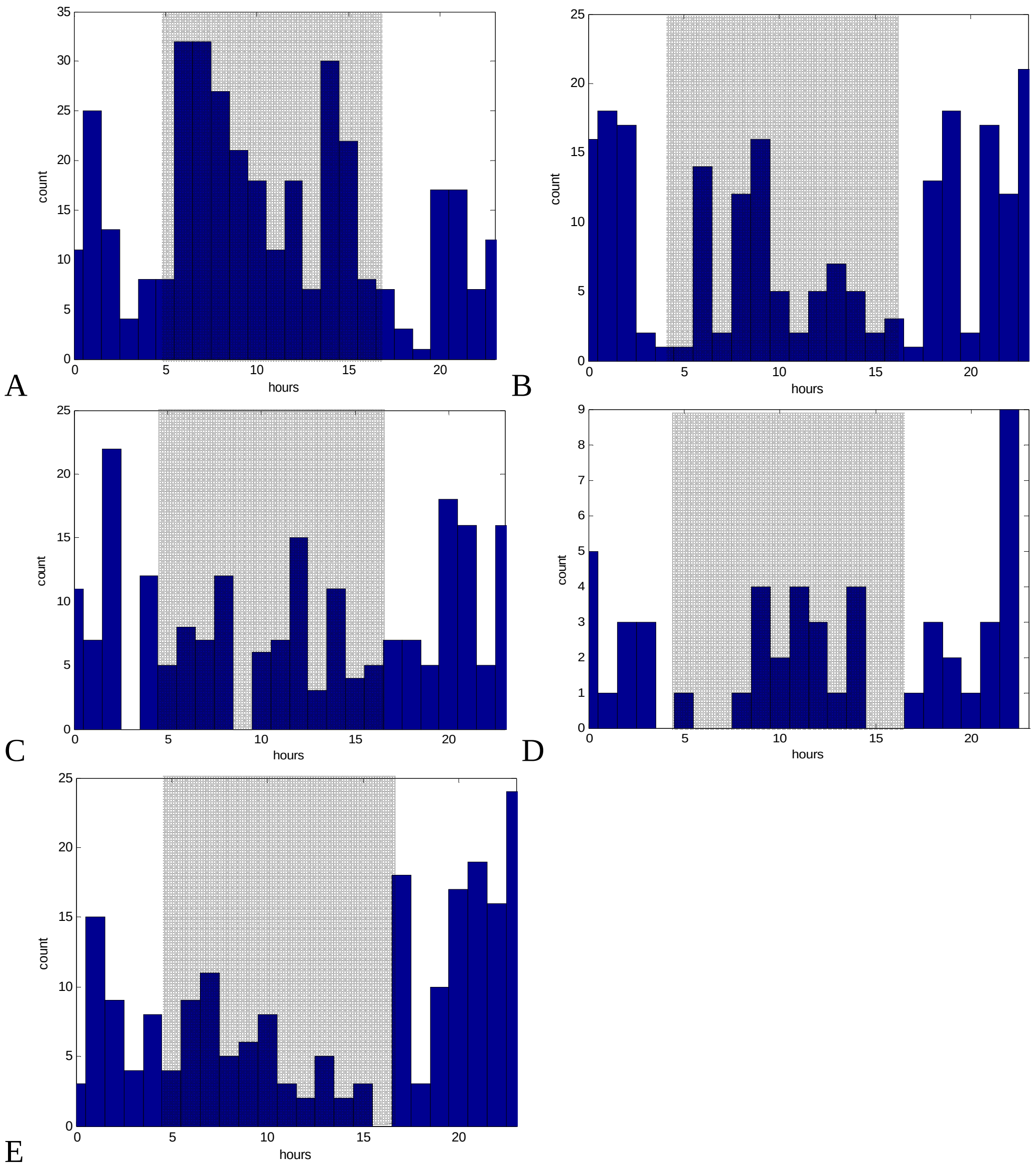


E: Beaked whale Hawaii 06, duty cycle 5/15

<u>Figure 10 continued:</u> Automatic detections of beaked whale echolocation pulses during deployment A) Hawaii 01, B) Hawaii 02, C) Hawaii 03, D) Hawaii 05, and E) Hawaii 06. Time is given in GMT, local approximate nighttime indicated with gray background. Duty cycle is shown as recording time/recording interval in minutes.



<u>Figure 11:</u> Distribution of number of consecutive days with beaked whale detections



<u>Figure 12:</u> Distribution of automatic detections of beaked whale echolocation pulses versus time of day during deployment A) Hawaii 01, B) Hawaii 02, C) Hawaii 03, D) Hawaii 05, and E) Hawaii 06. Counts are 75-s segments with beaked whale pulses. Time is given in GMT, local approximate nighttime indicated with gray background.

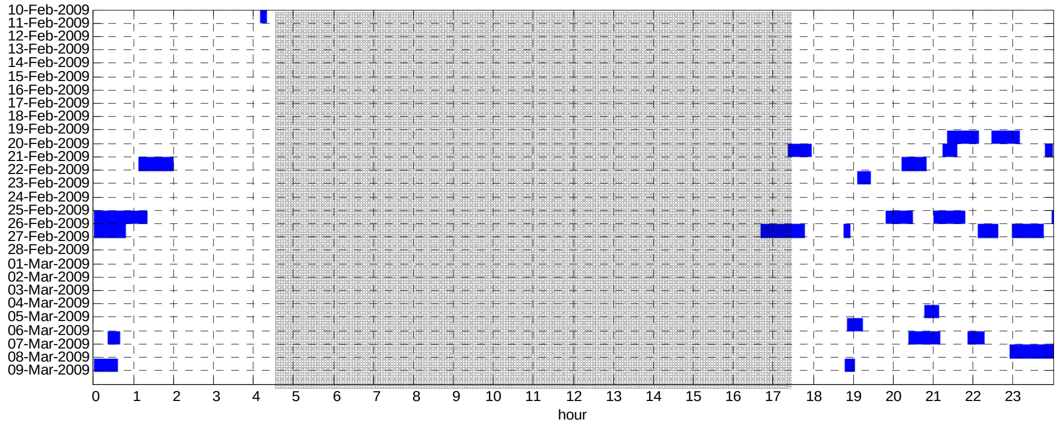
III) Classification and characterization of anthropogenic noise

A trained analyst manually screened the HARP data for deployment Hawaii 05 during the time period of February 10, 2009, 0000 hours GMT, until March 9, 2009, 0615 hours GMT. Start and end of an event of human-made noise were logged and assigned to the category of ship (detection of noise caused by the engine) or echosounder.

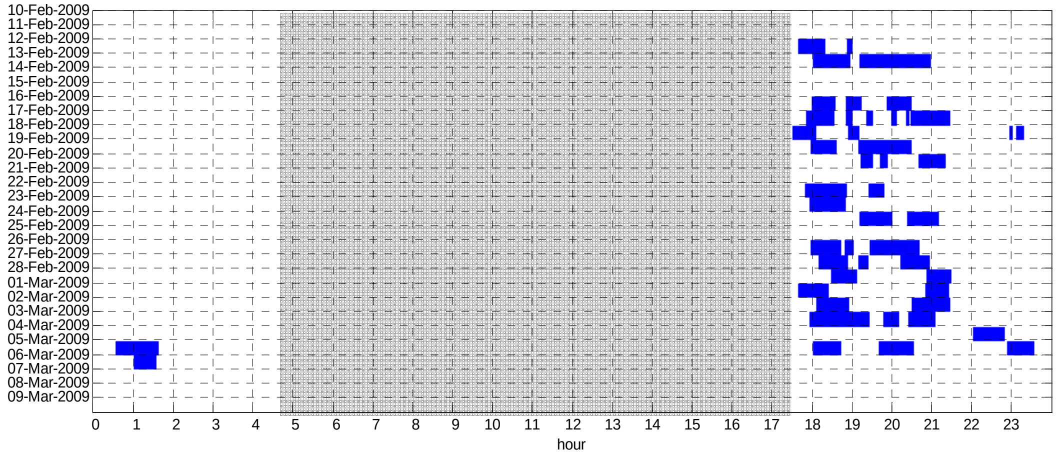
Given the proximity of the HARP to Honokohau and Kailua Harbors, as well as to a Fish Aggregating Device (the “VV” FAD), it is not surprising that ship noise was detected every day of the time period considered (Table 3, figure 13D). The detections encompassed 71% of the total hourly bins analyzed and were mostly present during the day.

The echosounders were manually classified according to their main frequency into seven classes: 25, 28.8, 30, 33, 43, 50 and 80 kHz. The most frequent echosounders were the 50 kHz (covering over 50% of the total time analyzed and present every day, Table 3, figure 13C), the 30 kHz (being present about 15% of the total time, and registered for 70% of the days, Table 3, figure 13B) and the 28.8 kHz (present 6% of the hourly bins and in about 44% of days, Table 3, figure 13A). The 28.8 and 30 kHz echosounders were detected during daytime (figure 13A and 13B), whereas the 50 kHz echosounder was detected throughout the whole day (figure 13C).

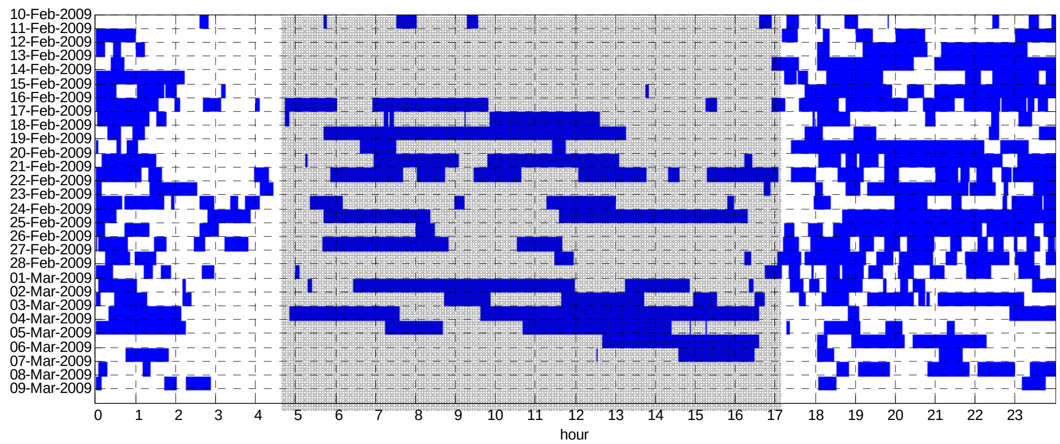
Additionally, power spectral density plots over the frequency range show the contribution in amplitude of every echosounder type to the overall ocean noise (figure 14). In all cases there is a prominent peak at 50 kHz and in most cases another at 30 kHz, which speaks for the considerable contribution of those echosounder types to the overall noise, sometimes more than 10 dB in 80-hour averages.



A: Echosounder 28.8 kHz

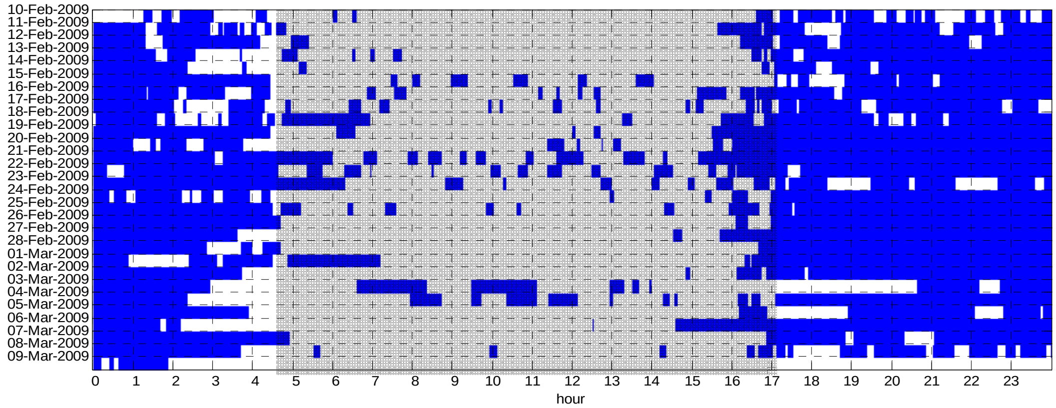


B: Echosounder 30 kHz



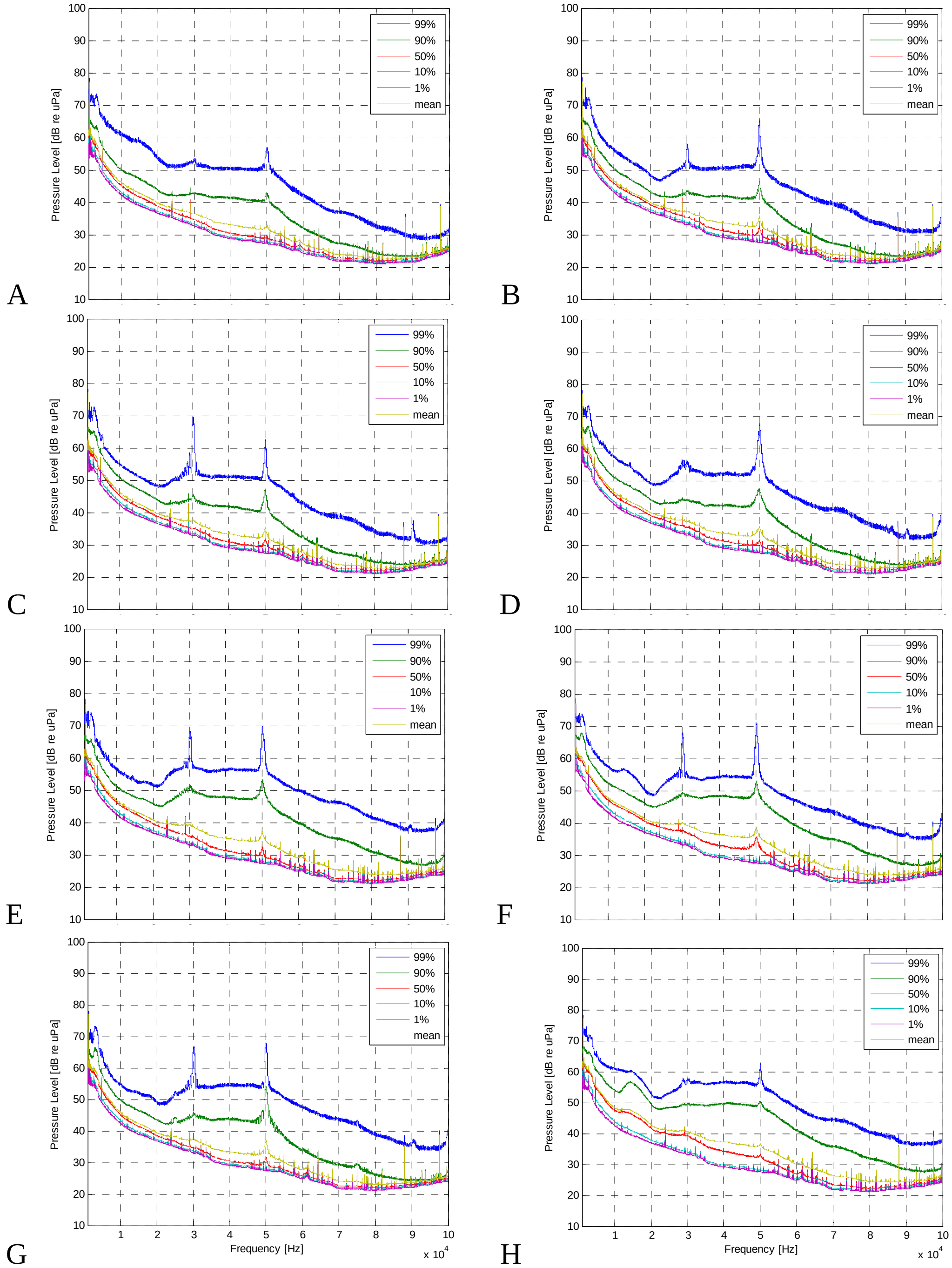
C: Echosounder 50 kHz

<u>Figure 13:</u> Manual detections of anthropogenic noise in Hawaii 05. A) Echosounders with main frequency at 28.8 kHz, B) Echosounders 30 kHz, C) Echosounders 50 kHz, and D) Ship engine noise.



D: Ship engine noise

<u>Figure 13 continued:</u> Manual detections of anthropogenic noise in Hawaii 05. A) Echosounders with main frequency at 28.8 kHz, B) Echosounders 30 kHz, C) Echosounders 50 kHz, and D) Ship engine noise.



<u>Figure 14:</u> Power spectral densities of 80 hours of recordings per plot. Different percentiles are depicted in color. Prominent peaks at 30 and 50 kHz of mainly the 99th and 90th percentile, corresponding to the contribution of echosounders to the overall ocean noise. In the plots C, D, E, F, and G there are smaller peaks at 90 kHz, being side band energy of the 30 kHz echosounder. Data from Hawaii 05 time period A) 2/9/2009, 0140 h – 2/13/2009, 0920 h, B) 2/13/2009, 0921 h – 2/16/2009,1844 h, C) 2/16/2009, 1845 h – 2/20/2009, 0730 h, D) 2/20/2009, 0731 h – 2/23/2009, 1331 h, E) 2/23/2009, 1332 h – 2/26/2009, 2255 h, F) 2/26/2009, 2256 h – 3/2/2009, 0819 h, G) 3/2/2009, 0820 h – 3/5/2009, 1742 h, and H) 3/5/2009, 1743 h – 3/9/2009, 0306 h.

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