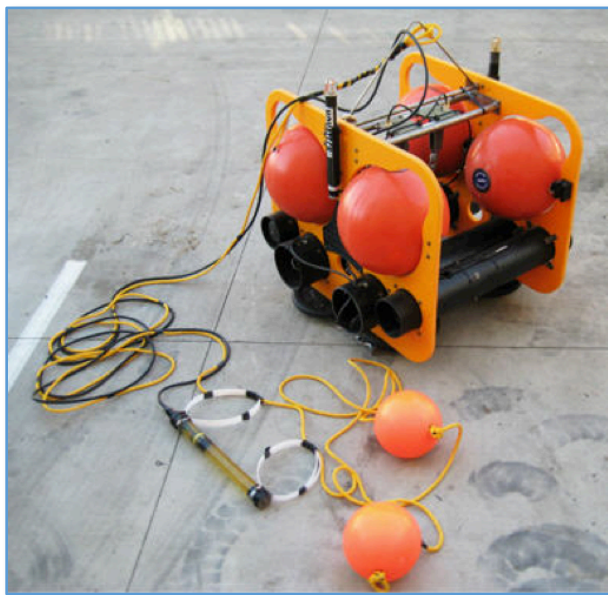


Summary of Marine Mammal Passive Acoustic Monitoring for the Atlantic Fleet using High-frequency Acoustic Recording Packages: 2017 Annual Report

John A. Hildebrand, Kaitlin E. Frasier, Jennifer S. Trickey, Bruce J. Thayre,
Macey Rafter, Sean M. Wiggins, and Simone Baumann-Pickering

Marine Physical Laboratory, Scripps Institution of Oceanography
University of California San Diego, La Jolla, CA 92037



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Individual technical reports and detailed analyses of HARP deployments are available through the Navy's Marine Species Monitoring Program web portal [PAM Deployment Explorer](#) and [Reading Room](#).

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High-frequency Acoustic Recording Package. Photo by Scripps Institution of Oceanography (accessed at <http://www.nefsc.noaa.gov/psb/acoustics/psbAcousticsMigration.html>)

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Executive Summary

Passive acoustic monitoring was conducted using High-frequency Acoustic Recording Packages (HARPs) deployed in waters offshore of Virginia, North Carolina, and Florida with support from the US Navy during 2016 - 2017. The HARPs recorded underwater sounds between 10 Hz and 100 kHz. Data analysis consisted of analyst scans of long-term spectral averages (LTSAs) and spectrograms, and automated computer algorithm detection when possible. Three frequency bands were analyzed for marine mammal vocalizations and anthropogenic sounds: (1) Low-frequency, between 10-1000 Hz, (2) Mid-frequency, between 1,000-5,000 Hz, and (3) High-frequency, between 1-100 kHz.

Introduction and Background

In 2007 Scripps Institution of Oceanography, in collaboration with Duke University, initiated a passive acoustic monitoring effort offshore of the northeast United States, in the Western Atlantic (WAT) with support from the U.S. Fleet Forces Command under the Navy's Marine Species Monitoring Program. The goal of this effort was to characterize vocalizations of marine mammal species recorded in the area and to determine their patterns of seasonal presence. This report describes recent High-frequency Recording Package (HARP) deployments and the analysis of sounds undertaken at three sites: Norfolk Canyon (NFC), Cape Hatteras (HAT), and Jacksonville Florida (JAX) (**Figure 1**).

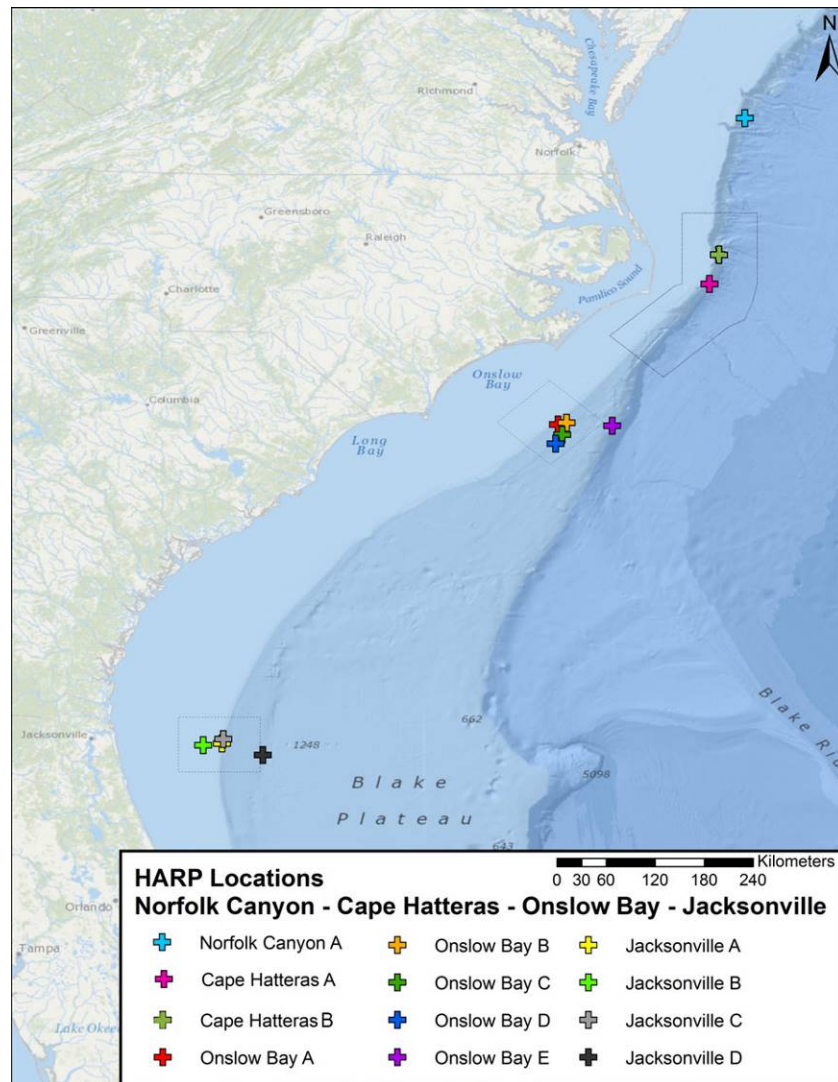


Figure 1. Location of High-frequency Acoustic Recording Package deployments (HARPs) at sites in Norfolk Canyon, Cape Hatteras, Onslow Bay, and Jacksonville Florida.

Methods

High-frequency Acoustic Recording Packages

HARPs are autonomous underwater acoustic recording devices that record sounds over a bandwidth from 10 Hz up to 160 kHz and that are capable of approximately one year of continuous recording. The HARPs deployed at NFC, HAT, and JAX during 2016-17 were in medium-sized mooring configurations with the hydrophones suspended approximately 20 m above the seafloor. Each HARP hydrophone was calibrated in the laboratory to provide frequency-dependent sound pressure receive level sensitivity. Representative data loggers and hydrophones were also calibrated at the Navy's TRANSDEC facility to verify the laboratory calibrations. HARP deployment conducted during 2016-2017 consisted of two configurations: (1) single-hydrophone compact moorings (**Figure 2**) and (2) four-hydrophone arrays (**Figure 3**).

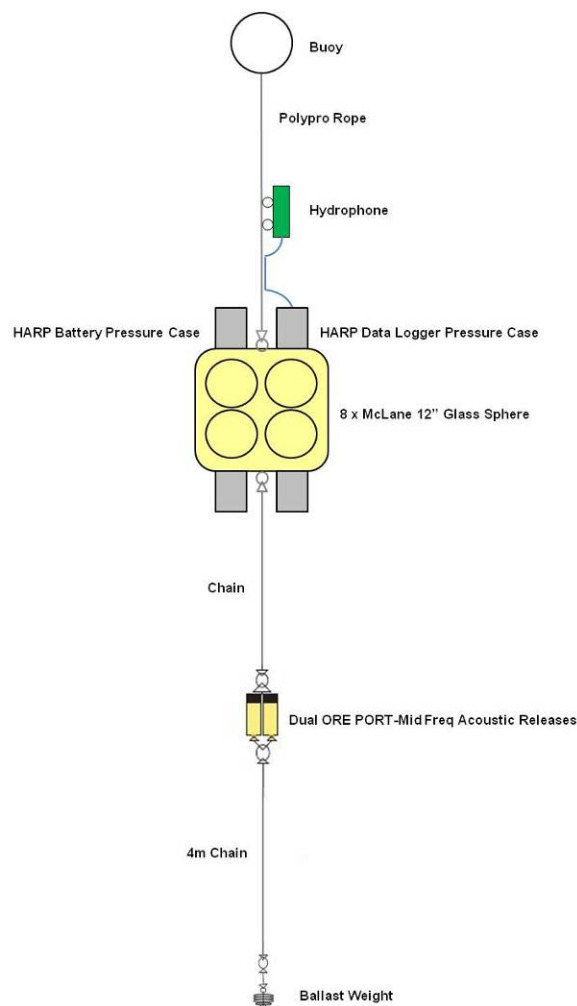


Figure 2. Schematic diagram showing details of a compact small mooring HARP. Note that diagram is not drawn to scale.

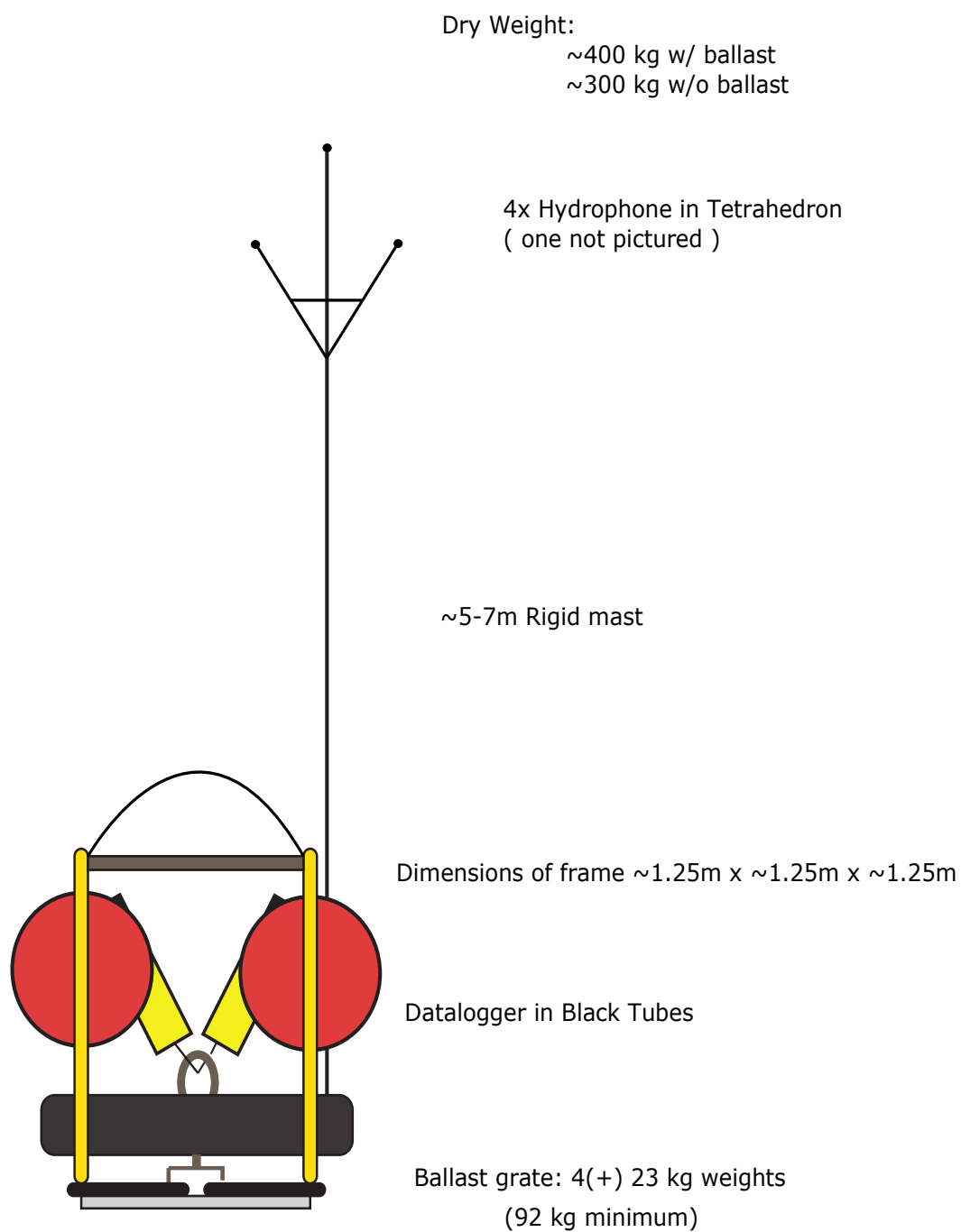


Figure 3 Schematic diagram showing details of a multi-channel HARP using a seafloor package. Note that diagram is not drawn to scale.

Data Collection

At Norfolk Canyon, the NFC02A HARP was deployed from April 2016 to June 2017, recording continuously for 424 days. Subsequently, NFC03A HARP was deployed in June 2017 and is planned for recovery in summer 2018. A summary of previous and current HARP deployments at Norfolk Canyon are given in **Table 1**.

At Cape Hatteras, the HAT06A HARP was deployed in April 2016 and recorded until February 2017, collecting 283 days of data. In May 2017, the location for HARP deployments at Cape Hatteras was moved approximately 17 nm to the northeast (designated site B) to better coordinate with the location for a planned Behavioral Response Studie (BRS) beginning in 2017 ([Southall et. al, 2018](#)). An array of three HARPs, consisting of one single-hydrophone instrument and two four-hydrophone instruments, were deployed at Cape Hatteras site B on 9 May 2017. The HAT01B single-hydrophone instrument was on station until 25 October 2017 and recorded 169 days of data. The two four-hydrophone instruments were recovered on 28 June 2017 and each recorded 50 days of data. The combination of these three instruments provide sufficient array coverage for tracking individual cetaceans, analysis of this data will be directed at the tracking of beaked whales in coordination with BRS controlled exposure experiments. The precise position of these instruments was determined by acoustic ranging to them from a surface vessel, while the vessel's position was determined from GPS satellite navigation. The uncertainty of their final positions was 7 – 22 m. A second array deployment was attempted on 29 June 2017, when the two four-channel instruments were recovered and redeployed with fresh batteries. Although both instrument were deployed successfully, after approximately a month the HAT_B#2-4C-02 instrument began transmitting with its ARGOS satellite transmitter at the surface, from a location in the central north Atlantic (33N 43W). Apparently, it prematurely released its anchor weight and after returning to the surface drifted eastward in the Gulf Stream current. It is unclear why the ARGOS transmitter did not send positions until the instrument was at considerable distance from shore, making recovery difficult. The instrument continues to transmit at this date (February 2018), remaining roughly stationary in the central north Atlantic gyre. HARP deployments at Cape Hatteras are given in **Table 2**.

Table 1. Previous and current HARP deployments at Norfolk Canyon. Currently deployed instrument highlighted in red.

NORFOLK CANYON												
Location	Deployment ID	Latitude	Longitude	Depth (m)	Deployment Date	Retrieval Date	Recording Start Date	Recording End Date	Duty Cycle (min on/off)	Mooring Type	Status of Analysis	Reports
Norfolk Canyon A	NFC01A	37.1662	-74.4669	982	19JUN14	07APR15	19JUN14	05APR15	continuous	compact	HF, LF	S , D
Norfolk Canyon A	NFC02A	37.1652	-74.4666	968	30APR16	30JUN17	30APR16	28JUN17	continuous	compact	In progress	
Norfolk Canyon A	NFC03A	37.1674	-74.4663	950	29JUN17		29JUN17		continuous	compact		

Table 2. Previous and current HARP deployments at Cape Hatteras. Currently deployed instrument highlighted in red.

CAPE HATTERAS												
Location	Deployment ID	Latitude	Longitude	Depth (m)	Deployment Date	Retrieval Date	Recording Start Date	Recording End Date	Duty Cycle (min on/off)	Mooring Type	Status of Analysis	Reports
Cape Hatteras A	HAT01A	35.3405	-74.8576	950	15MAR12	09OCT12	15MAR12	11APR12	continuous	large	HF, LF	S
Cape Hatteras A	HAT02A	35.3406	-74.8559	970	09OCT12	29MAY13	09OCT12	09MAY13	continuous	large	HF, LF	S , D
Cape Hatteras A	HAT03A	35.3444	-74.8521	970	29MAY13	8MAY14	29MAY13	15MAR14	continuous	large	HF, LF	S , D
Cape Hatteras A	HAT04A	35.3468	-74.8481	850	08MAY14	06APR15	9MAY14	11DEC14	continuous	large	HF, LF	S , D
Cape Hatteras A	HAT05A	35.3422	-74.8573	980	06APR15	29APR16	07APR15	21JAN16	continuous	compact	HF, LF	S , D
Cape Hatteras A	HAT06A	35.3057	-74.8776	1020	29APR16	9MAY17	29APR16	6FEB17	continuous	compact	In progress	
Cape Hatteras B	HAT-B#1-1C-01	35.5837	-74.7492	1118	9MAY17	25OCT17	9MAY17	25OCT17	continuous	compact	In progress	
Cape Hatteras B	HAT-B#2-4C-01	35.5797	-74.7559	1111	9MAY17	28JUN17	9MAY17	28JUN17	continuous	4-channel	In progress	
Cape Hatteras B	HAT-B#3-4C-01	35.5865	-74.7560	1095	9MAY17	28JUN17	9MAY17	28JUN17	continuous	4-channel	In progress	
Cape Hatteras B	HAT-B#2-4C-02	35.5793	-74.7569	1040	28JUN17	Lost-at-sea	28JUN17	N/A	continuous	4-channel	N/A	
Cape Hatteras B	HAT-B#3-4C-02	35.5861	-74.7558	1190	28JUN17	25OCT17	28JUN17	25OCT17	continuous	4-channel	In progress	
Cape Hatteras B	HAT-B#1-1C-02	35.5835	-74.7431	1117	25OCT17		25OCT17		continuous	compact		

Table 3. Previous and current HARP deployments at Jacksonville. Currently deployed instrument highlighted in red.

JACKSONVILLE												
Location	Deployment ID	Latitude	Longitude	Depth (m)	Deployment Date	Retrieval Date	Recording Start Date	Recording End Date	Duty Cycle (min on/off)	Mooring Type	Status of Analysis	Reports
JAX A	JAX01A	30.2771	-80.1258	82	30MAR09	16SEP09	02APR09	25MAY09	5/10	large	HF	S
JAX B	JAX01B	30.2582	-80.4282	37	30MAR09	16SEP09	02APR09	05SEP09	5/10	large	HF, M	S
JAX A	JAX02A	30.2805	-80.2160	83	16SEP09	21FEB10	16SEP09	15DEC09	5/10	large	HF, M	S
JAX B	JAX02B	30.2582	-80.4280	39	23SEP09	21FEB10	No data	No data	5/10	large	N/A	No – no data
JAX A	JAX03A	30.2811	-80.2153	89	21FEB10	26AUG10	22FEB10	30JUL10	5/10	large	HF, M	S
JAX B	JAX04B	30.2592	-80.4257	38	09MAR10	26AUG10	09MAR10	19AUG10	5/10	large	HF, LF	S , D
JAX A	JAX05A	30.2682	-80.2089	91	26AUG10	01FEB11	26AUG10	25JAN11	5/10	large	HF, LF	S , D
JAX B	JAX05B	30.2571	-80.4327	37	26AUG10	01FEB11	27AUG10	01FEB11	5/10	large	HF, LF	S , D
JAX A	JAX06A	30.2782	-80.2208	91	01FEB11	14JUL11	01FEB11	14JUL11	5/10	large	HF, LF	S , D
JAX B	JAX06B	30.2577	-80.4278	37	02FEB11	14JUL11	02FEB11	14JUL11	5/10	large	HF, LF	S , D
JAX A	JAX08A	30.2850	-80.2214	91	24JAN12	abandoned	27JAN12	N/A	continuous	large	N/A	No – no data
JAX C	JAX09C	30.3329	-80.2007	94	12MAY13	17FEB14	13MAY13	20JUN13	continuous	large	HF, LF	S , D
JAX C	JAX10C	30.3264	-80.2049	88	17FEB14	23AUG14	17FEB14	23AUG14	continuous	small	HF, LF	S , D
JAX D	JAX11D	30.1506	-79.7700	806	23AUG14	2JUL15	23AUG14	29MAY15	continuous	small	HF, LF	S , D
JAX D	JAX12D	30.1489	-79.7711	800	02JUL15	26APR16	02JUL15	04NOV15	continuous	small	HF, LF	S , D
JAX D	JAX13D	30.1518	-79.7702	736	26APR16	25JUN17	26APR16	25JUN17	continuous	compact	In progress	
JAX D	JAX14D	30.1527	-79.7699	740	25JUN17		25JUN17		continuous	compact		

Notes: All HARPs sampled at 200 kHz. For Status of Analysis: HF = high-frequency (odontocete, > 1 kHz) analysis completed; LF = low-frequency (mysticete, < 1 kHz) analysis completed; M = low-frequency analysis completed only for minke whale pulse trains. For Reports: S = summary report; D = detailed technical report; Key: m = meter(s).

At Jacksonville, the JAX13D HARP was deployed in April 2016 was recovered in June 2017 having recorded continuously for 425 days. JAX14D was deployed in June 2017 and is planned for recovery in summer 2018. A summary of previous and current HARP deployments at Jacksonville are given in **Table 3**.

Data Analysis

The data analysis process is described in terms of the major classes of marine mammal calls and anthropogenic sounds in the Atlantic region, and the procedures used to detect them. For efficiency, the analysis is divided into three frequency bands: (1) Low-frequency, 10-1,000 Hz (2) Mid-frequency, 1,000-5,000 Hz, and (3) High-frequency, 1-100 kHz.

To visualize the sound recordings, sound pressure level spectra were calculated for all data using a time average of 5 seconds and three frequency bin sizes (1, 10, 100 Hz). These Long-Term Spectral Averages (LTSAs) were visually examined by analysts as a means to detect marine mammal and anthropogenic sounds (Wiggins and Hildebrand, 2007). LTSAs were analyst-scanned in source-specific frequency bands and using automatic detection algorithms (described below). During visual analysis, when a sound of interest was identified but its origin was unclear, the corresponding waveform or spectrogram was examined further to classify the sounds to source (e.g. species and anthropogenic). Signal classification was carried out by comparison to known source-specific spectral and temporal characteristics.

Each band was analyzed for the sounds of an appropriate subset of species or anthropogenic sources. Baleen whales are detected in the low-frequency band. Nearby shipping, explosions, and airguns were categorized as mid-frequency. Echosounders, dolphin clicks, *Kogia* spp., sperm whale clicks, and beaked whale pulses were categorized as high-frequency. For the analysis of mid-frequency recordings, the recordings were decimated by a factor of 20, and for the low-frequency recordings by a factor of 100.

We summarize and characterize sounds that were consistently identified in the acoustic recordings.

Low-Frequency Marine Mammals

The western Atlantic is inhabited, at least for a portion of the year, by blue whales (*Balaenoptera musculus*), fin whales (*B. physalus*), Bryde's whales (*B. edeni*), sei whales (*B. borealis*), minke whales (*B. acutorostrata*), and North Atlantic right whales (*Eubalaena glacialis*). For the low-frequency data analysis, the 200 kHz sampled raw data were decimated by a factor of 100 for an effective bandwidth of 1 kHz. Long-term spectral averages (LTSAs) were created using a time average of 5 seconds and frequency bins of 1 Hz. The same LTSA and spectrogram parameters were used for manual detection of all call types using the custom software program *Triton*. During manual analysis of the data, the LTSA frequency was set to display between 1-300 Hz with a 1-hour plot length. To analyze individual calls, the spectrogram window was typically set to display 1-250 Hz with a 60 second plot length. The FFT length was generally set between

1500 and 2000 data points, yielding about 1 Hz frequency resolution, with an 85-95% overlap using a Hann window. When a call of interest was identified in the LTSA or spectrogram, its presence during that hour was logged.

The hourly presence of North Atlantic blue whale calls, blue whale arch sounds, fin whale 20 and 40 Hz calls, Bryde's whale Be7 and Be9 calls, minke whale pulse trains, and North Atlantic right whale up-calls was determined by manual examination of low-frequency LTSAs and spectrograms.

Blue Whales

Blue whales produce a variety of calls worldwide (McDonald *et al.*, 2006). Blue whale calls recorded in the western North Atlantic include the North Atlantic A–B call and the arch call (Mellinger and Clark, 2003).

Blue Whale North Atlantic Calls

The A-B call is a 17 Hz tone lasting approximately 8 s (A), often followed by an 17-15 Hz downsweep (B) lasting approximately 11 s (**Figure 4**).

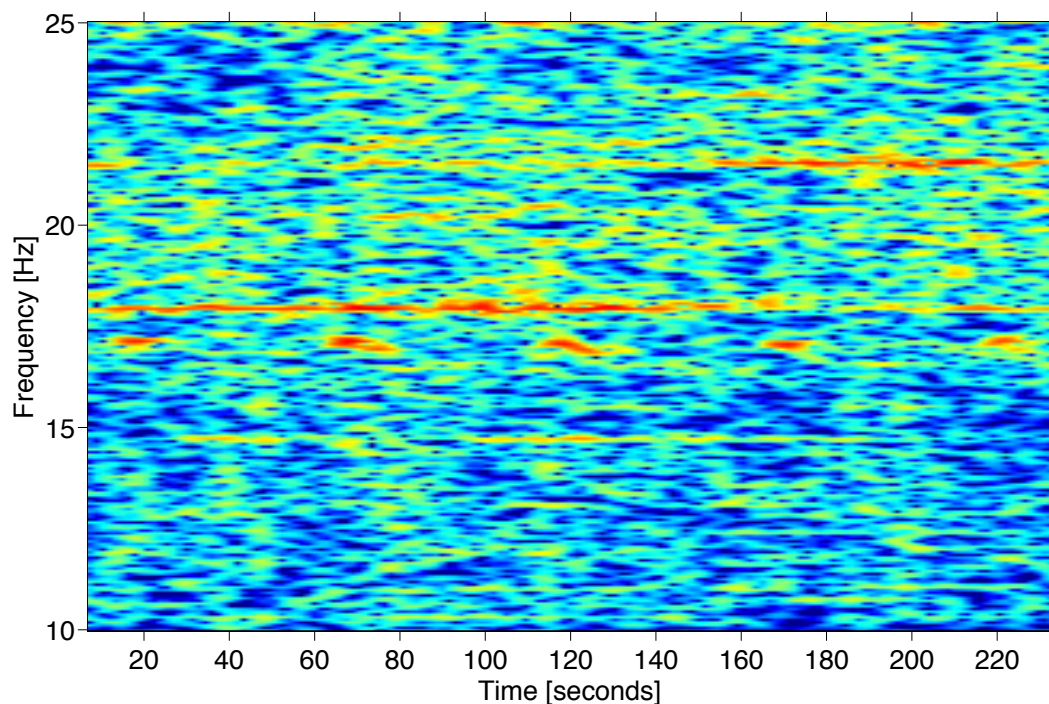


Figure 4. North Atlantic blue whale A and B calls from HAT03A.

Fin Whales

Fin whales produce two types of short (approximately 1 s duration), low-frequency calls: downsweeps in frequency from 30-15 Hz, called 20 Hz calls (Watkins, 1981) (Figure 5), and downsweeps from 75-40 Hz, called 40 Hz calls (Figure 6). The 20 Hz calls can occur at regular intervals as song (Thompson *et al.*, 1992), or irregularly as call counter-calls among multiple, traveling animals (McDonald *et al.*, 1995). The 40 Hz calls most often occur in irregular patterns.

Fin whale 20 Hz calls

Fin whale 20 Hz calls (**Figure 5**) were detected via manual scanning of the LTSA and subsequent verification from a spectrogram of the frequency and temporal characteristics of the calls. Although an automated detection algorithm was used for previous datasets (Hatteras 02A, 03A, 04A and Norfolk Canyon 01A) to calculate an acoustic index for fin whale 20 Hz calls. The automated detector was not used due to the presence of high amounts of low frequency noise in the LTSA, which may have masked calls and made them difficult to detect automatically.

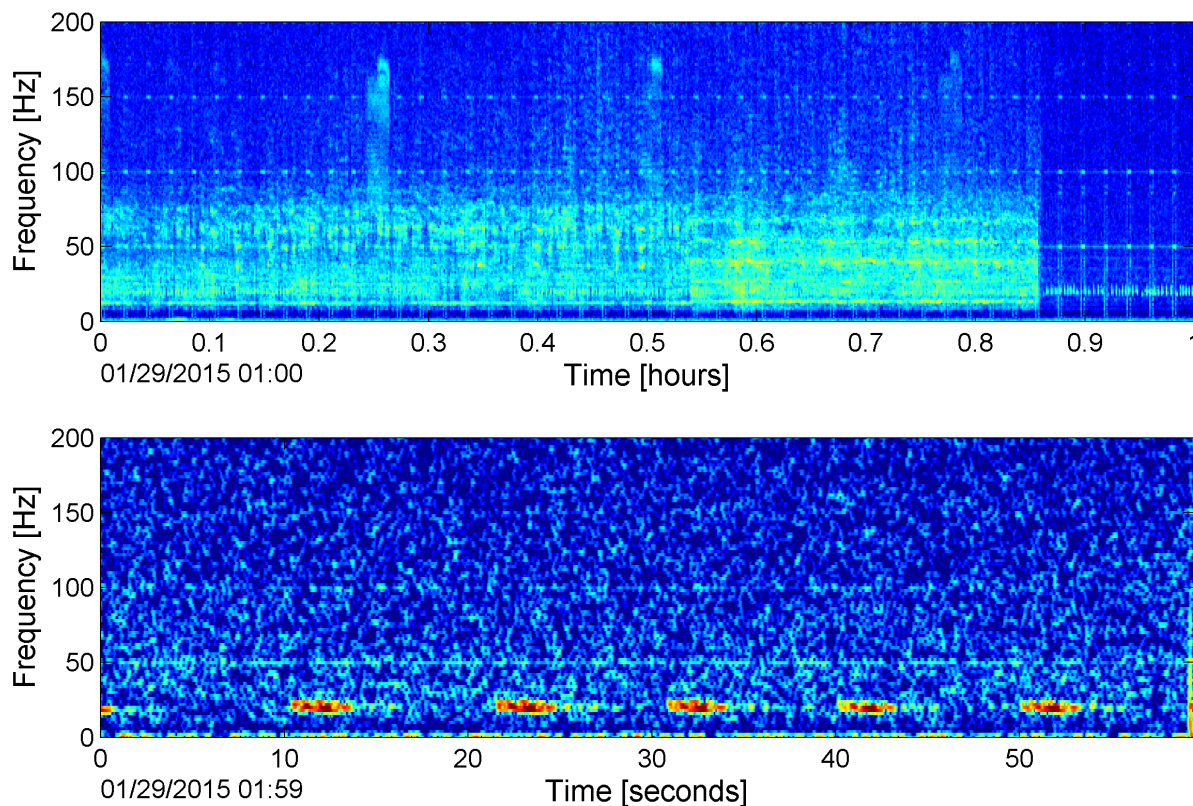


Figure 5. Fin whale 20 Hz calls in LTSA (top) and spectrogram (bottom) at JAX site D.

Fin whale 40 Hz calls

The potential presence of fin whale 40 Hz calls (**Figure 6**) was examined via manual scanning of the LTSA and subsequent verification from a spectrogram of the frequency and temporal characteristics of the calls.

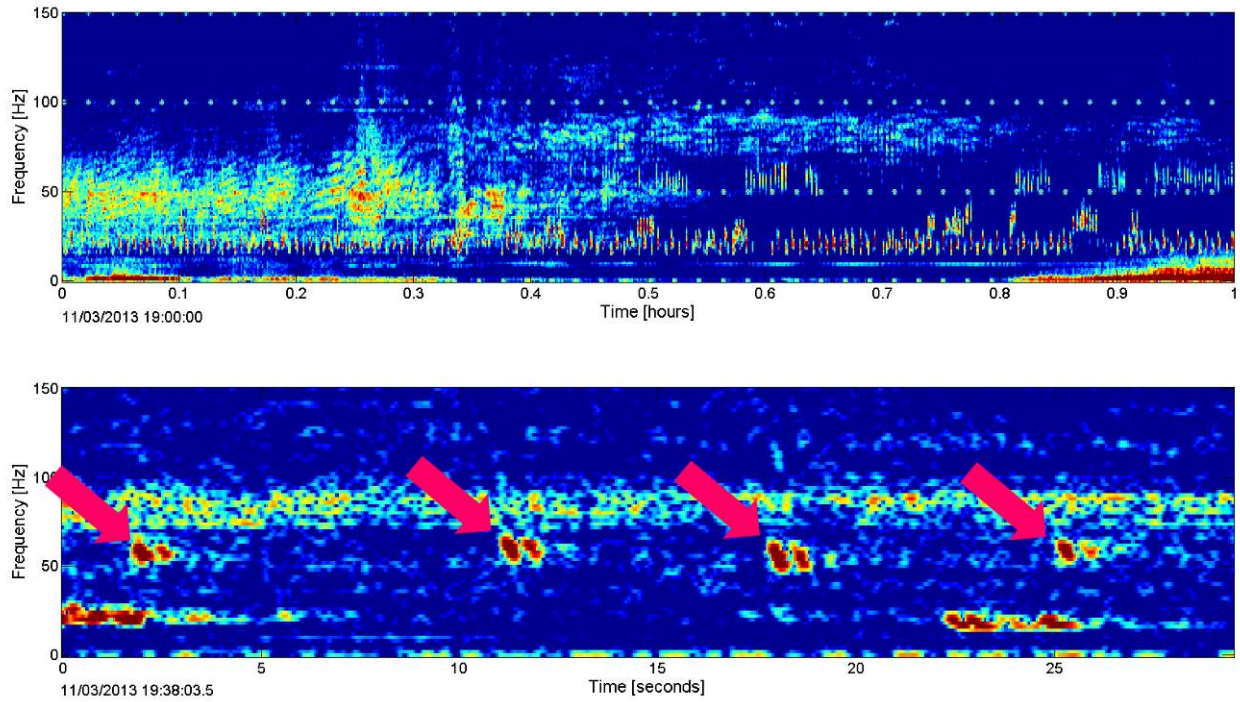


Figure 6. Fin whale 40 Hz calls in LTSA (top) and spectrogram (bottom) from southern California HARP data.

Bryde's Whales

Bryde's whales inhabit tropical and subtropical waters worldwide (Omura, 1959; Wade and Gerrodette, 1993), and the JAX site is considered to be near their northerly range limit.

Be 7 Calls

The Be7 call is one of several call types in the Bryde's whale repertoire, first described in the Southern Caribbean (Oleson *et al.*, 2003). The average Be7 call has a fundamental frequency of 44 Hz and ranges in duration between 0.8 and 2.5 s with an average inter-call interval of 2.8 minutes (**Figure 7**).

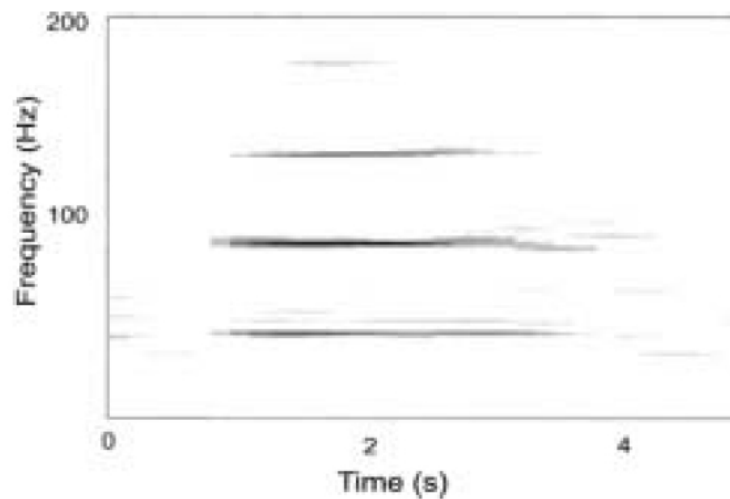


Figure 7. Bryde's whale Be7 call from Oleson *et al.*, 2003.

Be9 Calls

The Be9 call type, described for the Gulf of Mexico, is a downswept pulse ranging from 110 to 75 Hz, with each pulse approximately 0.7 s long (**Figure 8**).

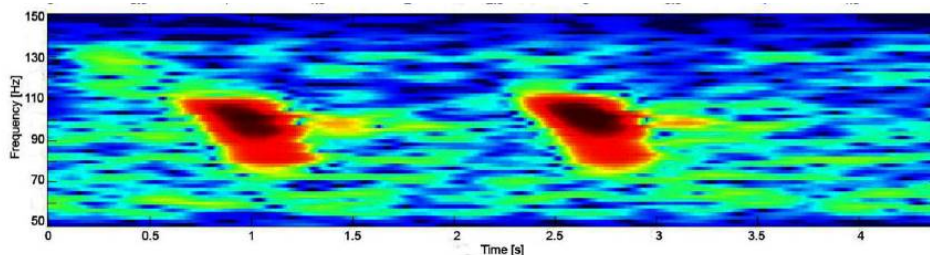


Figure 8. Bryde's whale Be9 call from the Gulf of Mexico (Širović *et al.*, 2014).

Sei Whales

Sei whales are found primarily in temperate waters and undergo annual migrations between lower latitude winter breeding grounds and higher latitude summer feeding grounds (Mizroch *et al.*, 1984; Perry *et al.*, 1999). Multiple sounds have been attributed to sei whales, including a low-frequency downsweep (Baumgartner and Fratantoni, 2008; Baumgartner *et al.*, 2008). These calls typically sweep from a starting frequency around 100 Hz to an ending frequency around 25 Hz (**Figure 9**).

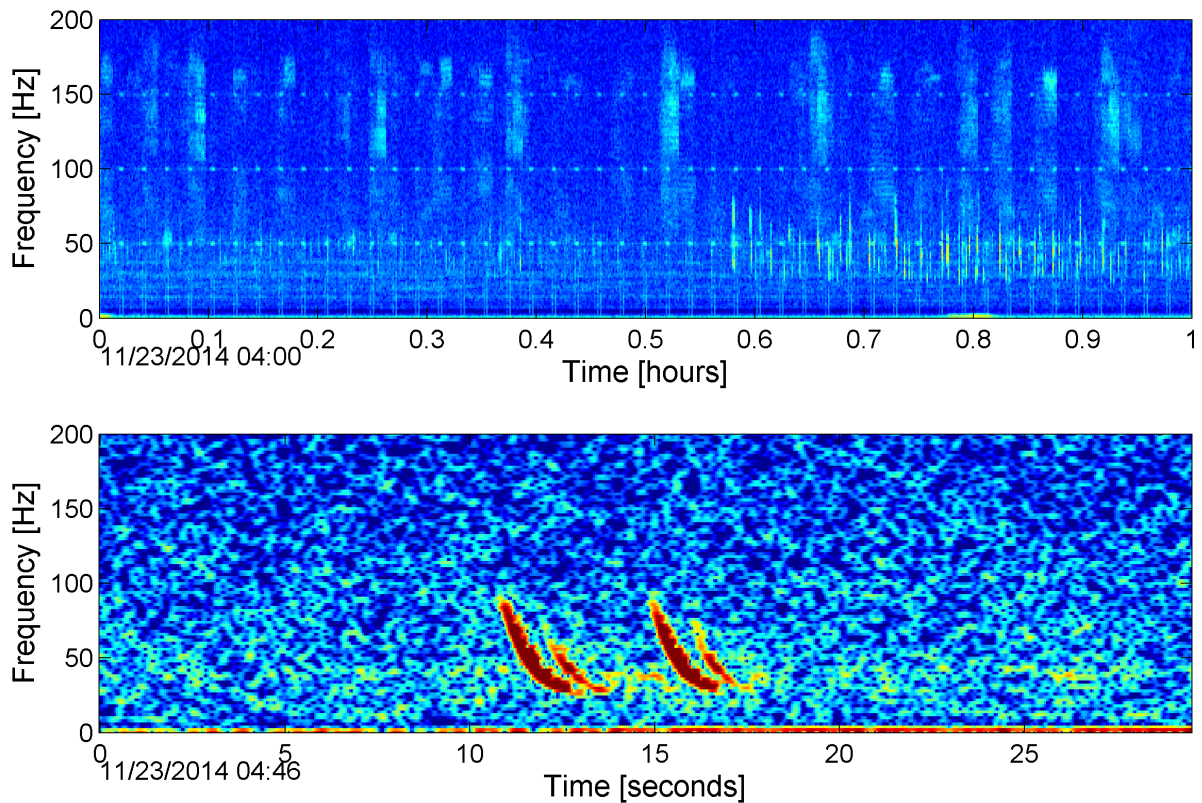


Figure 9. Downsweep calls similar to those reported to be from sei whales in the LTSA (top) and spectrogram (bottom) from JAX site D.

Minke Whales

Minke whales in the North Atlantic produce long pulse trains (**Figure 10**). Mellinger *et al.* (2000) describe minke whale pulse sequences near Puerto Rico as speed-up and slow-down pulse trains, with increasing and decreasing pulse rates respectively. Recently, these call types were detected in the North Atlantic and they were expanded to also include pulse trains with non-varying pulse rates (Risch *et al.*, 2013).

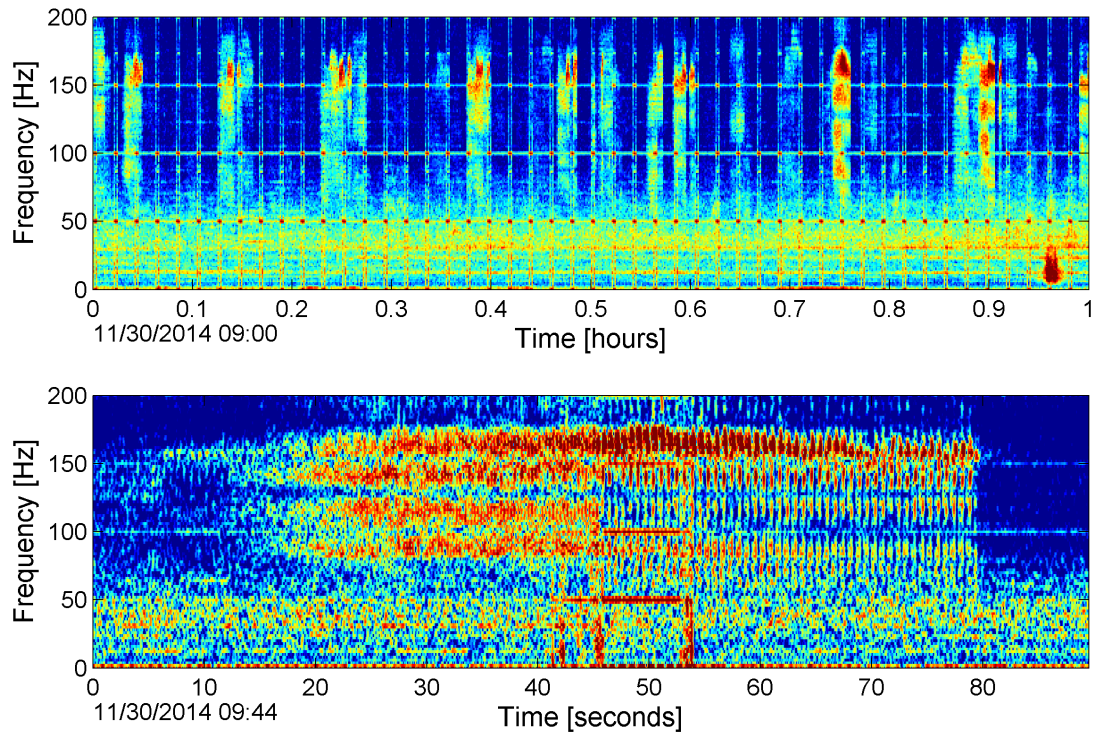


Figure 10. Minke whale pulse train in the LTSA (top) and spectrogram (bottom) recorded at JAX site D.

North Atlantic Right Whales

The critically endangered North Atlantic right whale is found in the Western North Atlantic, and the JAX region is included in their calving grounds, although typically in the shallow waters of the continental shelf. Several call types that have been described for the North Atlantic right whale include the scream, gunshot, blow, upcall, warble, and downcall (Parks and Tyack, 2005). For low-frequency analysis, we examined the data for upcalls, which are approximately 1 second in duration and range between 80 Hz and 200 Hz, sometimes with harmonics (**Figure 11**).

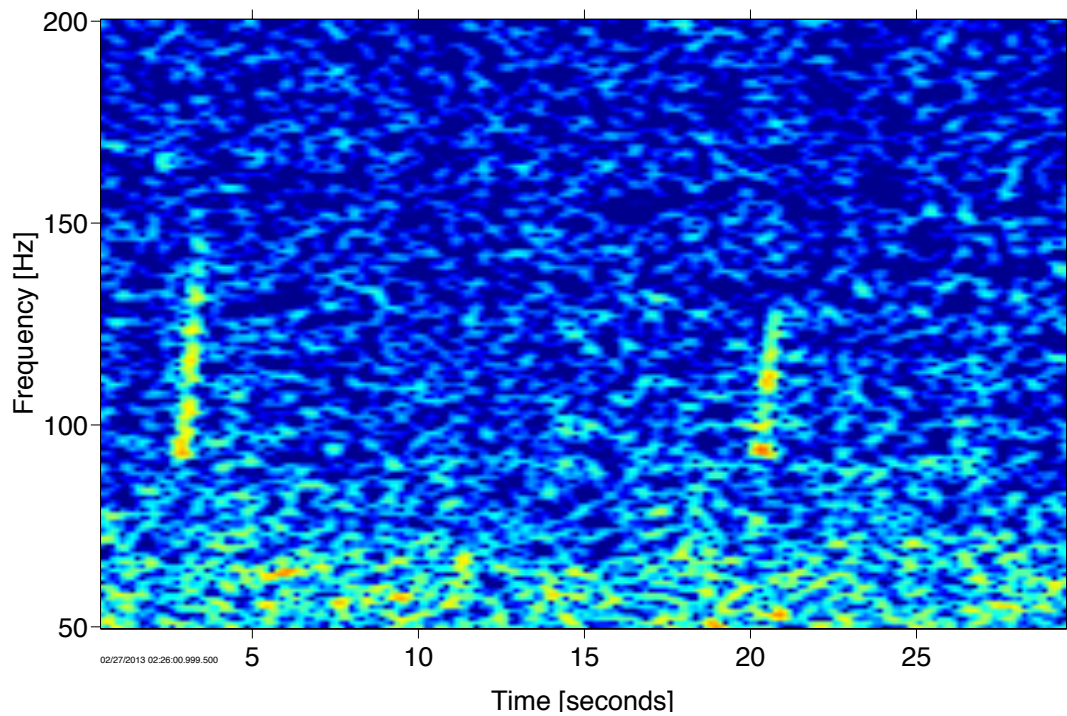


Figure 11. Right whale up-calls from HAT02A.

Low Frequency Ambient Soundscape

To provide a means of evaluating seasonal variability, average sound pressure spectrum levels were computed per day, with partial days and days with deployment/recovery ship sounds or with known instrument self-noise problems discarded. Daily-averaged spectra were processed into monthly-averages and plotted using the same monthly color scheme for each of the deployments so that months from different sites and years can be compared.

Mid-Frequency Marine Mammals

Marine mammal species with sounds in the mid-frequency range expected in the Atlantic include humpback whales (*Megaptera novaeangliae*) and killer whales (*Orcinus orca*). The presence of each call type was determined using an encounter-granularity, to one-minute precision, for each mid-frequency dataset. Humpback whales were detected automatically as described below (**Figure 12**). Automatic detections were subsequently verified for accuracy by a trained analyst. Whistles resembling those of killer whales were logged as unidentified odontocete whistles <5 kHz due to overlapping distributions with other large delphinids in the area.

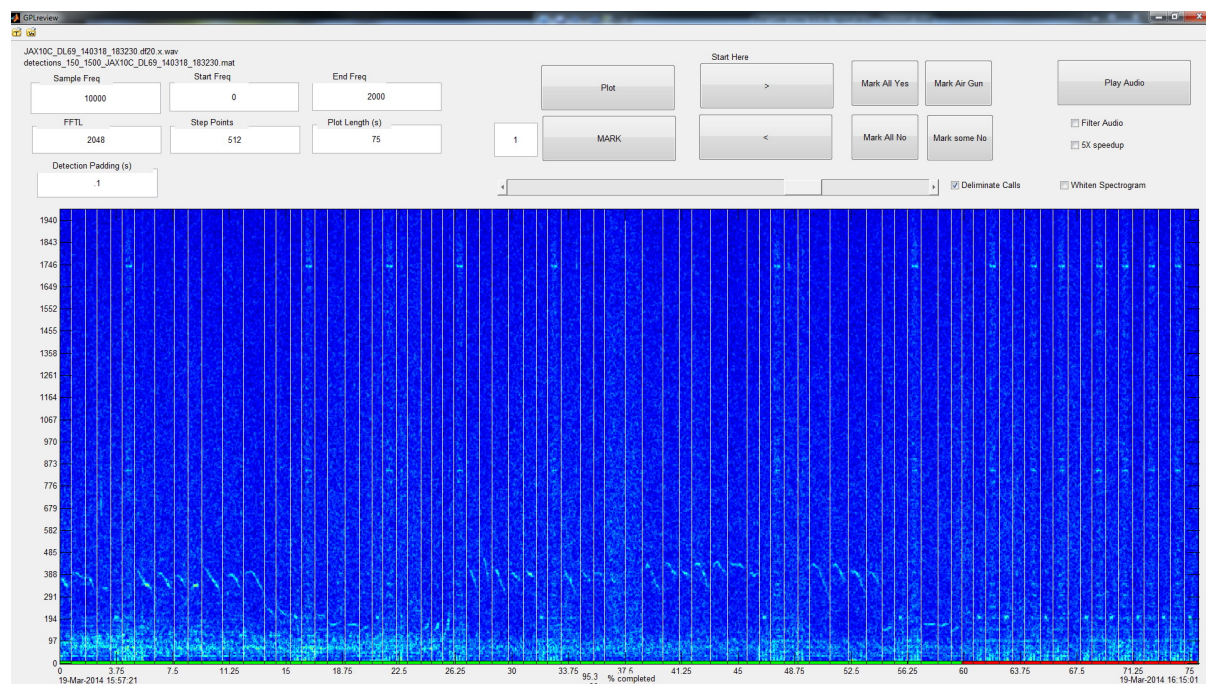


Figure 12. Humpback whale song from JAX site in the analyst verification stage of the detector. Green in the bottom evaluation line indicates true detections.

Humpback Whales

Humpback whales produce both song and non-song calls (Payne and McVay 1971, Dunlop *et al.* 2007, Stimpert *et al.*, 2011). The song is categorized by the repetition of units, phrases, and themes of a variety of calls as defined by Payne and McVay (1971). Most humpback whale vocalizations are produced between 100 - 3,000 Hz. We used an automatic humpback whale detector based on the generalized power law (Helble *et al.*, 2012).

High-Frequency Marine Mammals

Marine mammal species with sounds in the high-frequency range and possibly found in the Western Atlantic region include Atlantic white-sided dolphins (*Lagenorhynchus acutus*), short-beaked common dolphins (*Delphinus delphis*), Atlantic spotted dolphins (*Stenella frontalis*), Clymene dolphins (*S. clymene*), striped dolphins (*S. coeruleoalba*), Risso's dolphins (*Grampus griseus*), bottlenose dolphins (*Tursiops truncatus*), rough-toothed dolphins, (*Steno bredanensis*), false killer whales (*Pseudorca crassidens*), Northern bottlenose dolphins (*Hyperoodon ampullatus*), short-finned pilot whales (*Globicephala macrorhynchus*), long-finned pilot whales (*G. melas*), killer whales (*Orcinus orca*), sperm whales (*Physeter macrocephalus*), dwarf sperm whales (*Kogia sima*), pygmy sperm whales (*K. breviceps*), Cuvier's beaked whales (*Ziphius cavirostris*), Gervais' beaked whales (*Mesoplodon europaeus*), Blainville's beaked whales (*M. densirostris*), and Sowerby's beaked whales (*M. bidens*).

High-Frequency Call Types

Odontocete sounds can be categorized as echolocation clicks, burst pulses, or whistles. Echolocation clicks are broadband impulses with peak energy between 5 and 150 kHz, dependent upon the species. Buzz or burst pulses are rapidly repeated clicks that have a creak or buzz-like sound quality; they are generally lower in frequency than echolocation clicks. Dolphin whistles are tonal calls predominantly between 1 and 20 kHz that vary in frequency content, their degree of frequency modulation, as well as duration. These signals are easily detectable in an LTSA as well as the spectrogram (**Figure 13**).

Beaked Whales

Beaked whales can be identified acoustically by their echolocation signals (Baumann-Pickering *et al.*, 2014). These signals are frequency-modulated (FM) upswEEP pulses, which appear to be species specific and distinguishable by their spectral and temporal features. Identifiable signals are known for Blainville's, Cuvier's, Gervais', and Sowerby's beaked whales.

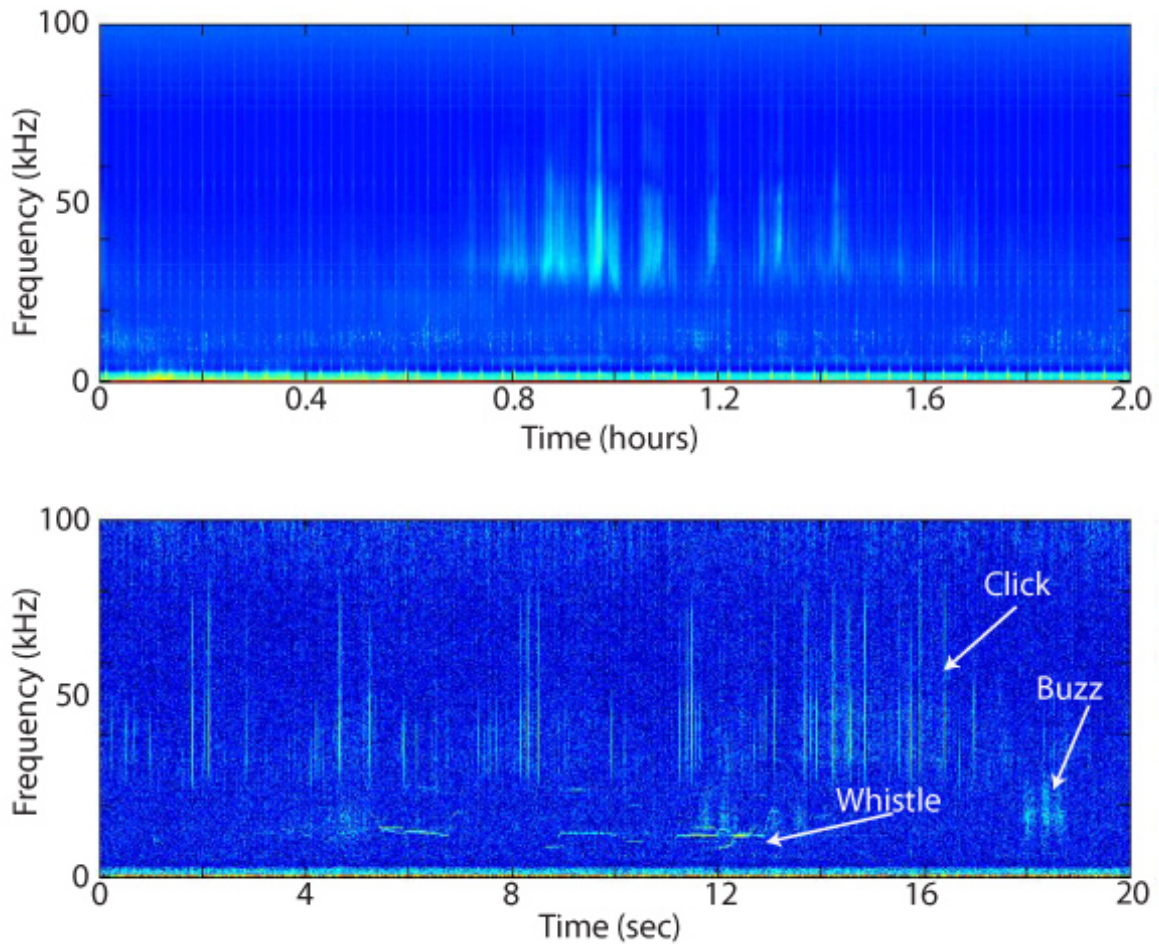


Figure 13. Generic example demonstrating odontocete signal types, in a LTSA (top) and spectrogram (bottom).

Beaked whale FM pulses were detected with an automated computer algorithm and was used for all identifiable beaked whale signals found in the Western Atlantic. First, echolocation signals were detected with a Teager Kaiser energy detector (Soldevilla *et al.*, 2008; Roch *et al.*, 2011), then an expert system discriminated between delphinid clicks and beaked whale FM pulses. A decision about presence or absence of beaked whale signals was based on detections within a 75 second recording segment. Only segments with more than 7 detections were used in further analysis. All echolocation signals with a peak and center frequency below 32 and 25 kHz, respectively, a duration less than 355 μ s, and a sweep rate of less than 23 kHz/ms were deleted. If more than 13% of all initially detected echolocation signals remained after applying these criteria, the segment was classified to have beaked whale FM pulses. A third classification step, based on computer assisted manual decisions by a trained analyst, was used to label the automatically detected segments to pulse type level and rejected false detections (Baumann-

Pickering *et al.*, 2013). The rate of missed segments is approximately 5%, varying slightly across deployments.

Blainville's Beaked Whales

Blainville's beaked whale echolocation signals are polycyclic, with a characteristic frequency-modulated upsweep, peak frequency around 34 kHz and uniform inter-pulse interval (IPI) of about 280 ms (Johnson *et al.*, 2006; Baumann-Pickering *et al.*, 2013). Blainville's FM pulses are also distinguishable in the spectral domain by their sharp energy onset around 25 kHz with only a small energy peak at around 22 kHz (**Figure 14**).

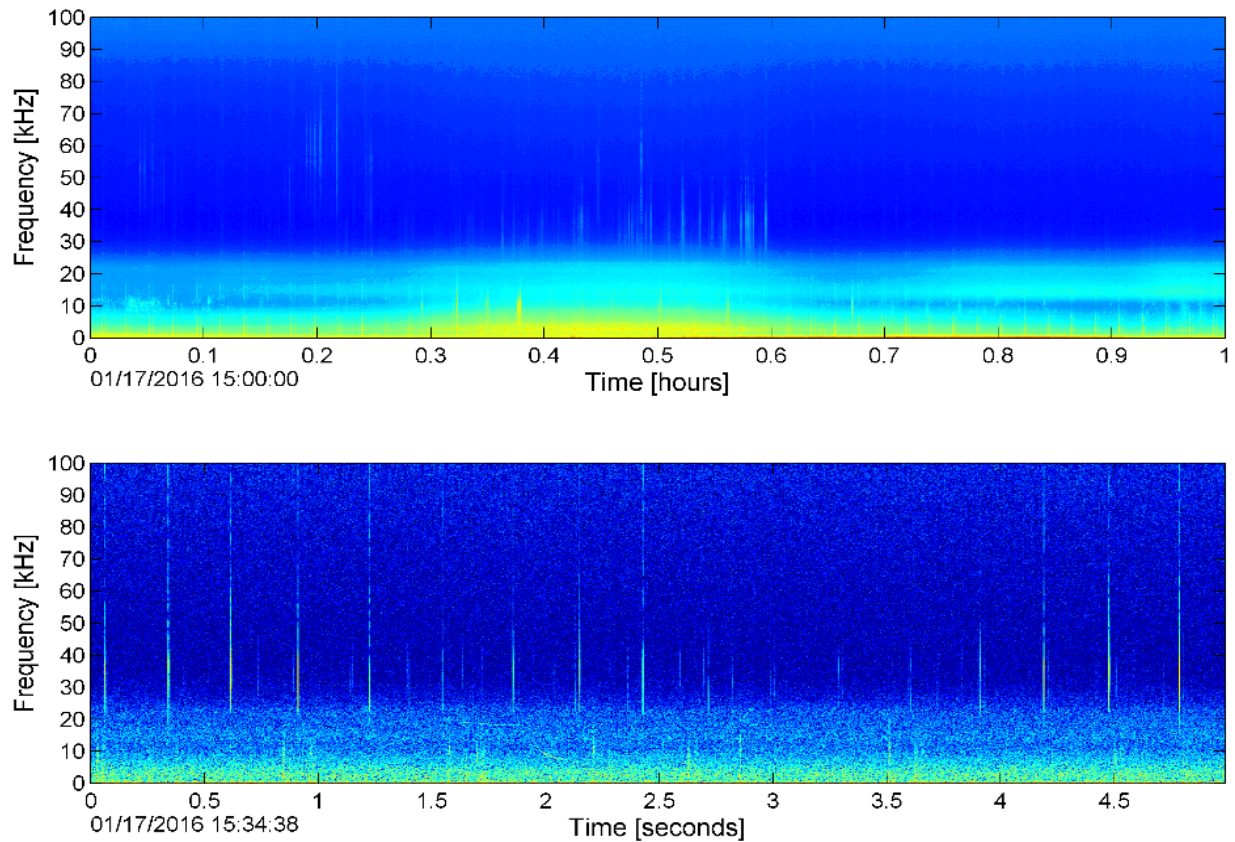


Figure 14. Blainville's beaked whale echolocation clicks in LTSA (top) and spectrogram (bottom) recorded offshore of Hatteras, North Carolina.

Cuvier's Beaked Whales

Cuvier's beaked whale echolocation signals are polycyclic, with a characteristic FM pulse upswEEP, peak frequency around 40 kHz (**Figure 15**), and uniform inter-pulse interval of about 0.5 s (Johnson *et al.*, 2004; Zimmer *et al.*, 2005). An additional feature that helps with the identification of Cuvier's FM pulses is that they have two characteristic spectral peaks around 17 and 23 kHz.

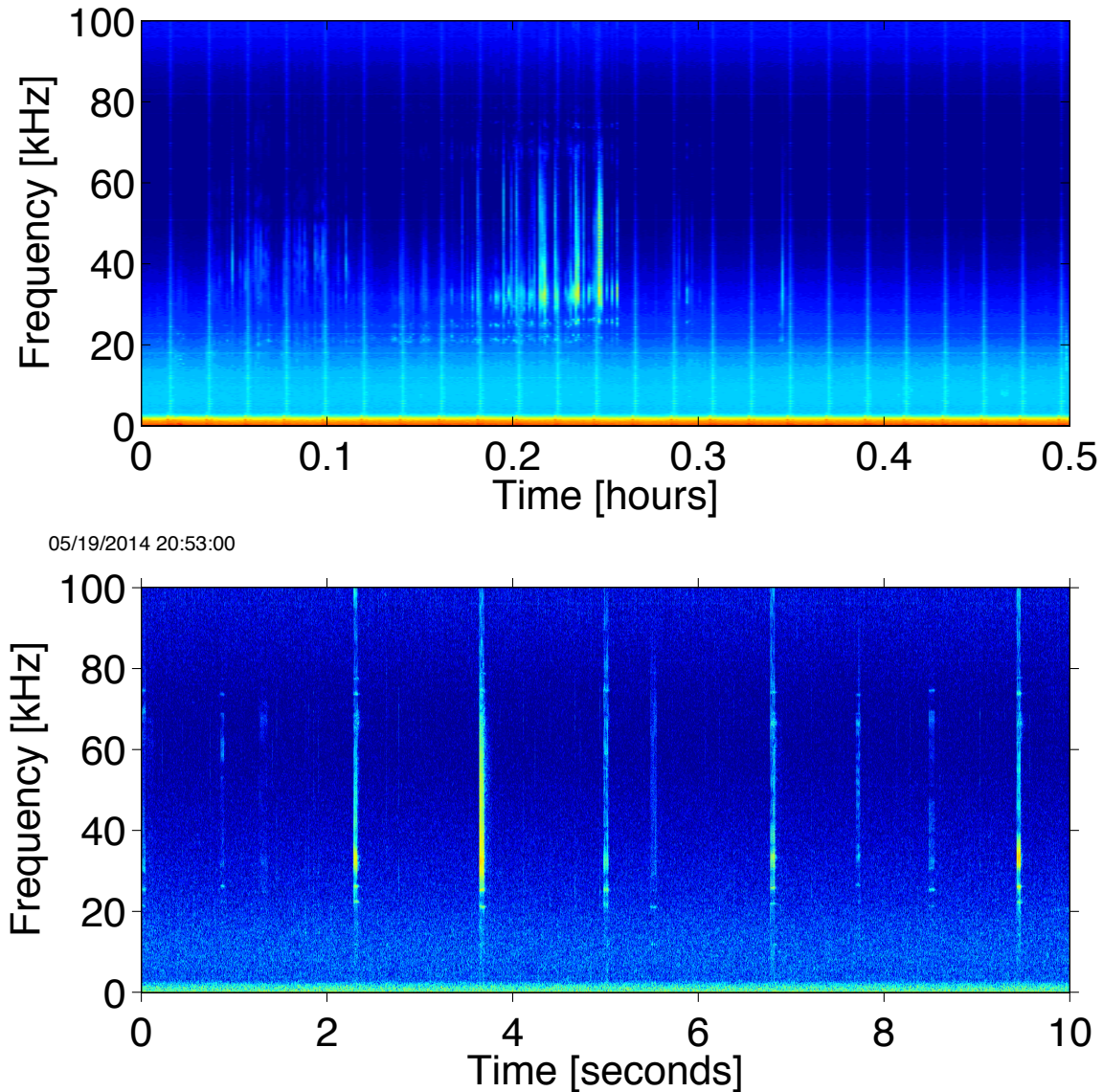


Figure 15. Cuvier's beaked whale echolocation clicks in LTSA (top) and spectrogram (bottom) recorded at HAT04A.

Gervais' Beaked Whales

Gervais' beaked whale signals have energy concentrated in the 30-50 kHz band (Gillespie *et al.*, 2009), with a peak at 44 kHz (Baumann-Pickering *et al.*, 2013). While Gervais' beaked whale signals are similar to those of Cuvier's and Blainville's beaked whales, the Gervais' beaked whale FM pulses are at a slightly higher frequency than those of the other two species. Similarly, Gervais' beaked whale FM pulses sweep up in frequency. The IPI for Gervais' beaked whale signals (Baumann-Pickering *et al.*, 2013) is typically around 275 ms (**Figure 16**).

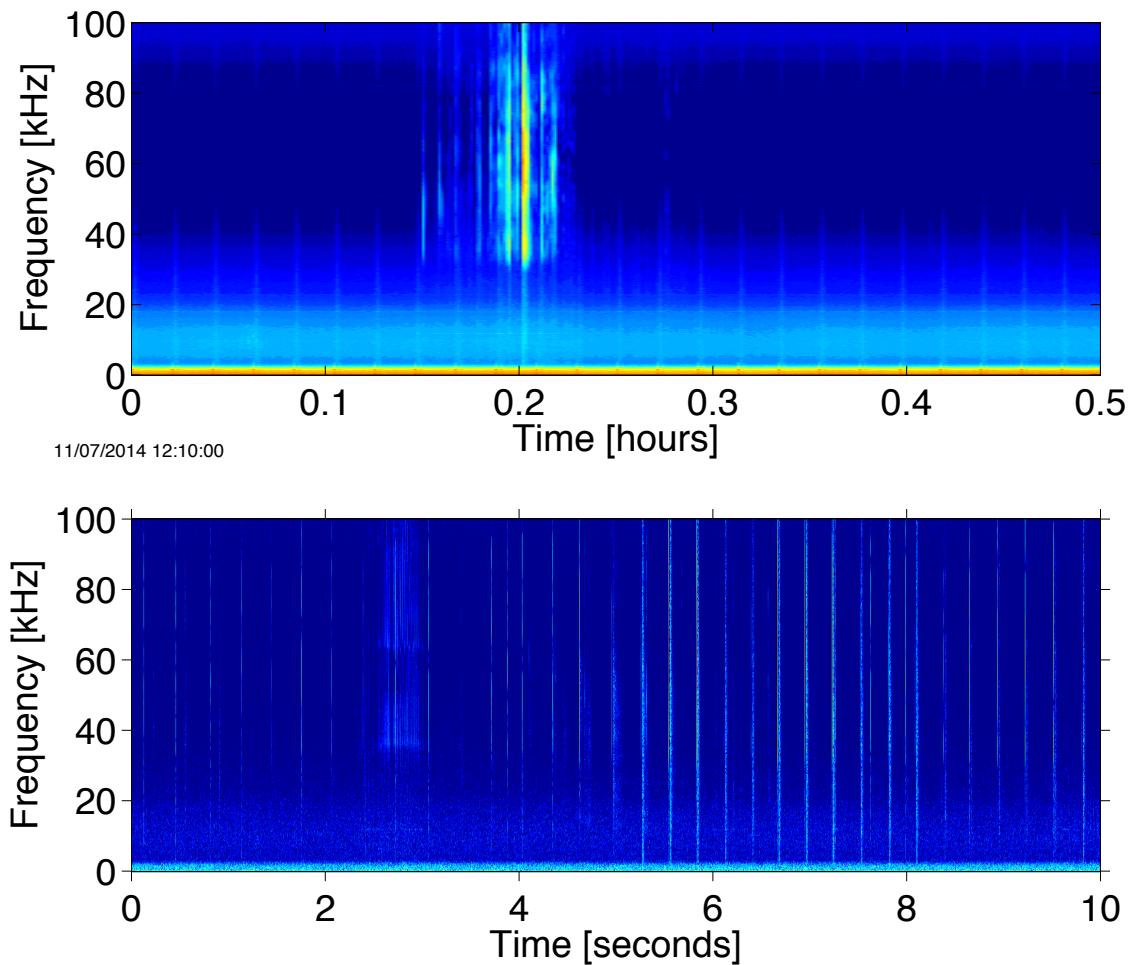


Figure 16. Gervais' beaked whale echolocation clicks in LTSA (top) and spectrogram (bottom) recorded at site HAT04A.

Sowerby's Beaked Whales

Sowerby's beaked whale echolocation signals have energy concentrated in the 50 – 95 kHz band, with a peak at 67 kHz (**Figure 17**). Sowerby's beaked whale signals have a characteristic FM upsweep, and are distinguishable from other co-occurring beaked whale signal types by their higher frequency content and a relatively short inter-pulse interval of around 150 ms (Cholewiak *et al.*, 2013).

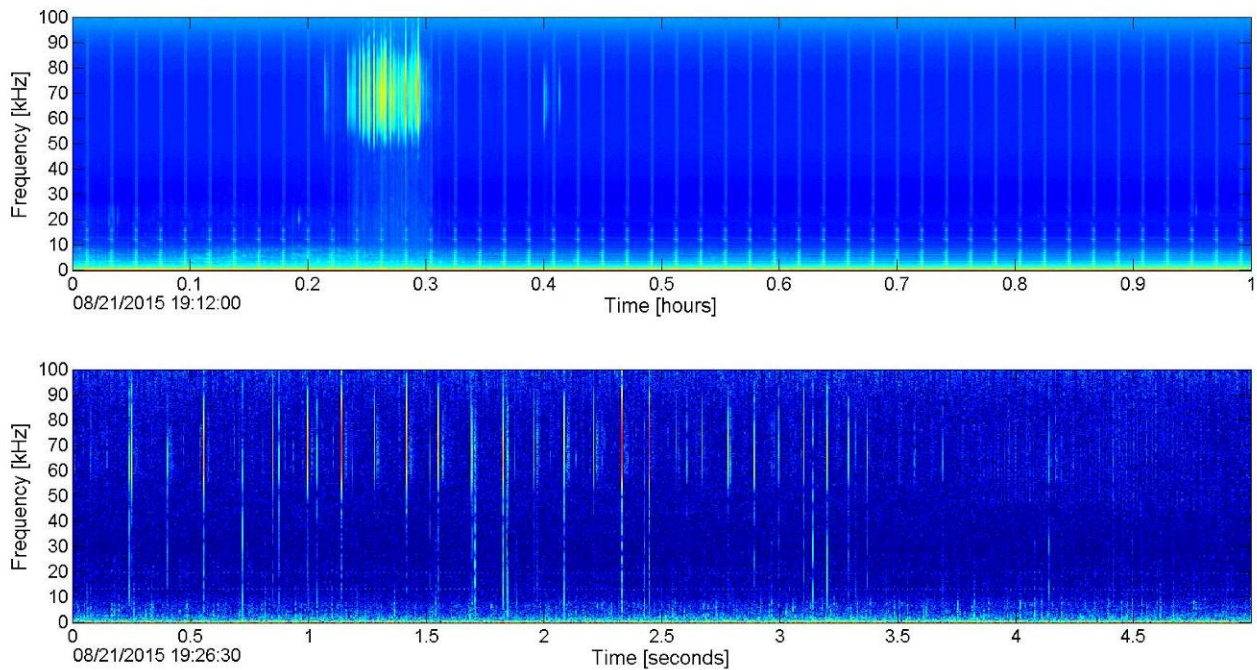


Figure 17. Sowerby's beaked whale echolocation clicks in LTSA (top) and spectrogram (bottom).

Sperm Whales

Sperm whale clicks contain energy from 2-20 kHz, with the majority of energy between 10-15 kHz (Møhl *et al.*, 2003) (**Figure 18**). Regular clicks, observed during foraging dives, demonstrate an ICI from 0.25-2s (Goold and Jones, 1995; Madsen *et al.*, 2002a). Short bursts of closely spaced clicks called creaks are observed during foraging dives and are believed to indicate a predation attempt (Watwood *et al.*, 2006). Slow clicks are used only by males and are more intense than regular clicks with long inter-click intervals (Madsen *et al.*, 2002b). Codos are stereotyped sequences of clicks which are less intense and contain lower peak frequencies than regular clicks (Watkins and Schevill, 1977). Effort was not expended to denote whether sperm whale detections were codos, regular or slow clicks.

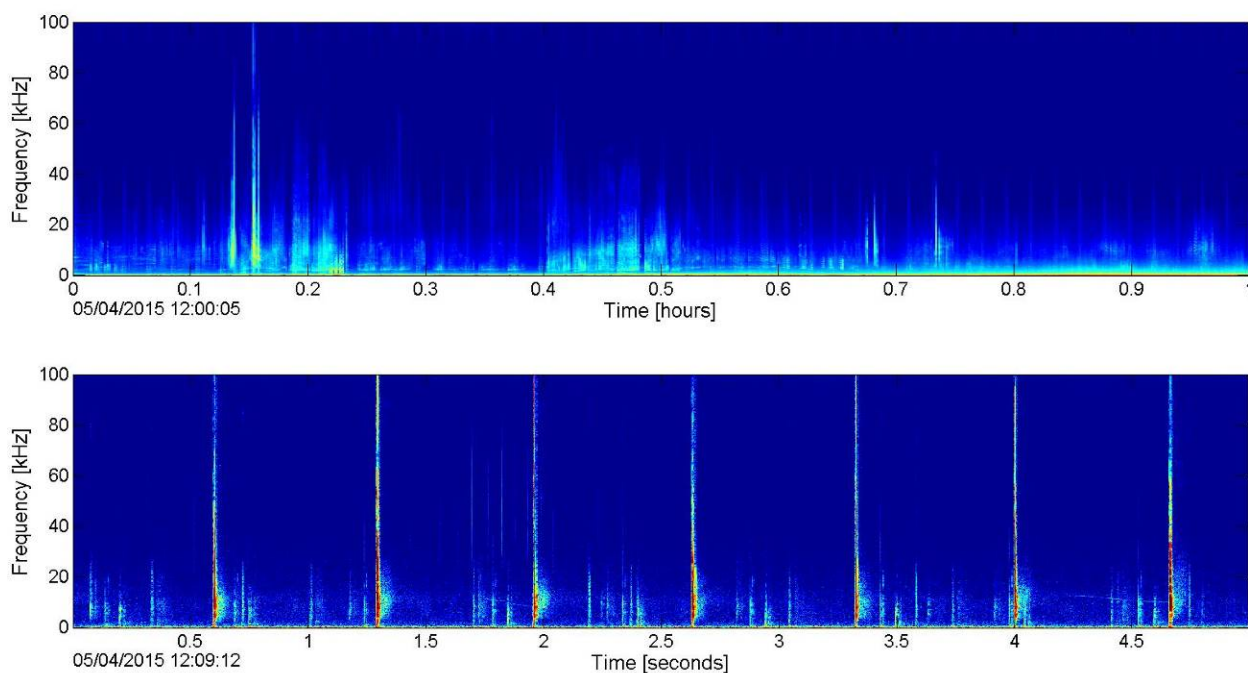


Figure 18. Sperm whale clicks in LTSA (top) and spectrogram (bottom).

Kogia spp.

Dwarf and pygmy sperm whales emit echolocation signals which have peak energy at frequencies near 130 kHz (Au, 1993). While this is above the upper frequency band recorded by the HARP during these deployments, energy from *Kogia* clicks can be recorded within the 100 kHz HARP bandwidth (**Figure 19**). The observed signal may result both from the low-frequency tail of the *Kogia* echolocation click spectra, and from aliasing of energy from above the Nyquist frequency of 100 kHz (**Figure 20**). *Kogia* echolocation clicks were analyzed using a multi-step detector. The first step was to identify clicks with energy in the 70-100 kHz band that simultaneously lacked energy in lower frequency bands. An expert system then classified these

clicks based on spectral characteristics and finally an analyst verified all echolocation click bouts manually. A bimodal click peak frequency distribution (**Figure 20**) may represent two distinct click subtypes.

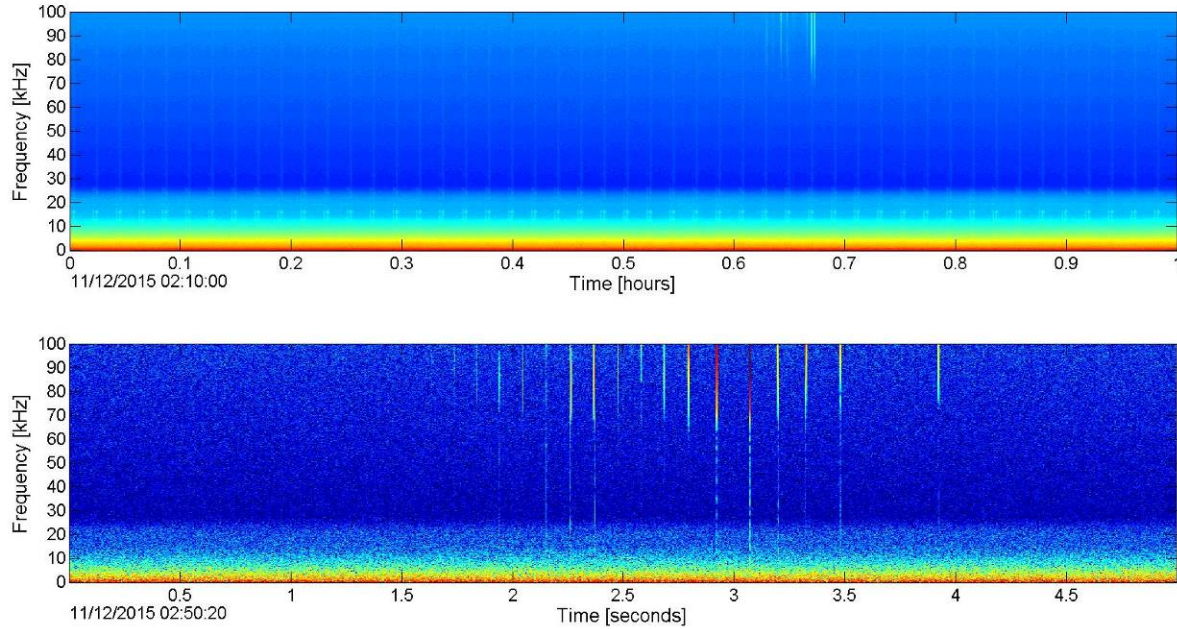


Figure 19. *Kogia* spp. clicks in LTSA (top) and spectrogram (bottom).

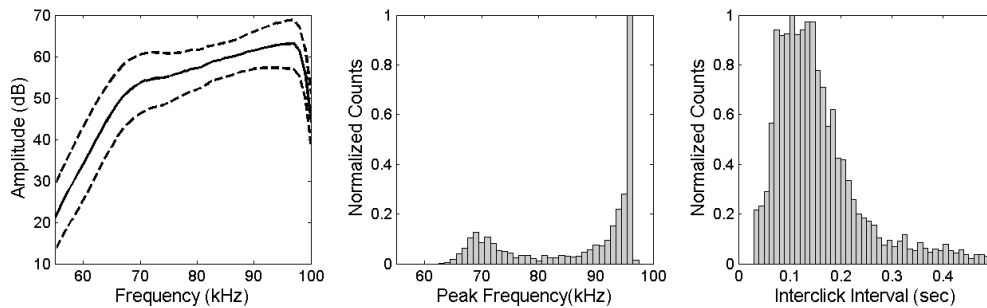


Figure 20. Left: Mean frequency spectrum of *Kogia* spp. clicks (solid line) and 25th and 75th percentiles (dashed lines); Center: Distribution of click peak frequencies with peak near the Nyquist frequency (100 kHz); Right: Distribution of inter-click-intervals.

Delphinid Click Types

Delphinid echolocation clicks were detected automatically using an energy detector with a minimum received level threshold of 120 dB_{pp} re: 1 µPa (Roch *et al.*, 2011; Frasier, 2015). False positives were identified and removed manually by an analyst, who reviewed LTSAs and mean spectra for each detected bout. A bout was defined as a period of clicking separated before and after by at least 15 minutes without clicking.

Dominant click types at these sites were identified automatically by dividing detections into successive five-minute windows and determining the dominant click type(s) in each window. An automated clustering algorithm was then used to identify recurrent types based on spectral features and inter-click interval (ICI) distributions across a subset of 10,000 windows aggregated across the three sites (Frasier *et al.*, in prep). Recurrent types were used as templates. Templates were attributed to a specific species if known (e.g. Risso's dolphin) or assigned a number if species was unknown. Templates were compared with the click type(s) in each five-minute window for matches. Click types that matched a template were classified by the matched template. Click types that did not match a template were labeled as unknown.

At least nine delphinid click types were identified and labeled click type 1 – 8 and Risso's from across the three sites, with the highest click type diversity found at site HZ. Variable data quality at site HZ, combined with high detection rates and frequent multi-species encounters limited the ability of both manual and automated analyses to distinguish within-type from between-type variability. Some reported click types may contain multiple subtypes. Further analysis will be required to refine click types and reduce classification confusion between similar types.

Risso's Dolphins

Risso's dolphin clicks (**Figure 21**) have frequency peaks at approximately 22, 26, and 33 kHz. These clicks have a modal ICI of approximately 0.15 seconds (**Figure 22**). Past studies have shown that spectral properties of Risso's dolphin clicks have slight variations with geographic region, although the multiple sharp frequency peaks and average ICI found at these Atlantic sites are similar to what has been found elsewhere. Two click types similar to Risso's dolphin clicks were identified at these sites, one with a distinct peak at 22 kHz, the other without. Further analysis will be required to determine whether these are distinct types.

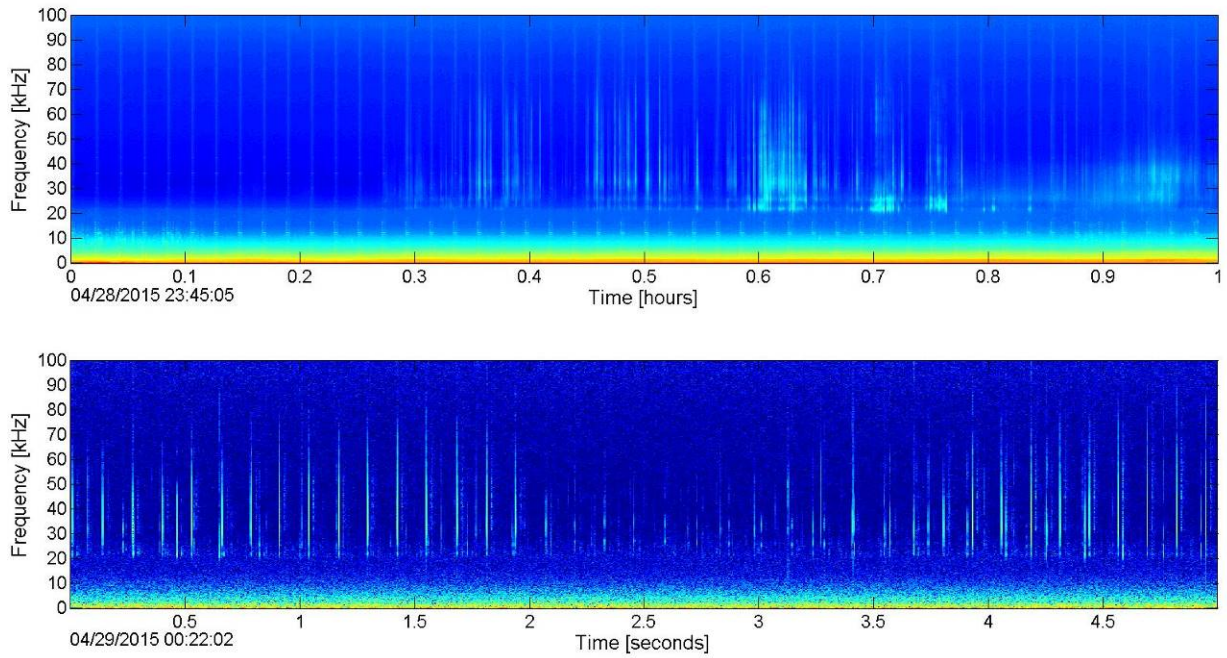


Figure 21. Risso's dolphin clicks in LTSA (top) and spectrogram (bottom).

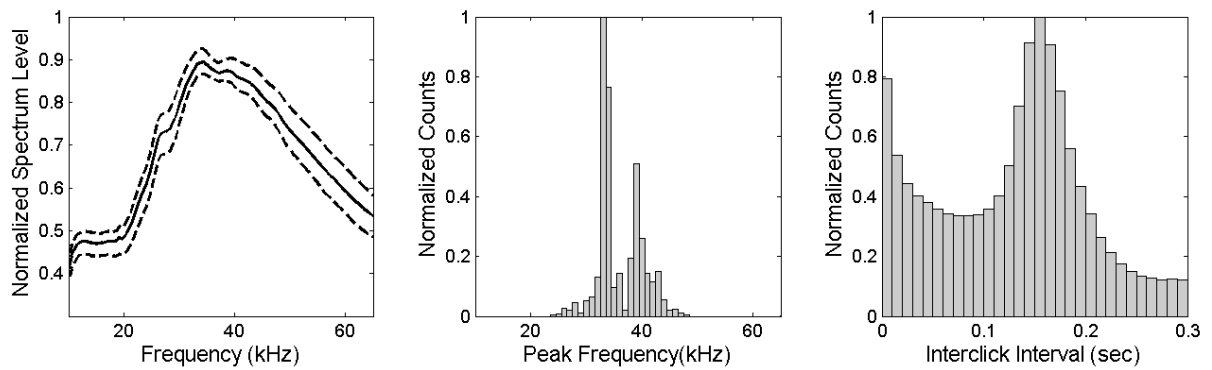


Figure 22. Left: Mean normalized received sound pressure level spectrum of Risso's dolphin click cluster (solid line) and 25th and 75th percentiles (dashed lines); Center: Distribution of click cluster peak frequencies with primary peak at 33 kHz; Right: Distribution of inter-click-intervals within cluster with modal peak at 0.15 seconds.

Click Type 1

Click type 1 clicks (**Figure 23**) have spectral peaks near 22, 26, and 33 kHz and a distinct trough at 28 kHz (**Figure 24**). These clicks have a modal ICI of approximately 0.15 seconds. Click type 1 is very similar in spectrum to Pacific white-sided dolphin clicks (Soldevilla *et al.*, 2008). The spectral peaks of this type are similar in spectrum and ICI to Risso's dolphins, and the two types are likely confused using current classification methods due in part to data quality issues in the 25-30 kHz band. Further classifier refinement is needed to reliably distinguish the two.

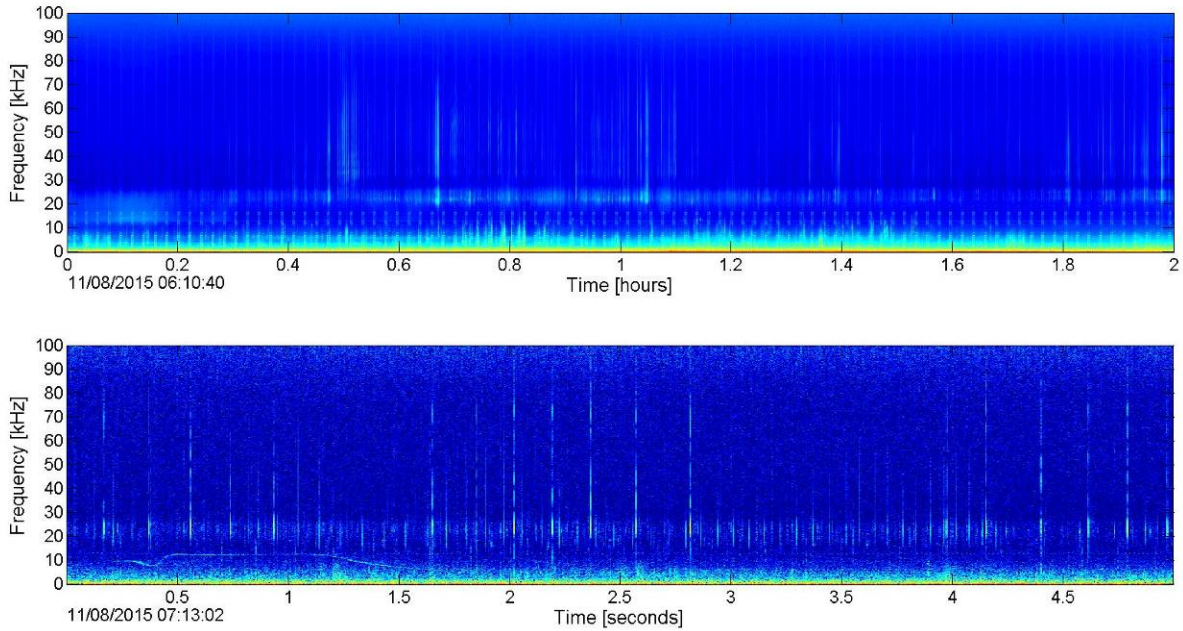


Figure 23. Click type 1 in LTSA (top) and spectrogram (bottom).

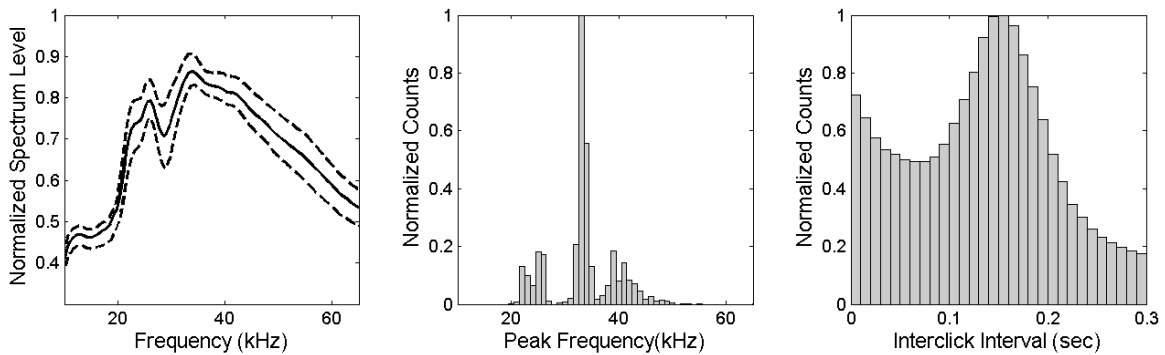


Figure 24. Left: Mean normalized received sound pressure level spectrum of click type 1 cluster (solid line) and 25th and 75th percentiles (dashed lines); Center: Distribution of click cluster peak frequencies with a peak at 33 kHz; Right: Distribution of inter-click-intervals within cluster with modal peak at 0.15 seconds.

Click Type 2

Click type 2 clicks (**Figure 25**) have a narrow spectral peak at 22 kHz and a broad peak from 32 to 43 kHz. These clicks have a modal ICI of approximately 0.07 seconds (**Figure 26**).

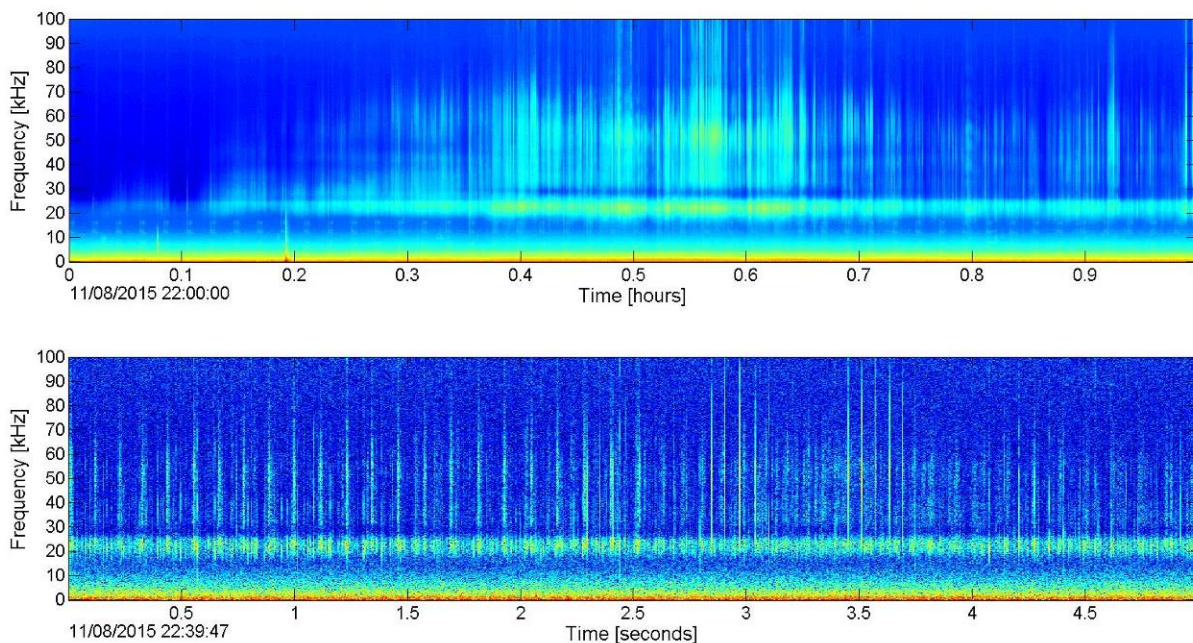


Figure 25. Click type 2 clicks in LTSA (top) and spectrogram (bottom).

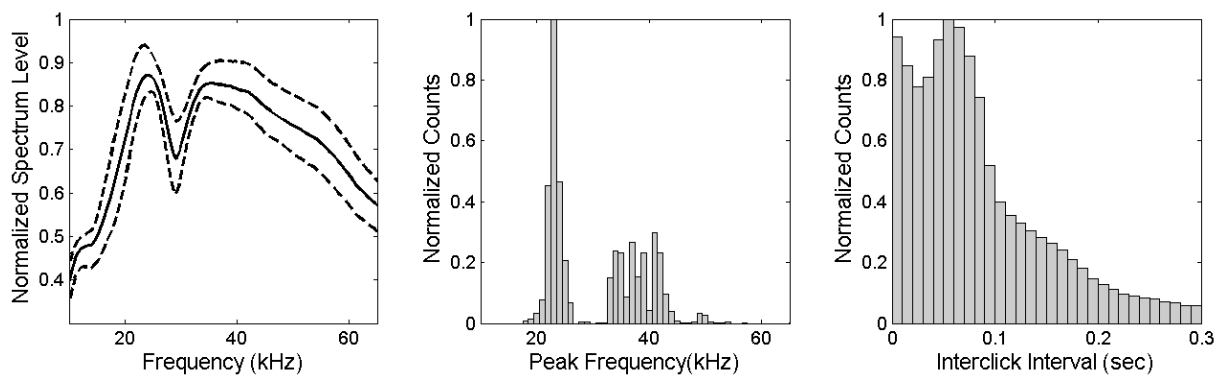


Figure 26. Left: Mean normalized received sound pressure level spectrum of click type 2 cluster (solid line) with 25th and 75th percentiles (dashed lines); Center: Distribution of click cluster peak frequencies with a peak at 22 kHz; Right: Distribution of inter-click-intervals within cluster with modal peak at 0.07 seconds.

Click Type 3

Click type 3 clicks (**Figure 27**) have a peak frequency of approximately 33 kHz, and a modal ICI of 0.06 seconds (**Figure 28**).

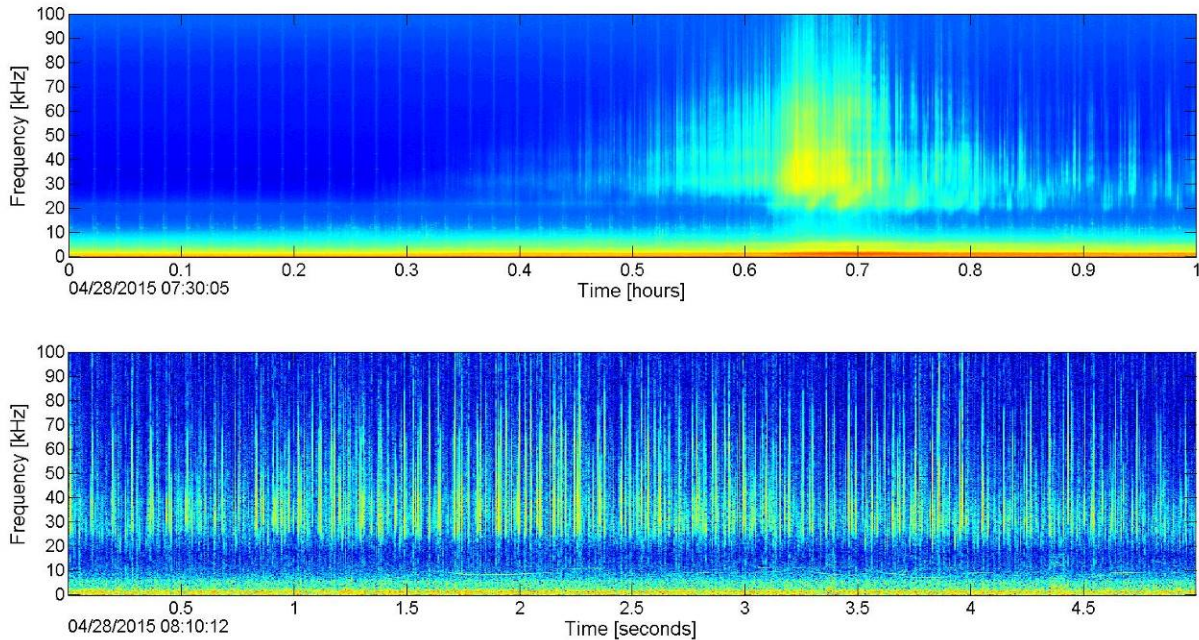


Figure 27. Click type 3 in LTSA (top) and spectrogram (bottom).

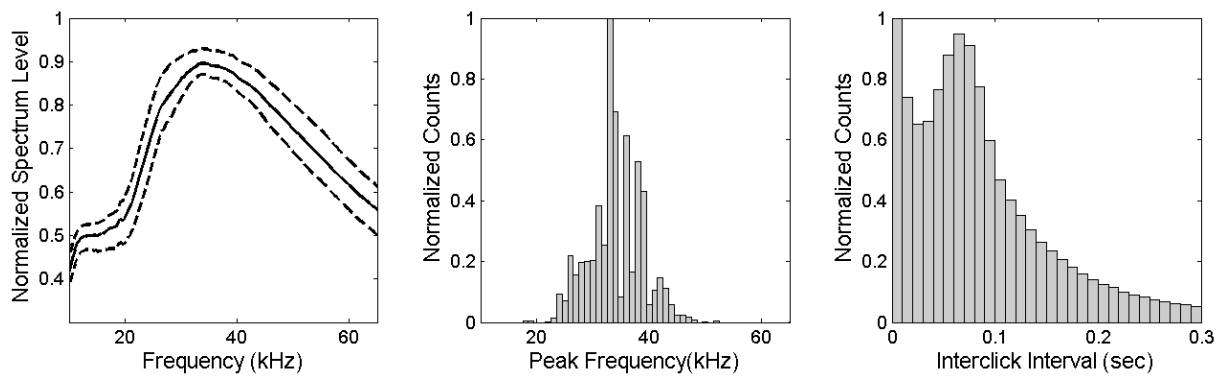


Figure 28. Left: Mean normalized received sound pressure level spectrum of click type 3 cluster (solid line) with 25th and 75th percentiles (dashed lines); Center: Distribution of click cluster peak frequencies with a peak at 33 kHz; Right: Distribution of inter-click-intervals within cluster with modal peak at 0.06 seconds.

Click Type 4

Click type 4 clicks (**Figure 29**) have a peak frequency of approximately 22 kHz, and a modal ICI of 0.14 seconds (**Figure 30**).

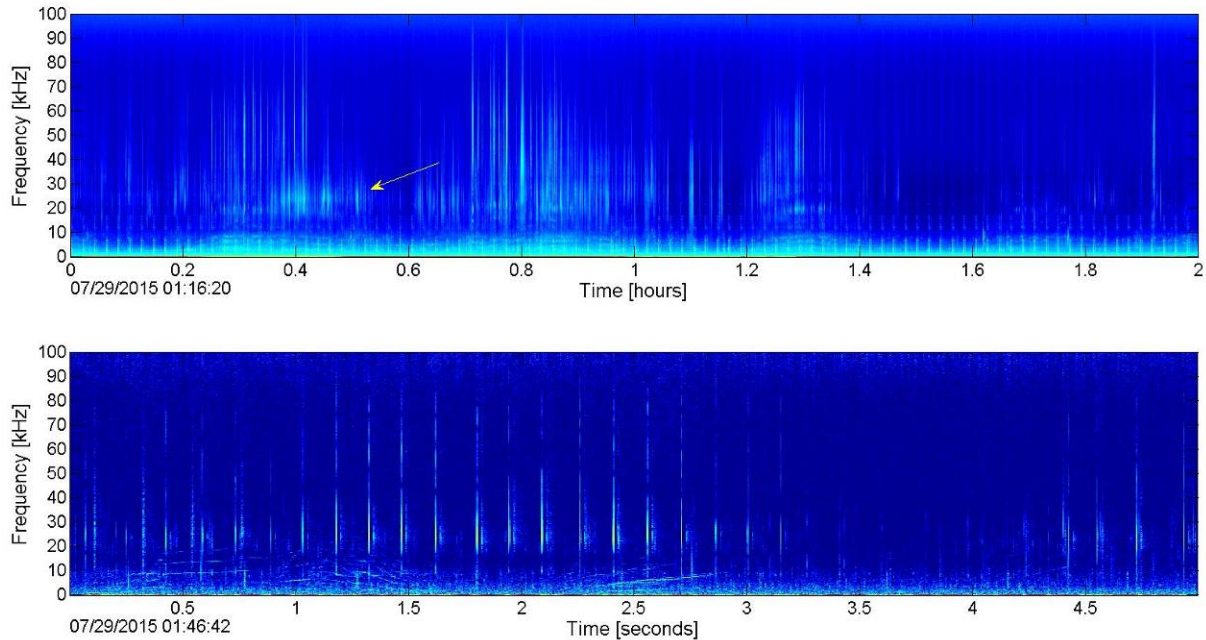


Figure 29. Click type 4 in LTSA (top) and spectrogram (bottom). Arrow indicates location of LTSA expanded in the spectrogram.

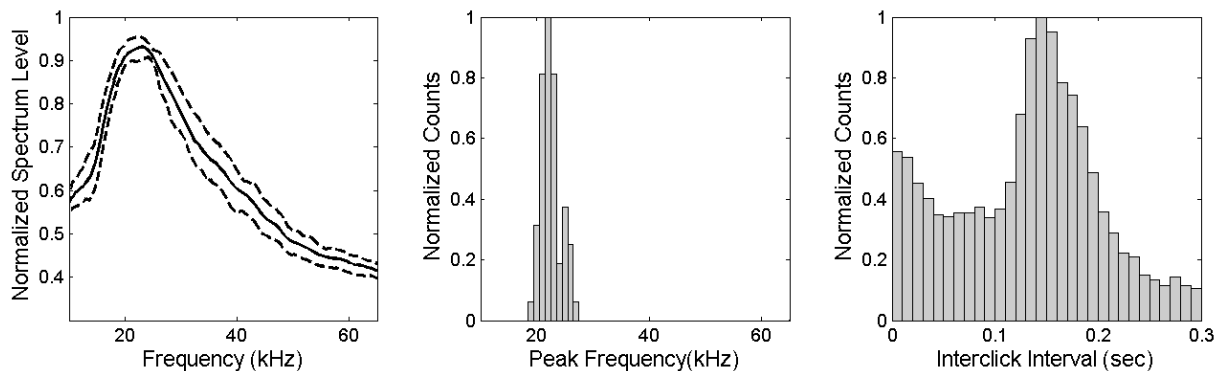


Figure 30. Left: Mean normalized received sound pressure level spectrum of click type 4 cluster (solid line) with 25th and 75th percentiles (dashed lines); Center: Distribution of click cluster peak frequencies with a peak at 22 kHz; Right: Distribution of inter-click-intervals within cluster with modal peak at 0.14 seconds.

Click Type 5

Click type 5 clicks (**Figure 31**) have a main peak frequency of approximately 46 kHz, and two minor spectral peaks at 20 and 26 kHz. This click type has a bimodal ICI distribution with peaks at 0.04 and 0.10 seconds (**Figure 32**). These may represent separate subtypes.

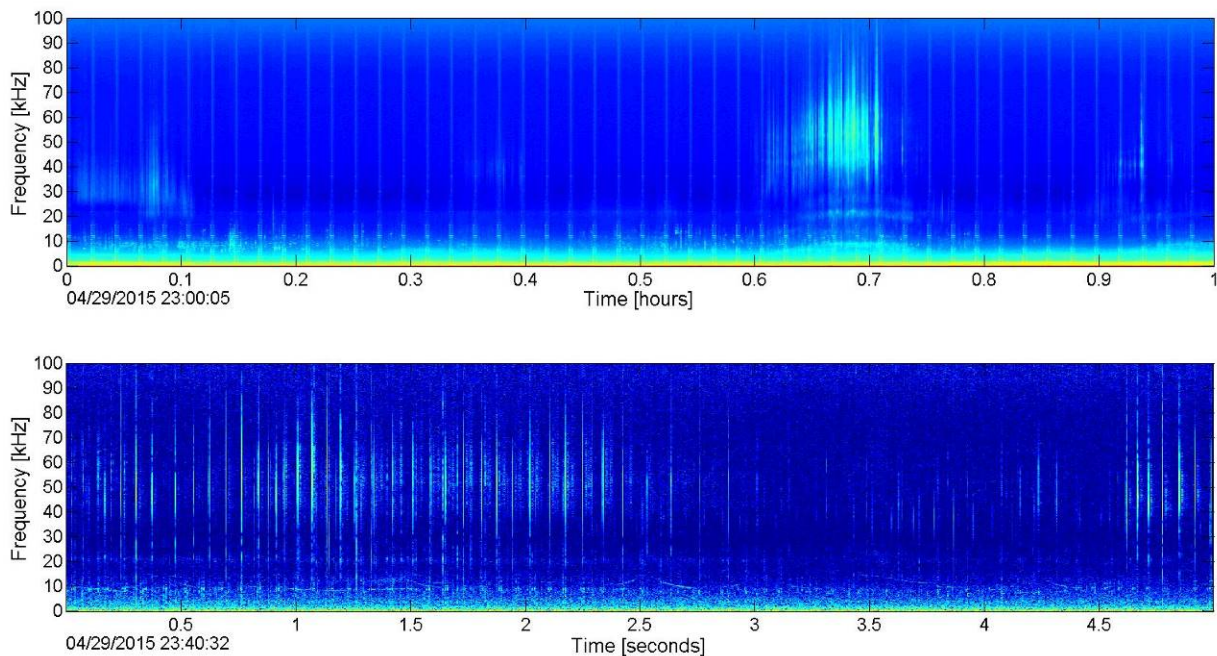


Figure 31. Click type 5 in LTSA (top) and spectrogram (bottom).

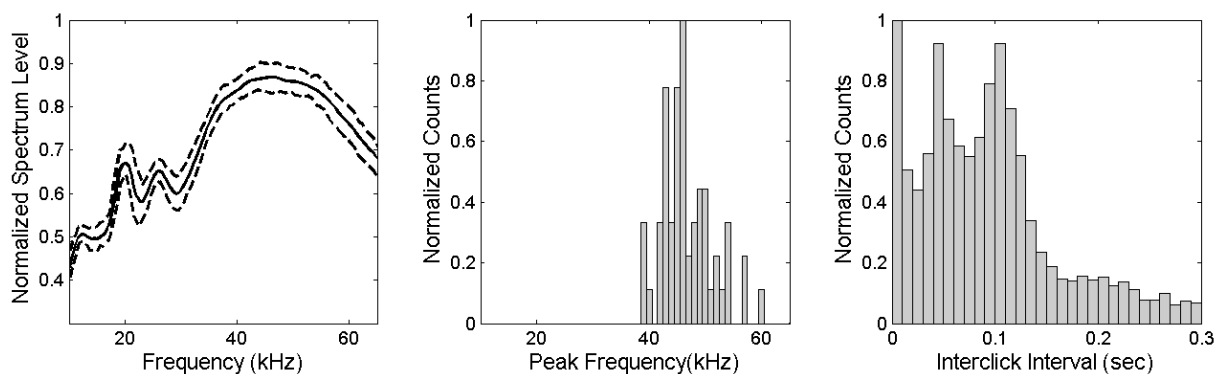


Figure 32. Left: Mean normalized received sound pressure level spectrum of click type 5 cluster (solid line) with 25th and 75th percentiles (dashed lines); Center: Distribution of click cluster peak frequencies with primary peak at 46 kHz; Right: Distribution of inter-click-intervals within cluster with bimodal peaks at 0.04 and 0.10 seconds.

Click Type 6

Click type 6 clicks (**Figure 33**) have a peak frequency of approximately 19 kHz and a modal ICI of 0.15 seconds (**Figure 34**).

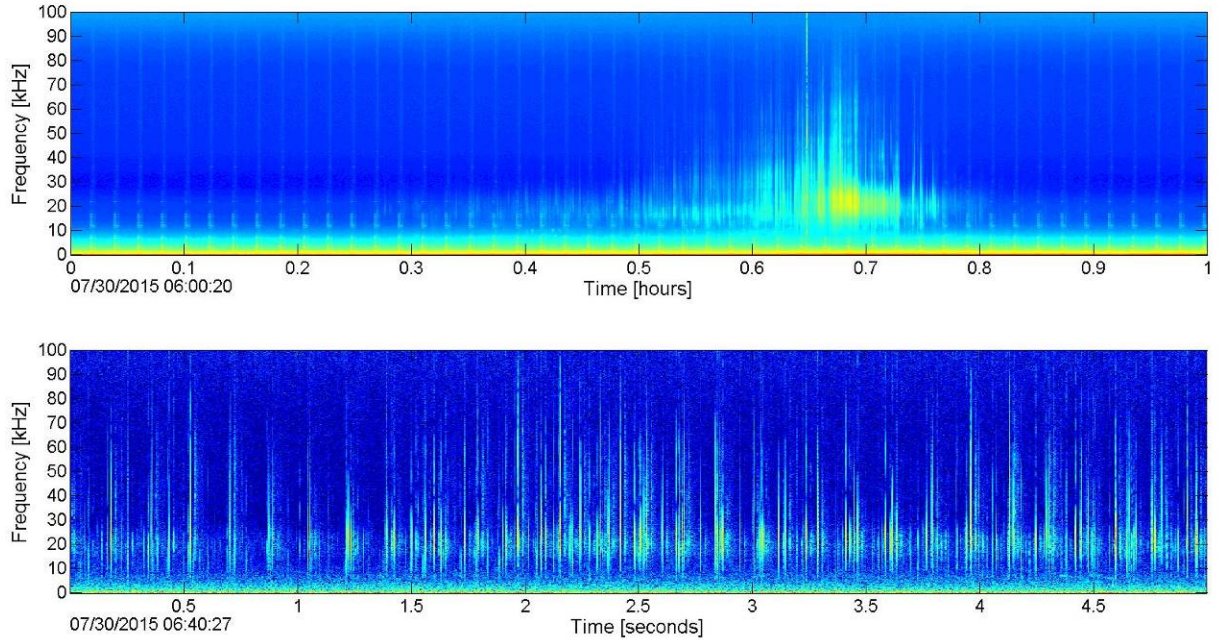


Figure 33. Click type 6 in LTSA (top) and spectrogram (bottom).

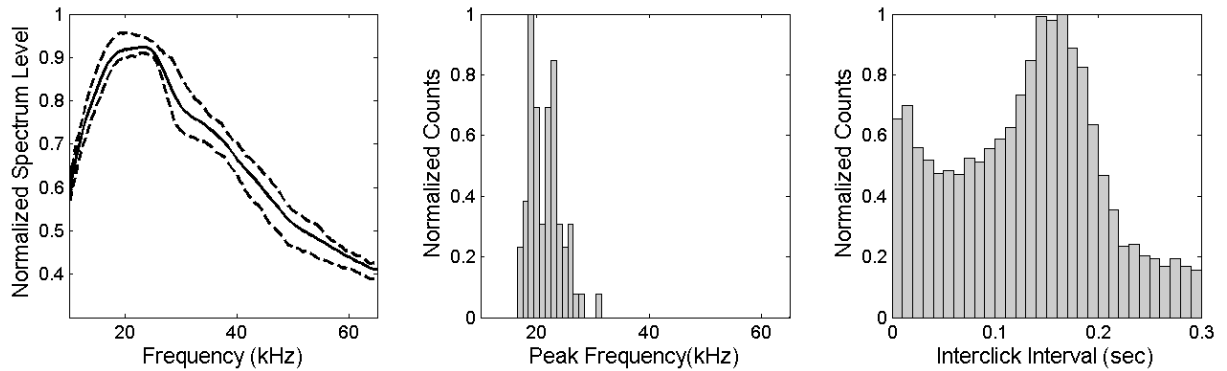


Figure 34. Left: Mean normalized received sound pressure level spectrum of click type 6 cluster (solid line) with 25th and 75th percentiles (dashed lines); Center: Distribution of click cluster peak frequencies with a peak at 19 kHz; Right: Distribution of inter-click-intervals within cluster with modal peak at 0.15 seconds.

Click Type 7

Click type 7 clicks (**Figure 35**) have a peak frequency of approximately 24 kHz and a modal ICI of 0.07 seconds (**Figure 36**).

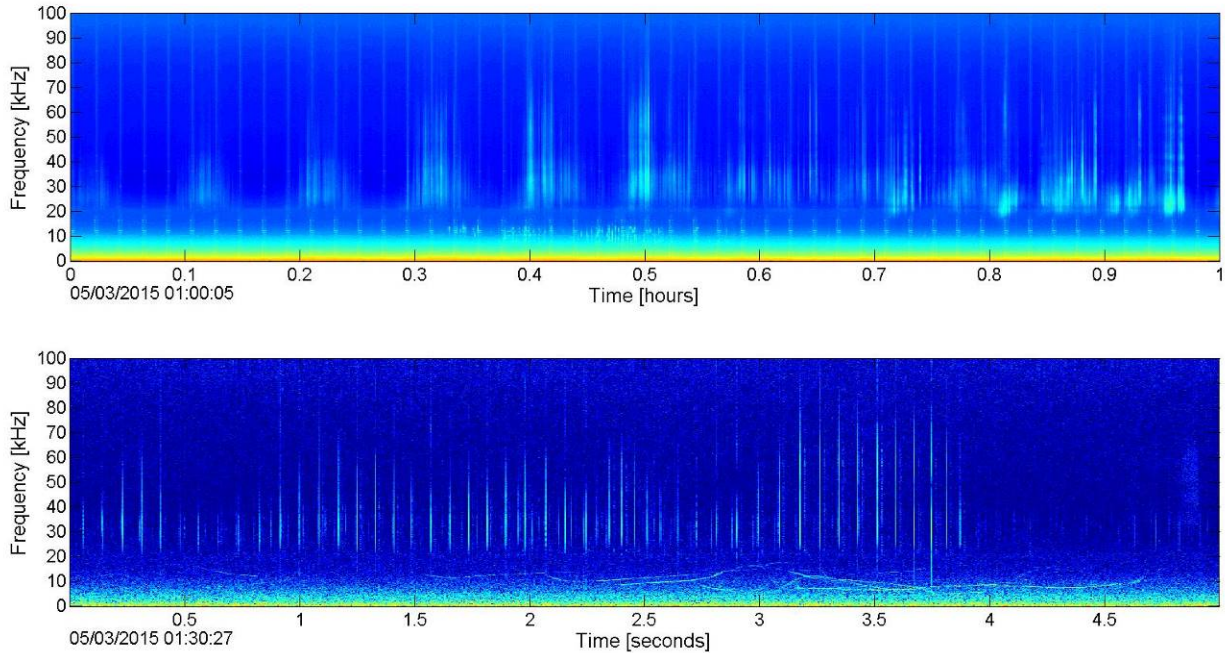


Figure 35. Click type 7 in LTSA (top) and spectrogram (bottom).

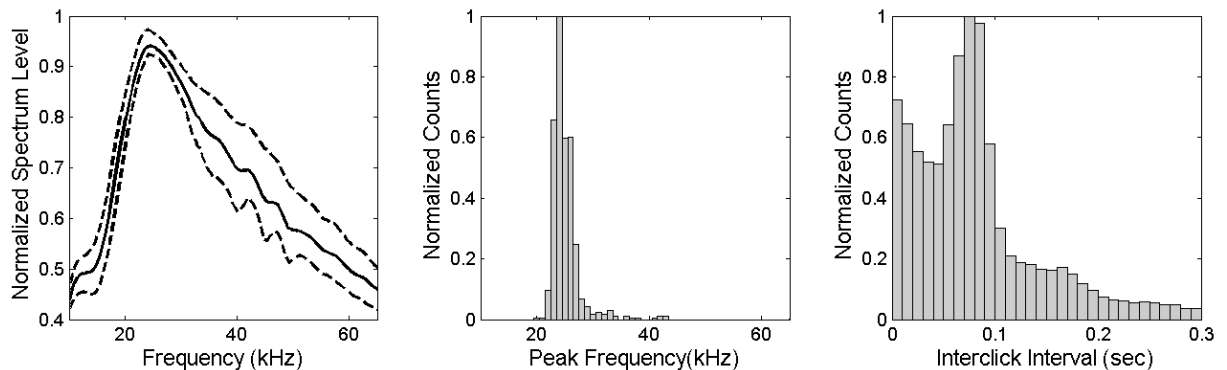


Figure 36. Left: Mean normalized received sound pressure level spectrum of click type 7 cluster (solid line) with 25th and 75th percentiles (dashed lines); Center: Distribution of click cluster peak frequencies with a peak at 24 kHz; Right: Distribution of inter-click-intervals within cluster with modal peak at 0.07 seconds.

Click Type 8

Click type 8 clicks (**Figure 37**) have a main peak frequency at approximately 41 kHz, and two minor spectral peaks at 15 and 18 kHz (**Figure 38**). This click type has a modal ICI of 0.11 seconds (Figure 38).

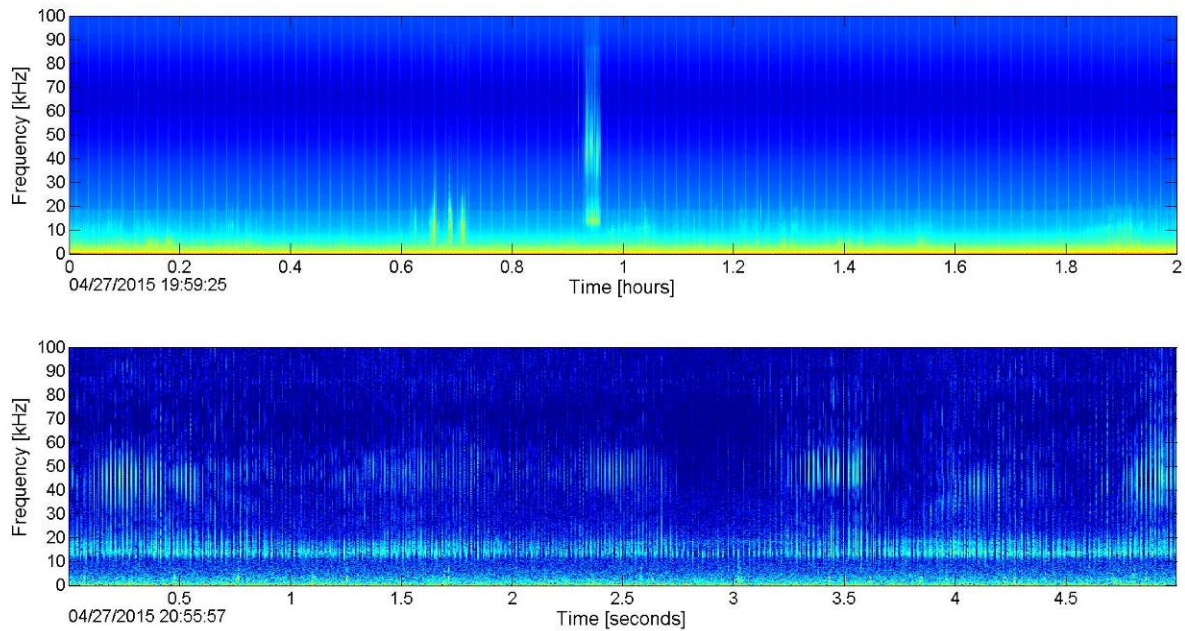


Figure 37. Click type 8 in LTSA (top) and spectrogram (bottom).

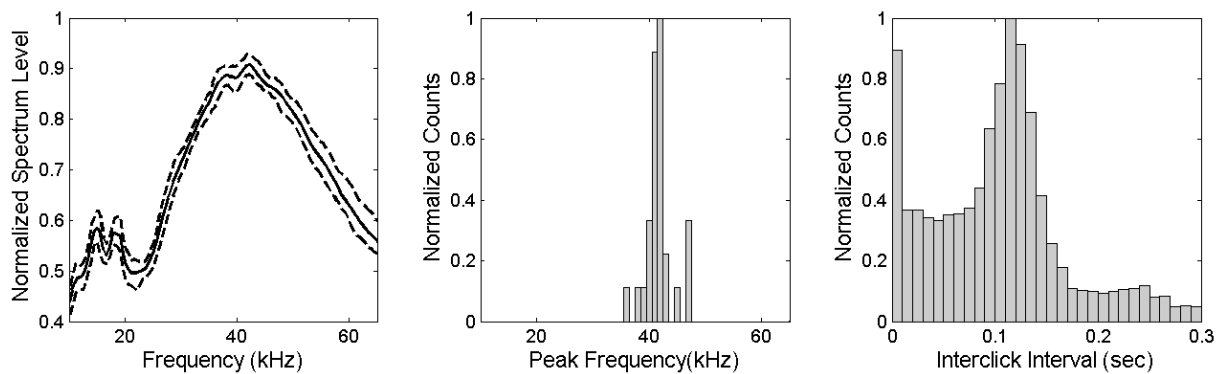


Figure 38. Left: Mean normalized received sound pressure level spectrum of click type 8 cluster (solid line) with 25th and 75th percentiles (dashed lines); Center: Distribution of click cluster peak frequencies with primary peak 41 kHz; Right: Distribution of inter-click-intervals within cluster with modal ICI of 0.11 seconds.

Anthropogenic Sounds

Several anthropogenic sounds were monitored for this report: broadband ship sound, explosions, airguns, and echosounders. The start and end of each individual sound or overall session was logged and their durations were added to estimate cumulative hourly presence. Manual effort was expended for broadband ship sound and echosounders (**Table 4**). A detector was used for the airgun and explosion analyses, both described below.

Table 4. Anthropogenic sound data analysis parameters.

Sound Type	LTSA Search Parameters	
	Plot Length (hr)	Frequency Range (Hz)
Broadband Ship Sound	3	10 – 5,000
Explosions	0.75	10 – 1,000
Airguns	0.75	10 – 2,000
Echosounders	1	5,000 – 100,000

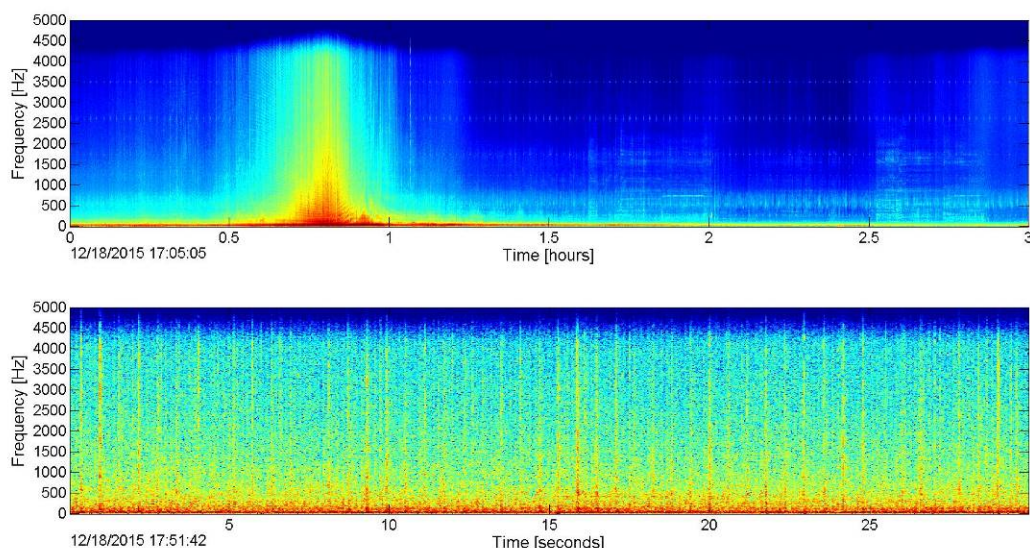


Figure 39. Broadband ship sound in the LTSA (top) and spectrogram (bottom).

Broadband Ship Sound

Broadband ship sound occurs when a ship passes within a few kilometers of the hydrophone. Ship sound can occur for many hours at a time, but broadband ship sound typically lasts from 10 minutes up to 3 hours. Ship sound has a characteristic frequency-range dependent interference pattern in the LTSA (McKenna *et al.*, 2012). Combination of sound wave direct paths and surface reflected paths produce constructive and destructive interference (bright and dark bands) in the spectrogram that varies by frequency and distance between the ship and the receiver (**Figure 39**). Noise can extend above 10 kHz, though it typically falls off above a few kHz. Broadband ship analysis effort consisted of manual scans of the LTSA set at 3 hours with a frequency range of 10 – 5,000 Hz.

Explosions

Effort was directed toward detecting explosive sounds in the recordings including military explosions, shots from sub-seafloor exploration, and seal bombs used by the fishing industry. An explosion appears as a vertical spike in the LTSA that, when expanded in the spectrogram, has a sharp onset with a reverberant decay (**Figure 40**). Explosions were detected automatically using a matched filter detector on data decimated to 10 kHz sampling rate. The timeseries was filtered with a 10th order Butterworth bandpass filter between 200 and 2,000 Hz. Cross-correlation was computed between 75 seconds of the envelope of the filtered timeseries and the envelope of a filtered example explosion (0.7 s, Hann windowed) as the match filter signal. The cross-correlation was squared to ‘sharpen’ peaks of explosion detections. A floating threshold was calculated by taking the median cross-correlation value over the current 75 seconds of data to account for detecting explosions within noise, such as shipping. A cross-correlation threshold of 3×10^{-6} above the median was set. When the correlation coefficient reached above threshold, the timeseries was inspected more closely. Consecutive explosions were required to have a minimum time distance of 0.5 second to be detected. A 300-point (0.03 s) floating average energy across the detection was computed. The start and end times above the threshold were determined when the energy rose by more than 2 dB above the median energy across the detection. Peak-to-peak (pp) and root-mean-square (rms) received sound pressure levels (RL) were computed over the potential explosion period as well as a timeseries of the length of the explosion template before and after the explosion. The potential explosion was classified as a false detection and deleted if 1) the dB difference of pp and rms levels between signal and time after the detection was less than 4 dB or 1.5 dB respectively; 2) the dB difference of pp and rms levels between signal and time before the signal was less than 3 dB or 1 dB, respectively; and 3) the detection was shorter than 0.03 or longer than 0.55 seconds of duration. The thresholds were evaluated based on the distribution of histograms of manually verified true and false detections. A trained analyst subsequently verified the remaining potential explosions for accuracy. Explosions have energy as low as 10 Hz and often extend up to 2,000 Hz or higher, lasting for a few seconds including the reverberation.

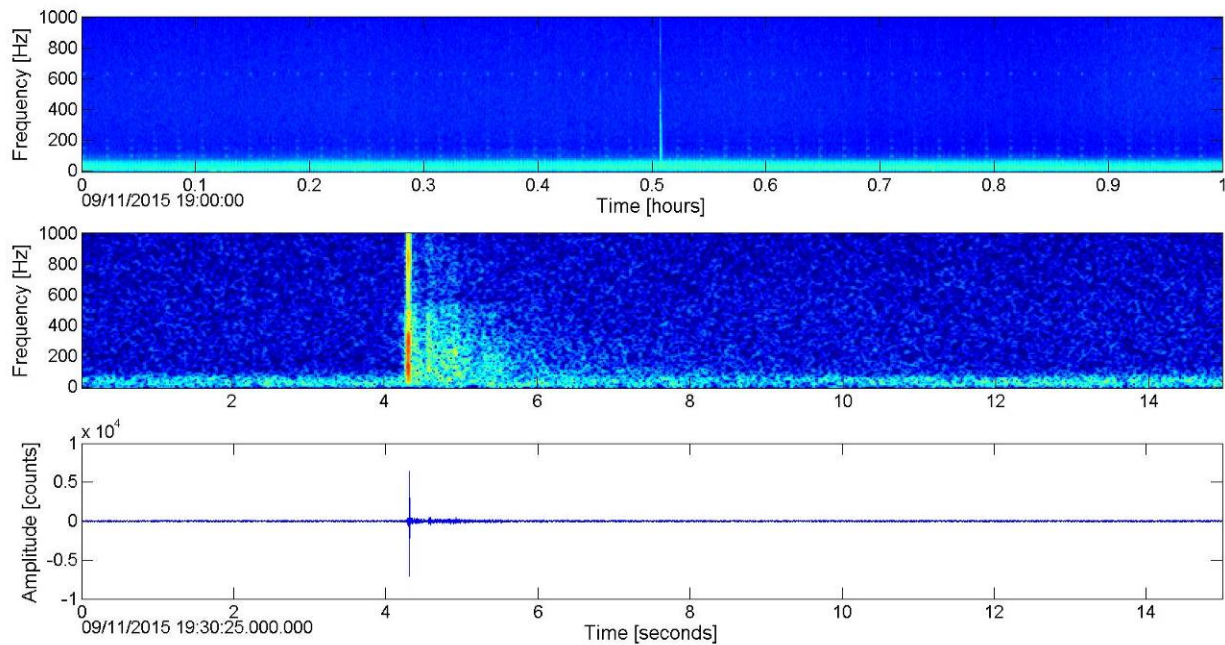


Figure 40. Explosion example in the LTSA (top), spectrogram (middle) and timeseries (bottom).

Airguns

Airguns are regularly used in seismic exploration to investigate the ocean floor and what lies beneath it. A container of high-pressure air is momentarily vented to the surrounding water, producing an air-filled cavity which expands and contracts violently several times (Barger and Hamblen, 1980). While most of the energy produced by an airgun array falls below 250 Hz, airguns can produce significant energy at frequencies up to at least 1 kHz (Blackman *et al.*, 2004). Source levels tend to be over 200 dB re 1 $\mu\text{Pa}\cdot\text{m}$, and have been measured up to 260 dB rms re 1 $\mu\text{Pa}\cdot\text{m}$ (Hildebrand, 2009). These blasts typically have an inter-pulse interval of approximately 10 seconds and can last from several hours to days (**Figure 41**). Airguns were detected automatically using a matched filter detector on data decimated to 10 kHz sampling rate. The timeseries was filtered with a 10th order Butterworth bandpass filter between 25 and 200 Hz. Cross correlation was computed between 75 seconds of the envelope of the filtered timeseries and the envelope of a filtered example explosion (0.7 s, Hann windowed) as the matched filter signal. The cross correlation was squared to ‘sharpen’ peaks of airgun blast detections. A floating threshold was calculated by taking the median cross correlation value over the current 75 seconds of data to account for detecting airguns within noise, such as shipping. A cross correlation threshold of 2×10^{-6} above the median was set. When the correlation coefficient reached above this threshold, the timeseries was inspected more closely. Consecutive airgun blasts were required to have a minimum time distance of 2 seconds to be detected. A 300-point

(0.03 s) floating average energy across the detection was computed. The start and end times above the threshold were marked when the energy rose by more than 2 dB above the median energy across the detection. Peak-to-peak and rms received sound pressure levels were computed over the potential blast period as well as a timeseries of the length of the airgun blast template before and after the explosion. The potential airgun blast was classified as a false detection and deleted if 1) the dB difference of pp and rms between signal and time after the detection was less than 4 dB or 0.5 dB respectively; 2) the dB difference of pp and rms between signal and time before the signal was less than 3 dB or 0.5 dB, respectively; and 3) the detection was shorter than 0.03 or longer than 10 s. The thresholds were evaluated based on the distribution of histograms of manually verified true and false detections. Airgun blast interpulse intervals were used to discard potential airgun detections that were not part of a sequence. A trained analyst subsequently verified the remaining potential airgun detections for accuracy. Airgun blasts have energy as low as 10 Hz and can extend up to 250 Hz or higher, lasting for a few seconds including the reverberation.

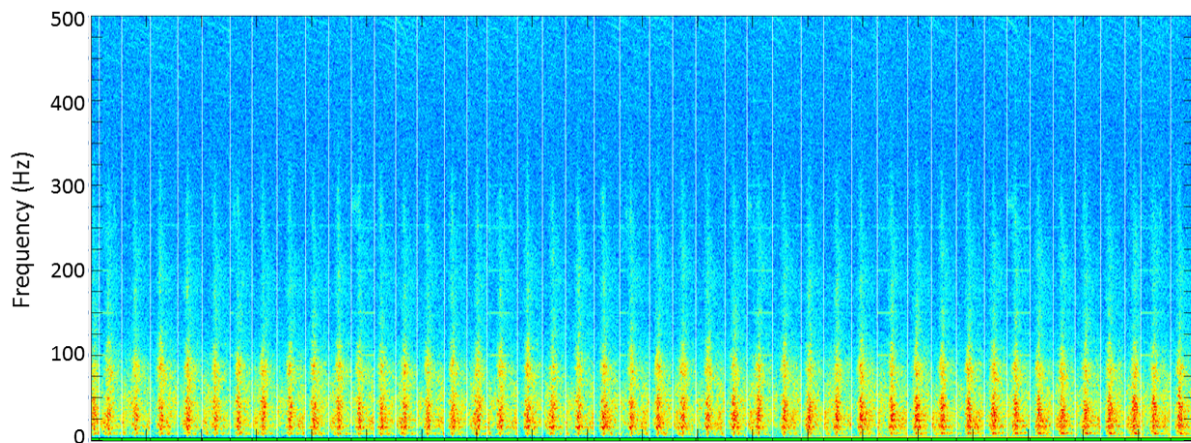


Figure 41. Airgun pulses in the analyst verification stage of the detector.

Echosounders

Echosounding sonars transmit short pulses or frequency sweeps, typically in the high-frequency (above 5 kHz) band (**Figure 42**), though echosounders are occasionally found in the mid-frequency range (2-5 kHz). Many large and small vessels are equipped with echosounding sonar for water depth determination; typically, these echosounders are operated much of the time a ship is at sea, as an aid for navigation. In addition, sonars may be used for sea bottom mapping, fish detection, or another ocean sensing. Presence of high-frequency echosounders was manually detected by analysts reviewing LTSA plots.

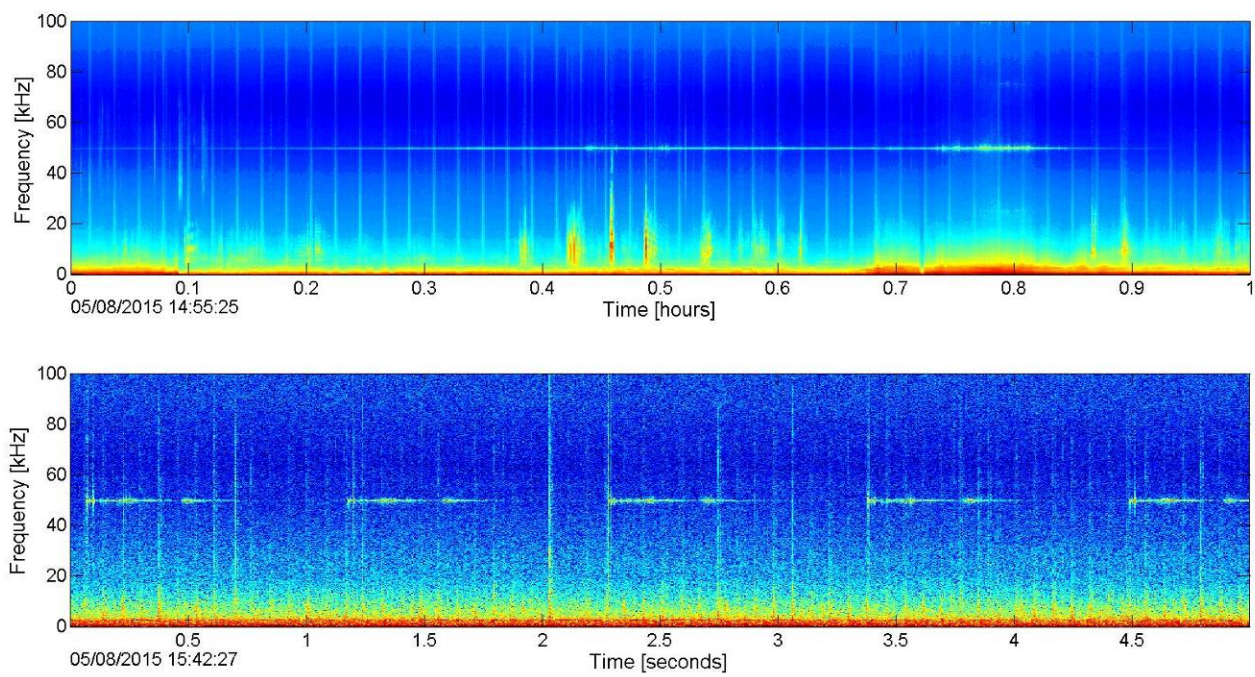


Figure 42. Echosounder at 50 kHz in the LTSA (top) and spectrogram (bottom).

Results

The detailed analysis of these data sets is in progress as outlined in **Table 5**. All three datasets have gone through data transfer from the field disks and conversion from compressed (HRP) format to standard audio (XWAV) format, and LTSA's have been calculated for both full bandwidth and decimated data. Most effort has been applied to the JAX13D data set in terms of both manual and automatic detectors (85% complete). The NFC02A data set has received the next most effort (50% complete), whereas the HAT06A data set is awaiting processing. The technical reports with complete results will be available by summer of 2018. Two representative analyses from the JAX13D detailed report are presented below.

Table 5. Progress in data analysis for deployments NFC02A, HAT06A, and JAX13D.

Step in Data Analysis	NFC02A	HAT06A	JAX13D
Data Transferred from Field Disks	X	X	X
Create XWAVS and LTSA	X	X	X
Humpback whale detector /manual verify			X
Minke whale manual detection	X		X
Right whale manual detection	X		X
Blue whale manual detection	X		X
Fin whale 40 Hz manual detection	X		X
Fin whale energy detector			X
Bryde's whale manual detection	X		X
Sei whale manual detection	X		X
Odontocete whistles > 10 kHz			X
Odontocete whistles < 5 kHz			X
Beaked whale detector / manual verify			X
Kogia detector / manual verify			
Dolphin click detector / manual verify			X
Sperm whale detector / manual verify			
Ambient noise monthly analysis			
Broadband ship manual detection	X		X
Explosion detector / manual verify	X		X
Echosounders and HFA > 5 kHz			X
MFA detector /manual verify			X
LFA < 500 Hz manual detection	X		X
LFA > 500 Hz manual detection	X		X

Unidentified Odontocete Whistles Greater Than 10 kHz

At JAX 13D, unidentified odontocete whistles greater than 10 kHz were detected frequently between April 2016 and June 2017. Detections were highest from January 2017 to May 2017 (**Figure 30**). There was no diel pattern for whistles greater than 5 kHz (**Figure 31**). Pilot whales are the most likely species to have produced these whistles.

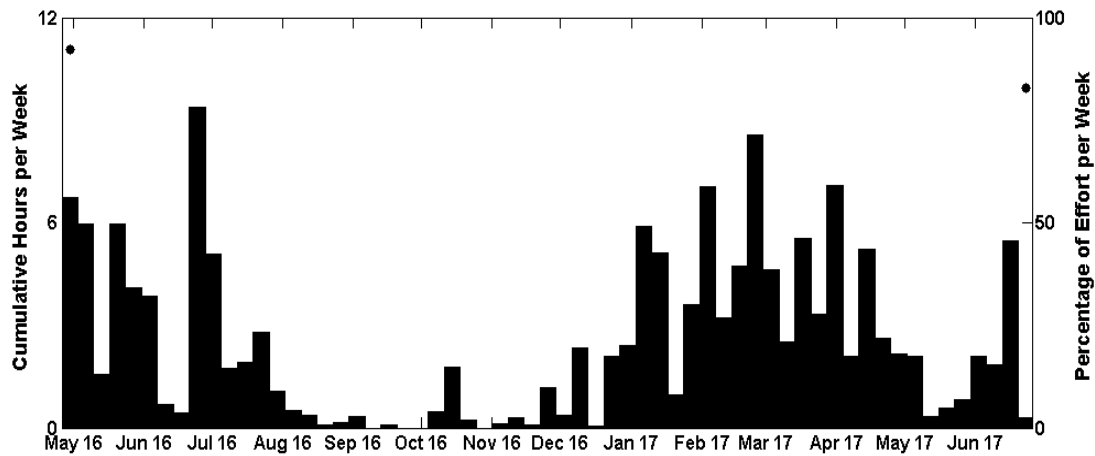


Figure 30. Weekly presence of unidentified odontocete whistles greater than 10 kHz between April 2016 and June 2017 at JAX 13 D.

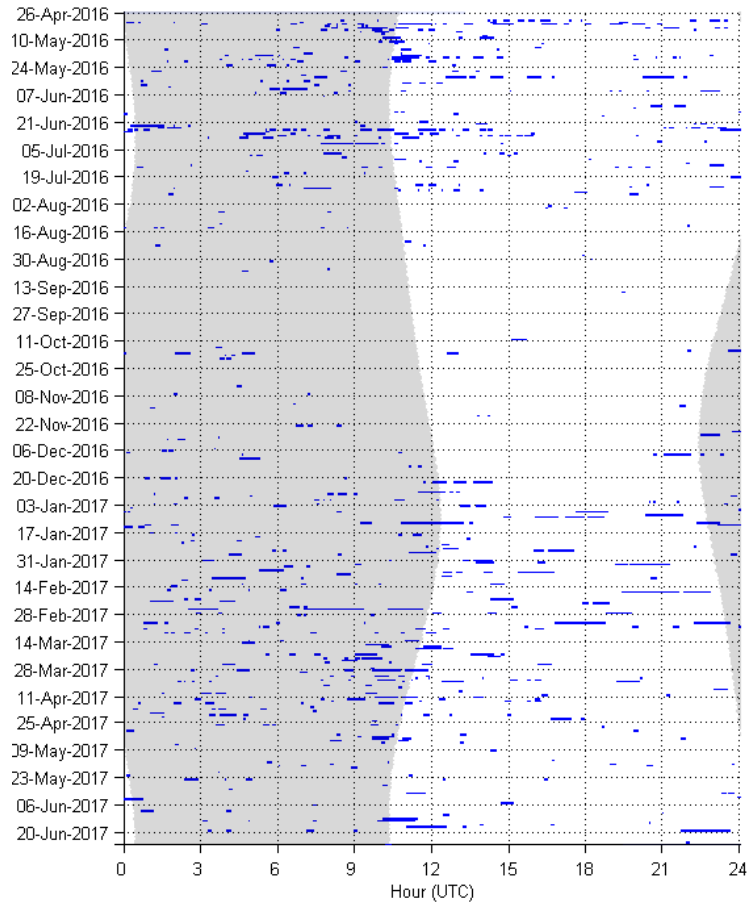
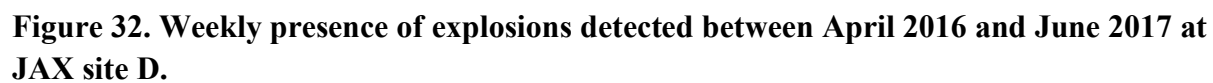


Figure 31. Unidentified odontocete whistles greater than 10 kHz in one-minute bins between April 2016 and June 2017 at JAX 13 D.

Explosions

At the JAX 13 D, a few explosions were detected from May 2016 to August 2016 and again during October 2016 (Figure 32). Manual analysis was conducted to ensure that explosions were not missed by the automated detector. No diel pattern for explosions was seen during the recording period (Figure 33).



References

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