Conducted in support of the U.S. Navy's Northwest Training Range Complex 2015 Annual Monitoring Report

Passive Acoustic Monitoring for Marine Mammals in the Northwest Training Range Complex July 2013 – April 2014

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Dall's porpoise, photo by Amanda J. Debich

MPL TECHNICAL MEMORANDUM # 557
June 2015

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
06-2015

2. REPORT TYPE
Monitoring report

3. DATES COVERED *(From - To)*
Jul 2013 - Apr 2014

4. TITLE AND SUBTITLE
Passive Acoustic Monitoring for Marine Mammals in the Northwest Training Range Complex July 2013 – April 2014

5a. CONTRACT NUMBER

5b. GRANT NUMBER
W9126G-14-2-0040

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Whale Acoustics Laboratory, Marine Physical Laboratory, Scripps Institution of Oceanography, University of California San Diego, La Jolla, CA 92037

8. PERFORMING ORGANIZATION REPORT NUMBER
MPL TECHNICAL MEMORANDUM # 557

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Commander, U.S.Pacific Fleet, 250 Makalapa Drive, Pearl Harbor, HI

10. SPONSOR/MONITOR'S ACRONYM(S)
CPF

11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Passive acoustic monitoring was conducted in the Navy's Northwest Training Range Complex from July 2013 to April 2014 to detect marine mammal and anthropogenic sounds. Three baleen whale species were detected: blue whales, fin whales, and humpback whales. Minke whale boings, which were first recorded in the NWTRC in November 2012, were not detected during this monitoring period. Likewise, North Pacific right whale up-calls were detected for the first time in the NWTRC in June 2013, but there were no definitive detections of this species during this recording period. Frequency-modulated echolocation pulses from three beaked whale species were detected at the offshore site. Three anthropogenic sounds were detected in the recordings: mid-frequency active and low-frequency active sonars, and explosions.

15. SUBJECT TERMS
Monitoring, passive acoustic, marine mammal, anthropogenic sound, Nortwest Training Range Complex

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON / 19b. TELEPONE NUMBER (*Include area code*)
Unclassified	Unclassified	Unclassified	UU	44	Department of the Navy / (619) 767-1567

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Executive Summary

Passive acoustic monitoring was conducted in the Navy's Northwest Training Range Complex from July 2013 to April 2014 to detect marine mammal and anthropogenic sounds. High-frequency Acoustic Recording Packages (HARPs) recorded sounds between 10 Hz and 100 kHz at two locations: an offshore shelf slope site near Quinault Canyon (site QC, 1,384 m depth) and an inshore site on the shelf near Cape Elizabeth (site CE, 120 m depth).

Data analysis was performed using automated computer algorithms, augmented with analyst scans of long-term spectral averages (LTSAs) and spectrograms. Three frequency bands were analyzed for marine mammal vocalizations and anthropogenic sounds.

Three baleen whale species were detected: blue whales, fin whales, and humpback whales. Seasonal patterns for Northeast Pacific blue whale B calls, fin whale 20 Hz calls, and humpback whale calls were similar, all showing peaks during the winter months. In contrast, blue whale D calls were only detected in July 2013 at site CE. Minke whale boings, which were first recorded in the NWTRC in November 2012, were not detected during this monitoring period. Likewise, North Pacific right whale up-calls were detected for the first time in the NWTRC in June 2013, but there were no definitive detections of this species during this recording period.

Frequency-modulated (FM) echolocation pulses from three beaked whale species were detected at the offshore site QC. Stejneger's beaked whale detections were more common than any other beaked whale signal recorded in this monitoring period and peaked in January 2014. Cuvier's beaked whales were infrequently detected during the winter months, while Baird's beaked whale detections occurred intermittently throughout the monitoring period. Killer whale detections predominantly occurred at site CE and peaked in August 2013. Unidentified porpoises were detected in low numbers at site CE in July 2013.

Three anthropogenic sounds were detected in the recordings: mid-frequency active (MFA) and low-frequency active (LFA) sonars, and explosions. Mid-frequency active (MFA) sonar was rare, with only a single detection occurring in January 2014. Low-frequency active (LFA) sonar events were also relatively rare, and were detected on three separate occasions. Explosions, most likely from fishery-related seal bombs, were detected throughout the deployment at site CE, with a peak in detections in August 2013.

Project Background

The Navy's Northwest Training Range Complex (NWTRC) contains an offshore area that extends west 250 nautical miles beyond the coasts of Washington, Oregon, and Northern California. This region is a productive ecosystem inhabited by many species of marine mammals. The area includes deep water habitats, utilized by beaked and sperm whales, as well as continental shelf waters that are frequented by coastal cetaceans, pinnipeds, and porpoises. Endangered species known to occupy this area include blue whales, fin whales, North Pacific right whales, humpback whales, sperm whales, and killer whales.

An acoustic and visual monitoring effort for marine mammals was initiated within the boundaries of the NWTRC with a focus on the Quinault Underwater Tracking Range (QUTR), off the coast of Washington, beginning in July 2004. Two High-frequency Acoustic Recording Packages (HARPs) have been intermittently deployed near the QUTR since 2004, one in deeper waters on the shelf slope within Quinault Canyon (QC) and a second on the continental shelf off Cape Elizabeth (CE). In 2014, support for continuation of acoustic monitoring in the NWTRC was provided by the Pacific Fleet to Scripps Institution of Oceanography under the Californian Cooperative Ecosystems Studies Unit 08-09a administered by the US Army Corps of Engineers. The goal of this effort was to characterize the vocalizations of marine mammal species present in the area, to determine their seasonal presence patterns, and to evaluate the potential for impact from naval operations.

This report documents the analysis of data recorded by two HARPs that were deployed within the NWTRC at sites QC and CE (Figure 1). Data from site QC were analyzed for the July 2013 through April 2014 time period, while data from site CE were analyzed for the July 2013 through August 2013 time period (Table 1).

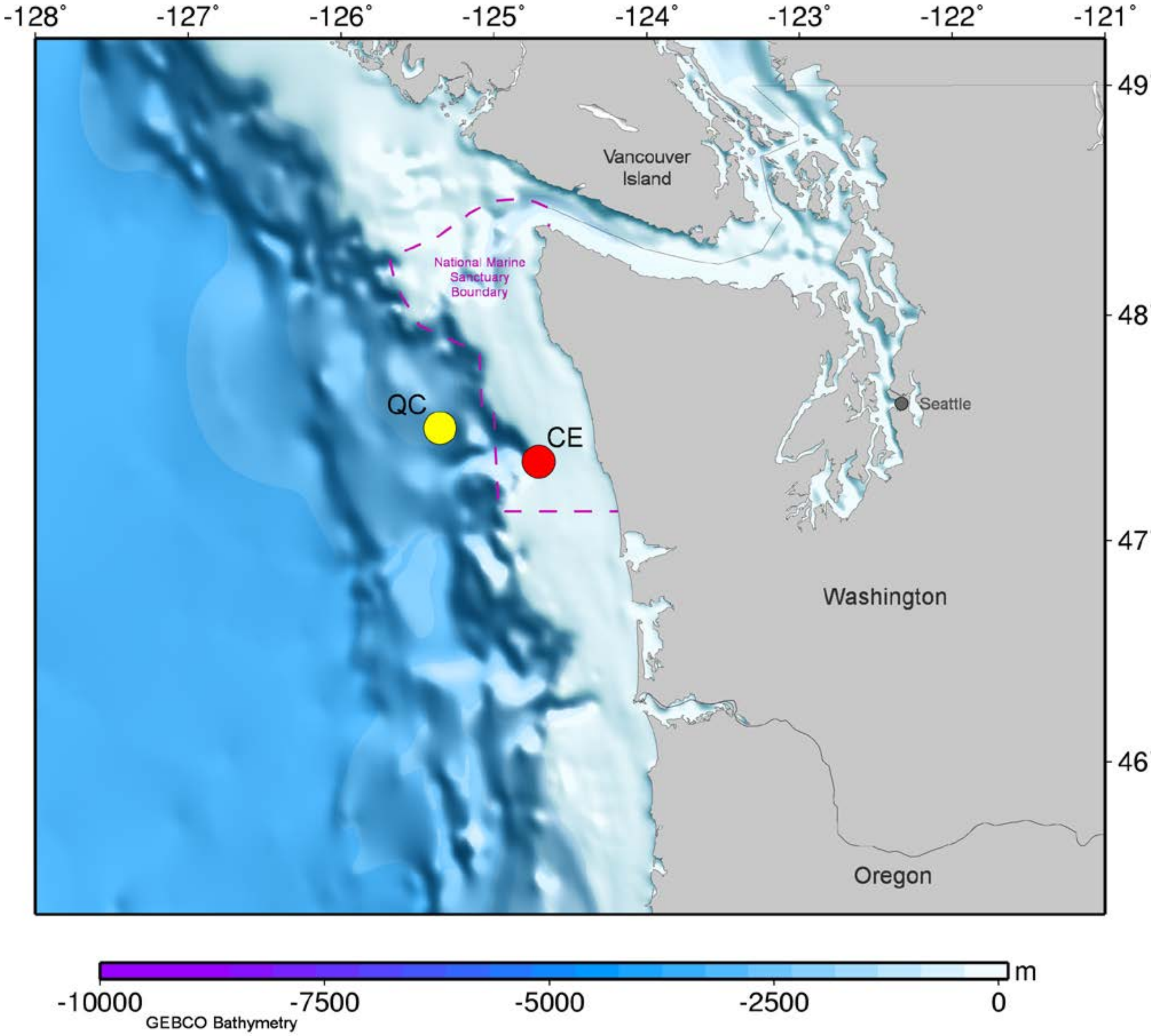

Figure 1. Locations of the High-frequency Acoustic Recording Packages (HARPs) at sites QC and CE deployed in the NWTRC study area July 2013 through April 2014. The purple dotted line represents the Olympic Coast National Marine Sanctuary boundary. Color is bathymetric depth.

Table 1. NWTRC acoustic monitoring since 2004. Periods of instrument deployment analyzed in this report are shown in bold.

Acoustic Monitoring Period	Sample Rate & Duty Cycle (on/off, in min)	QC: Slope	CE: Shelf
OCNMS01: July – October 2004	80 kHz Continuous	Yes	Lost
OCNMS02: October 2004 – January 2005	80 kHz 10/20	Yes	--
OCNMS03: July 2005 – February 2006	80 kHz 6/12	Yes	--
OCNMS04: August 2006 – February 2007	80 kHz 6/12	Yes	Yes
OCNMS05: April – July 2007	80 kHz Continuous	Yes	Yes
OCNMS06: July 2007 – June 2008	200 kHz 5/35	Yes	--
OCNMS07: October 2007 – June 2008	200 kHz 5/30	--	Yes
OCNMS08: June 2008 – June 2009	200 kHz 5/35	Lost	Yes
OCNMS09: December 2009 – January 2011	200 kHz 5/30	--	Lost
OCNMS12: January – October 2011	200 kHz Continuous	Yes	--
OCNMS13: May – November 2011	200 kHz Continuous	--	Yes
OCNMS14: December 2011 – July 2012	200 kHz Continuous	Yes	Yes
OCNMS15: September 2012 – June 2013	200 kHz Continuous	Yes	Yes
OCNMS16: July 2013 – April 2014	**200 kHz Continuous**	**Yes**	**Yes**

Methods

High-frequency Acoustic Recording Package

HARPs were used to record marine mammal sounds and characterize anthropogenic sounds and ambient noise in the NWTRC area. HARPs can record underwater sounds from 10 Hz up to 160 kHz, and are capable of approximately 300 days of continuous data storage. The HARPs were in a seafloor package configuration with the hydrophones suspended 10 m above the seafloor. Each HARP was calibrated in the laboratory to provide a quantitative analysis of the received sound field. Representative data loggers and hydrophones were also calibrated at the Navy's TRANSDEC facility to verify the laboratory calibrations (Wiggins and Hildebrand, 2007).

Data Collected

Acoustic data were collected at two sites within the NWTRC using autonomous HARPs sampling continuously at 200 kHz (Table 1). The sites are designated site QC (47° 30.04'N, 125° 21.26'W, depth 1,384 m) and site CE (47° 21.17'N, 124° 42.47'W, depth 120 m). Site QC yielded data from July 17, 2013 to April 3, 2014. Site CE only yielded data from July 17, 2013 to August 4, 2013. A total of 6,720 hours, covering 280 days of acoustic data, were recorded in the deployments analyzed in this report. Earlier data collection in the NWTRC is documented in previous annual reports (Oleson *et al.*, 2009; Širović *et al.*, 2011; Širović *et al.*, 2012; Kerosky *et al.*, 2013; Debich *et al.*, 2014).

Data Quality

The recording from site CE terminated prematurely because of a laptop disk drive failure, resulting in only 19 days of good acoustic data. These hard disk drives are no longer commercially available and efforts to replace the HARP's mass data storage with modern technology to increase reliability are underway with support from the Navy's Living Marine Resources program. Recordings from site CE also exhibited low-frequency strumming, as is common with shallow water deployments due to tidal flows, but strumming was not severe.

The recording from site QC was 260 days in duration, but a hydrophone malfunction reduced the quality of the low- and mid-frequency data (<25 kHz) by increasing electronic self-noise. The malfunction was not consistent in severity or over time, allowing for analysis but typically with reduced data quality. Analysis of echolocation clicks was unaffected by the hydrophone malfunction, but the detection of odontocete whistles, mysticete calls, and anthropogenic sounds was hampered. A hydrophone re-design is underway to prevent this type of malfunction in future deployments.

Data Analysis

To visualize the acoustic data, frequency spectra were calculated for all data using a time average of 5 seconds and variable size frequency bins (1, 10, and 100 Hz). These data, called Long-Term Spectral Averages (LTSAs), were then examined as a means to detect marine mammal and anthropogenic sounds. Data were analyzed by visually scanning LTSAs in source-specific frequency bands or, when appropriate, using automatic detection algorithms (described below).

Mid-frequency active (MFA) sonar were detected manually. During manual analysis, when a sound of interest was identified in the LTSA but its origin was unclear, the waveform or spectrogram of the sound was examined to further classify the sounds to species or source. Signal classification was carried out by comparison to known species-specific spectral and temporal characteristics.

Recording over a broad frequency range of 10 Hz – 100 kHz allows detection of baleen whales (mysticetes), toothed whales (odontocetes), and anthropogenic sounds. The presence of acoustic signals from multiple marine mammal species and anthropogenic noise was evaluated in the data. To document the data analysis process, we describe the major classes of marine mammal calls and anthropogenic sounds in the NWTRC, as well as the procedures used to detect them. For effective analysis, the data were divided into three frequency bands: (1) Low-frequency, between 10-300 Hz, (2) Mid-frequency, between 10-5,000 Hz, and (3) High-frequency, between 1-100 kHz. Each band was analyzed for the sounds of an appropriate subset of species or sources. Blue whale, fin whale, and North Pacific right whale sounds were classified as low-frequency. Humpback whale, minke whale, underwater communications, explosions, and sonar sounds were classified as mid-frequency. The remaining odontocete sounds were considered high-frequency.

We summarize acoustic data collected between July-August 2013 at site CE and July 2013-April 2014 at site QC. We discuss seasonal occurrence and relative abundance of calls for different species and anthropogenic sounds that were consistently identified in the acoustic data.

Low-Frequency Marine Mammals

The hourly presence of Northeast Pacific blue whale B calls, blue whale D calls, fin whale 20 Hz calls, and North Pacific right whale up-calls was determined by manual scrutiny of low-frequency LTSAs and spectrograms. The 200 kHz sampled raw data were decimated by a factor of 100 for an effective bandwidth of 1 kHz, and 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 low-frequency call types using the custom software program *Triton*. During manual scrutiny of the data, the LTSA frequency was set to display between 1-300 Hz with a 1 hour plot length. To observe individual calls, the spectrogram window was typically set to display 1-200 Hz with a 60 second plot length. The FFT was generally set between 1000 and 2000 data points, yielding about 1 Hz frequency resolution, with an 85-95% overlap. When a call of interest was identified in the LTSA or spectrogram, its presence during that hour was logged.

Blue Whales

Blue whales (*Balaenoptera musculus*) produce a variety of calls worldwide (McDonald *et al.*, 2006). Blue whale calls recorded in the eastern North Pacific include the Northeast Pacific blue whale B call (Figure 2), which is a geographically distinct call potentially associated with mating functions (McDonald *et al.*, 2006; Oleson *et al.*, 2007). B calls are low-frequency (fundamental frequency < 20 Hz), have long duration (> 10 s), and often are regularly repeated. Blue whales also produce D calls, which are downswept in frequency (approximately 100-40 Hz) with durations of several seconds (Figure 3). These calls are similar worldwide and are associated with feeding animals; they may be produced as call-counter call between multiple animals (Oleson *et al.*, 2007).

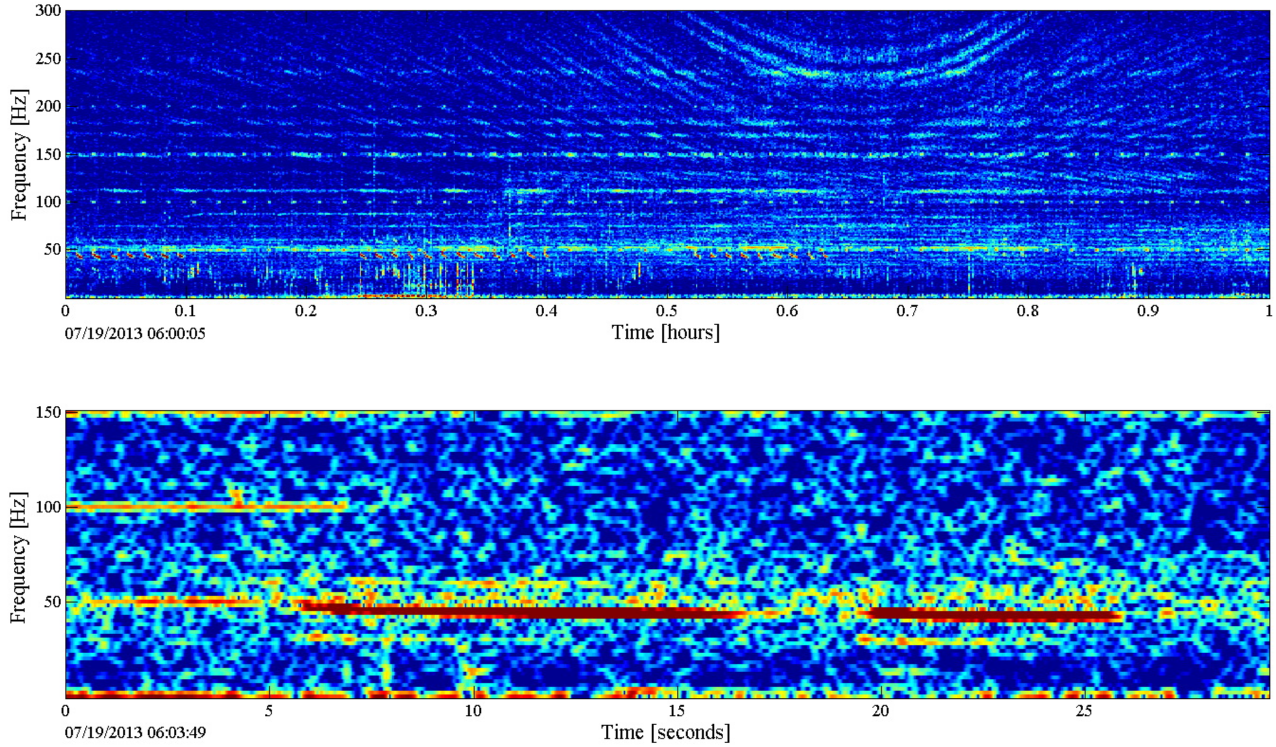

Figure 2. Blue whale B call in LTSA (top) and spectrogram (bottom).

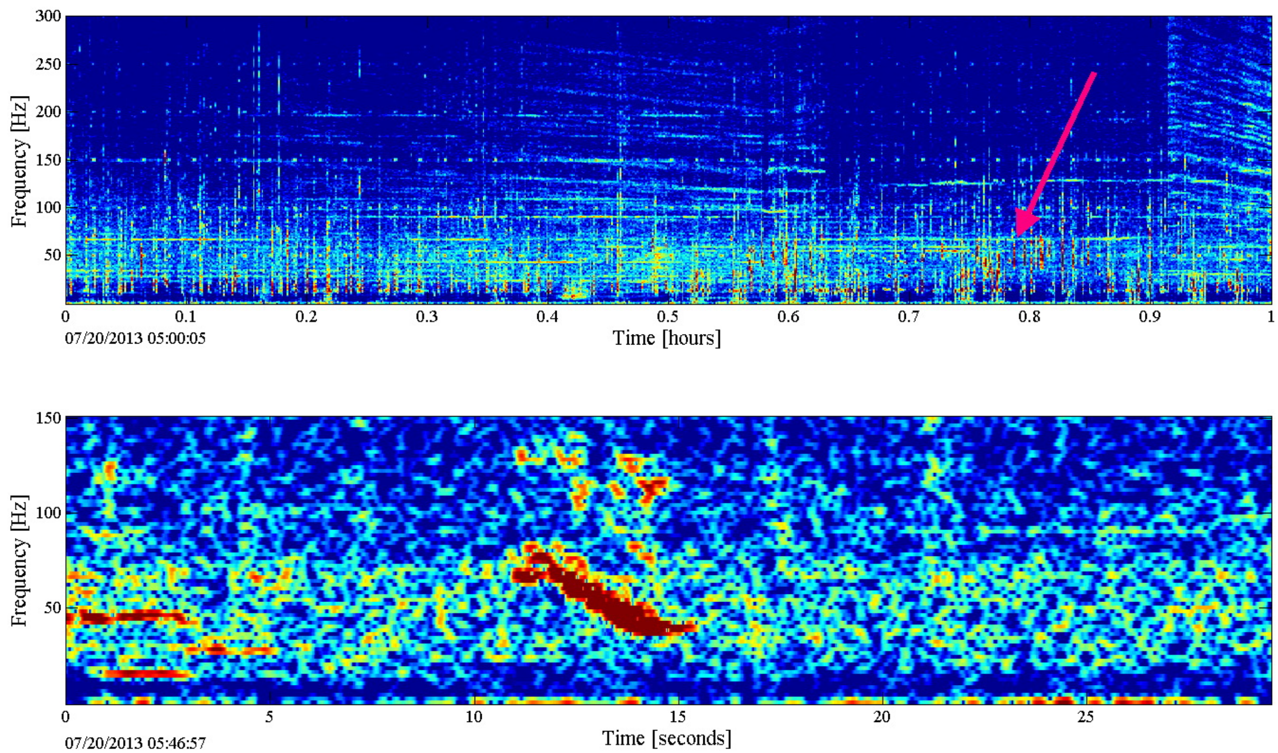

Figure 3. Blue whale D call in LTSA (top) and spectrogram (bottom).

Fin Whales

Fin whale (*B. physalus*) calls recorded in the eastern North Pacific include short (~ 1 s duration), low-frequency calls that are downsweeps in frequency from 30-15 Hz and are referred to as 20 Hz calls (Watkins, 1981) (Figure 4). 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).

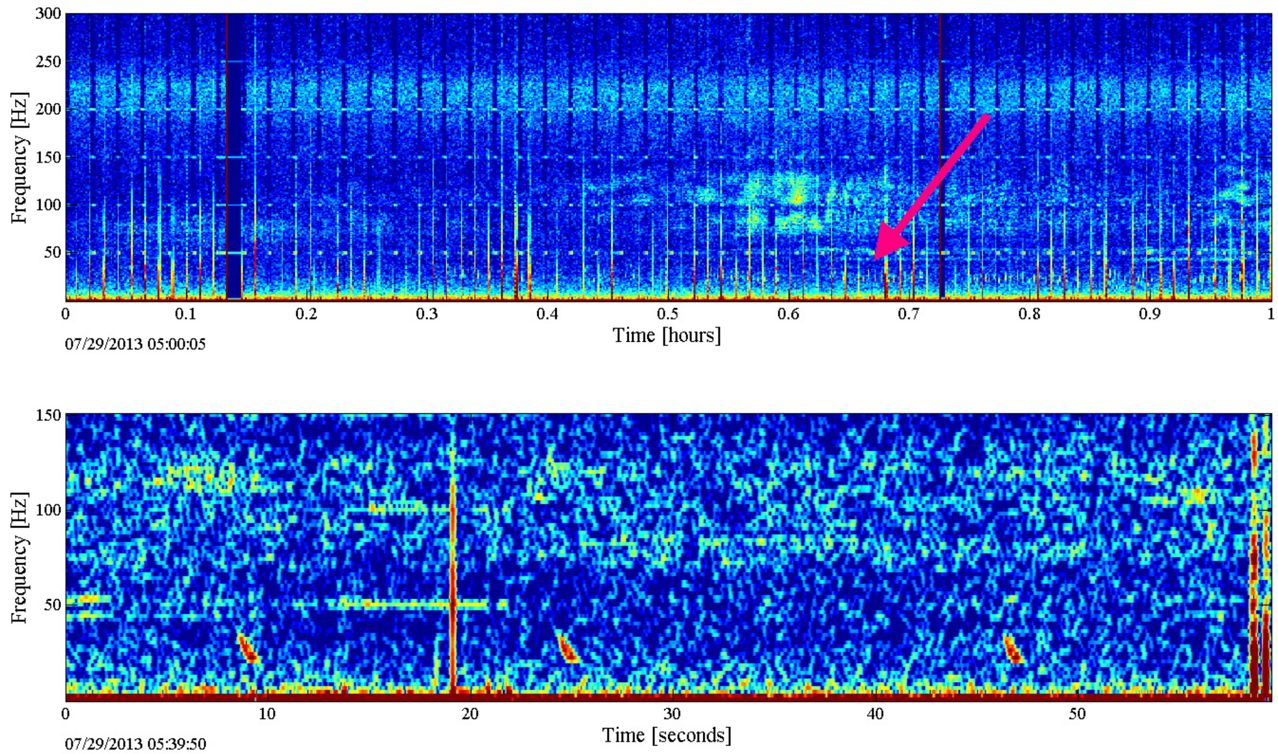

Figure 4. Fin whale 20 Hz calls in LTSA (top) and spectrogram (bottom) at site QC.

North Pacific Right Whales

North Pacific right whales (*Eubalaena japonica*) are a highly endangered cetacean species that was plentiful in the Gulf of Alaska prior to intense commercial whaling (Brownell *et al.*, 2001; Scarff, 1986). These whales make a variety of sounds, of which the most common is the "up-call". The up-call typically sweeps from about 90 to 150 Hz, or as high as 200 Hz, and has a duration of approximately one second (McDonald & Moore, 2002). The first recordings of these up-calls in the NWTRC occurred at site QC in June 2013 (Figure 5) (Debich *et al.*, 2014; Širović et al. 2015). No North Pacific right whale up-calls were detected during this monitoring period. Although there were no definite detections of North Pacific rights whales, there were two possible "down-calls" (McDonald & Moore, 2002; Širović et al. 2015) recorded at site CE on July 17, 2013. However, we were unable to conclusively determine whether these signals belong to North Pacific right whales.

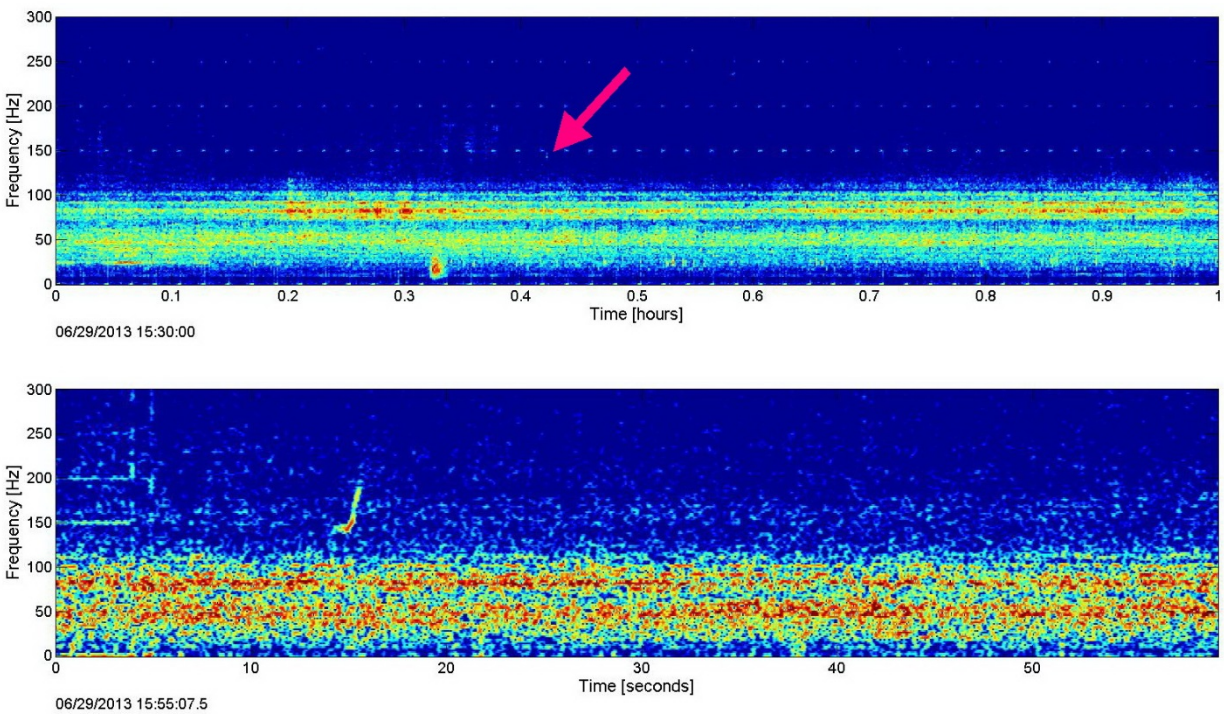

Figure 5. North Pacific right whale "up-call" example in the LTSA (top) and spectrogram (bottom) from a previous deployment at site QC on June 29, 2013.

Mid-Frequency Marine Mammals

Marine mammal species that produce sounds in the mid-frequency data range and are expected to occur off Washington include humpback whales and minke whales. Humpback whale calls and minke whale boings were detected automatically, as described below.

Humpback Whales

Humpback whales (*Megaptera novaeangliae*) produce both song and non-song calls (Payne & 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 & McVay (1971). Most humpback whale vocalizations are produced between 100 - 3,000 Hz. Humpback whale calls were detected using an automatic algorithm based on the generalized power law (Helble *et al.*, 2012). A trained analyst subsequently verified the detections (Figure 6). There was no effort to separate song and non-song calls.

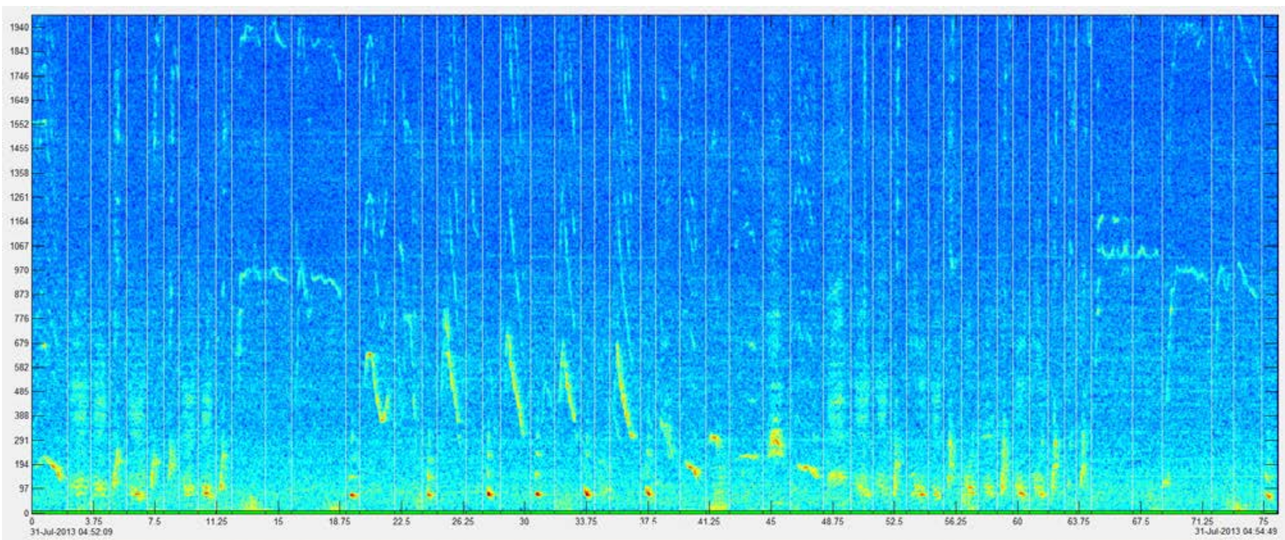

Figure 6. Humpback whale calls in the analyst verification stage of the detector. Green in the bottom evaluation line indicates true detections.

Minke Whales

Minke whale (*B. acutorostrata*) “boings” consist of 2 parts, beginning with a burst and followed by a long buzz, with the dominant energy band just below 1,400 Hz (Figure 7). Boings are divided geographically into eastern and central Pacific variants, with a dividing line at about 135°W. Eastern boings have an average duration of 3.6 s and a pulse repetition rate of 92 s^{-1} (Rankin & Barlow 2005). Minke whale boings were first detected in the NWTRC in November 2012 at site QC (Debich *et al.*, 2014). Effort was directed towards finding minke whale boings in the recordings using an automatic detection algorithm based on the generalized power law (Helble *et al*., 2012), and the automatic detections were subsequently verified for accuracy by a trained analyst. No minke whale boings were detected during this monitoring period.

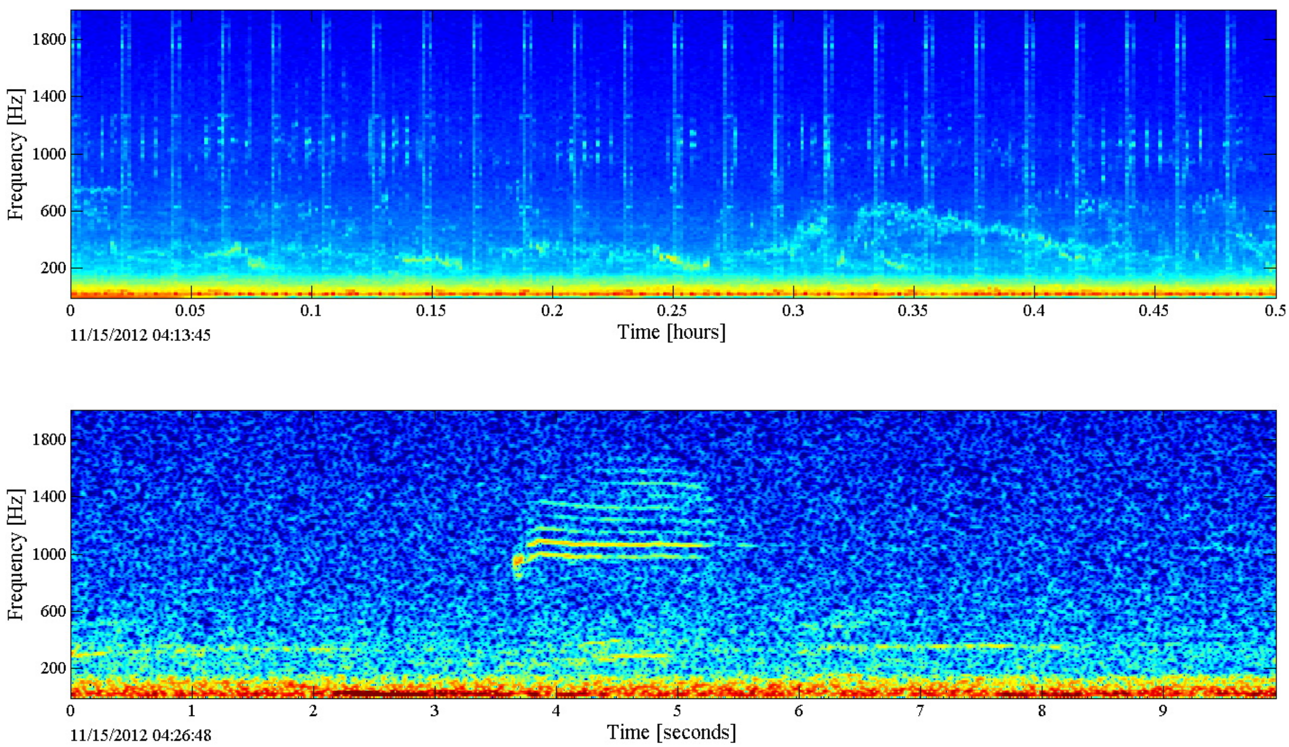

Figure 7. Minke whale boings in LTSA (top) and spectrogram (bottom).

High-Frequency Marine Mammals

High-frequency, species-specific sounds monitored in this report include: killer whales, Stejneger's beaked whales, Cuvier's beaked whales, and Baird's beaked whales. Also monitored were narrow-band high frequency clicks from unidentified porpoise. The start and end of each acoustic encounter was logged and their durations were added to estimate cumulative hourly presence of each high-frequency sound source in the dataset.

Killer Whales

Killer whales are known to produce four call types: pulsed calls, low-frequency whistles, echolocation clicks, and high-frequency modulated (HFM) signals (Ford 1989, Samarra *et al.* 2010, Simonis *et al.* 2012). Killer whale pulsed calls are well documented and are the best described of all killer whale call types (Figure 8). The primary energy of pulsed calls is between 1 and 6 kHz, with high frequency components occasionally >30 kHz and duration primarily between 0.5 and 1.5 seconds (Ford & Fisher 1983; Ford 1989). HFM signals have only recently been attributed to killer whales in both the Northeast Atlantic (Samarra et al. 2010) and the North Pacific (Filatova *et al.* 2012, Simonis et al. 2012), and have fundamental frequencies between 17 and 75 kHz, the highest of any known delphinid tonal calls (Figure 9). Killer whale calls were detected via manual scanning of the recordings. No killer whale clicks or HFM signals were detected in this analysis.

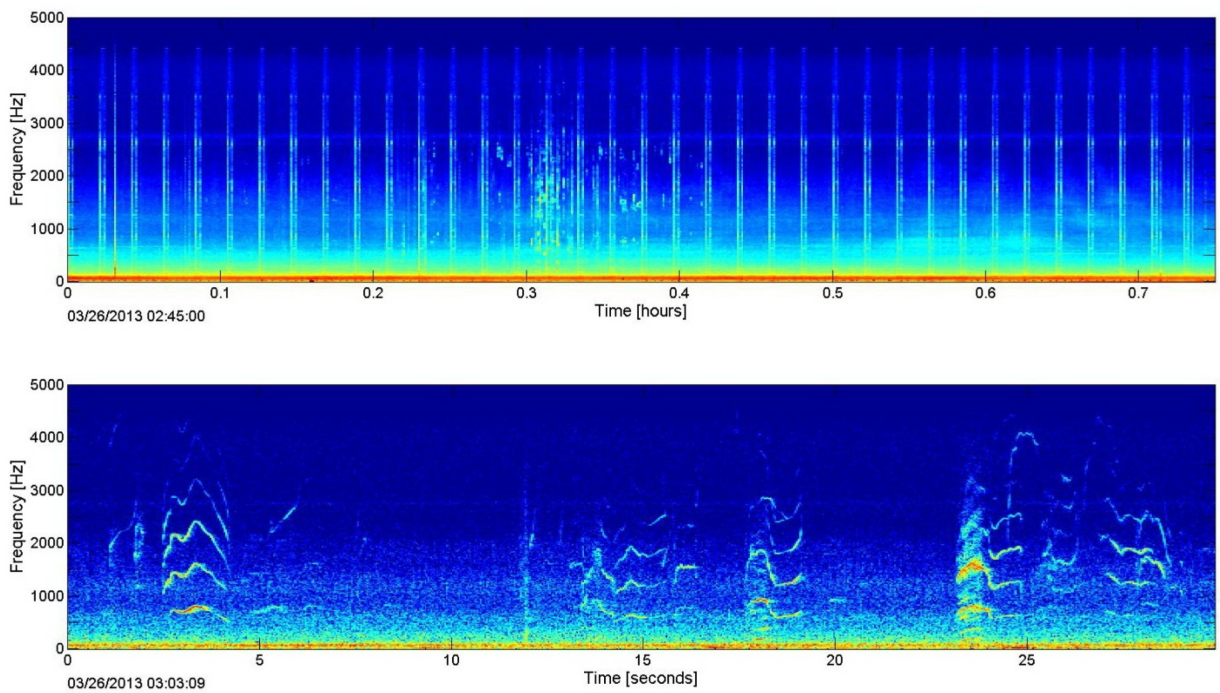

Figure 8. Killer whale whistles and pulsed calls in LTSA (top) and spectrogram (bottom).

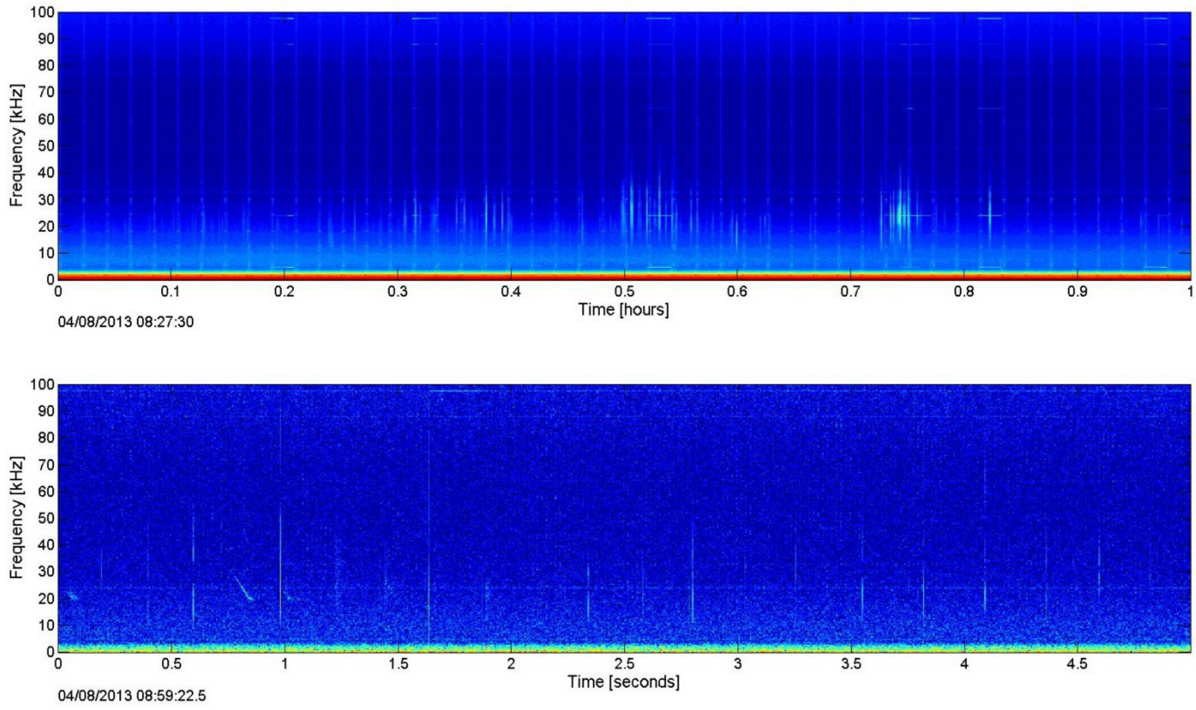

Figure 9. Killer whale echolocation clicks and HFM signals in LTSA (top) and spectrogram (bottom).

Beaked Whales

Beaked whales found in the NWTRC include Baird's (*Berardius bairdii*), Cuvier's (*Ziphius cavirostris*), and Stejneger's (*Mesoplodon stejnegeri*) beaked whales (Jefferson *et al.*, 2008). Advances have been made in acoustically identifying beaked whales 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 the three aforementioned species of beaked whales.

Beaked whale FM pulses, except for those produced by Baird's beaked whales, were detected with an automated method. After all echolocation signals were identified with a Teager Kaiser energy detector (Soldevilla *et al.* 2008, Roch *et al.* 2011), 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 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 μs, 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, labeled the automatically detected segments to pulse type level and rejected false detections (Baumann-Pickering *et al.*, 2013). The rate of missed segments was approximately 5%, varying slightly between deployments. Baird's beaked whale echolocation signals were determined by manual scrutiny of LTSAs and spectrograms.

Stejneger's Beaked Whales

Stejneger's beaked whales are known to occur with some regularity in the northern Pacific Ocean. Their echolocation signals are easily distinguished from other species' acoustic signals; they have the typical beaked whale polycyclic structure and frequency-modulated (FM) pulse upsweep with a peak frequency around 50 kHz and uniform inter-pulse interval around 90 ms (Figure 10) (Baumann-Pickering *et al*., 2013a; Baumann-Pickering *et al*., 2013b).

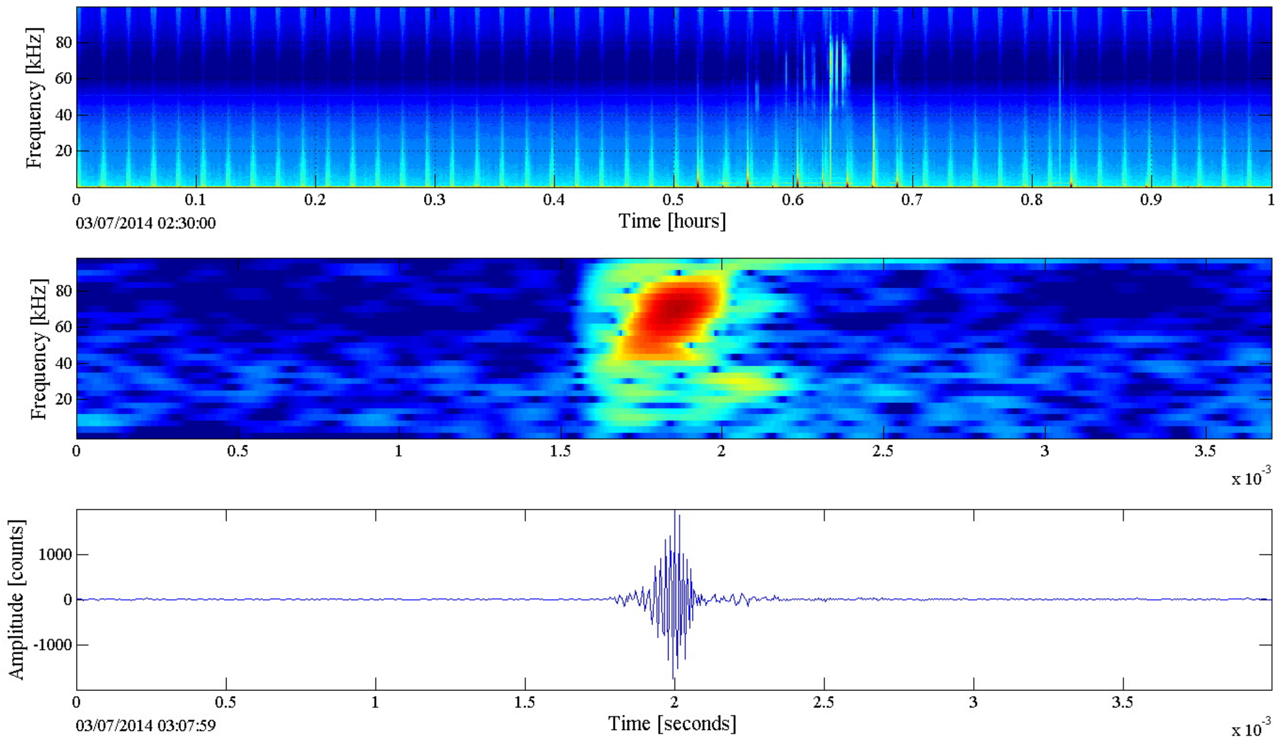

Figure 10. Echolocation sequence of Stejneger's beaked whale in LTSA (top) and example FM pulse in spectrogram (middle) and time series (bottom).

Cuvier's Beaked Whales

Cuvier's echolocation signals are polycyclic, with a characteristic FM pulse upsweep, peak frequency around 40 kHz, 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 11).

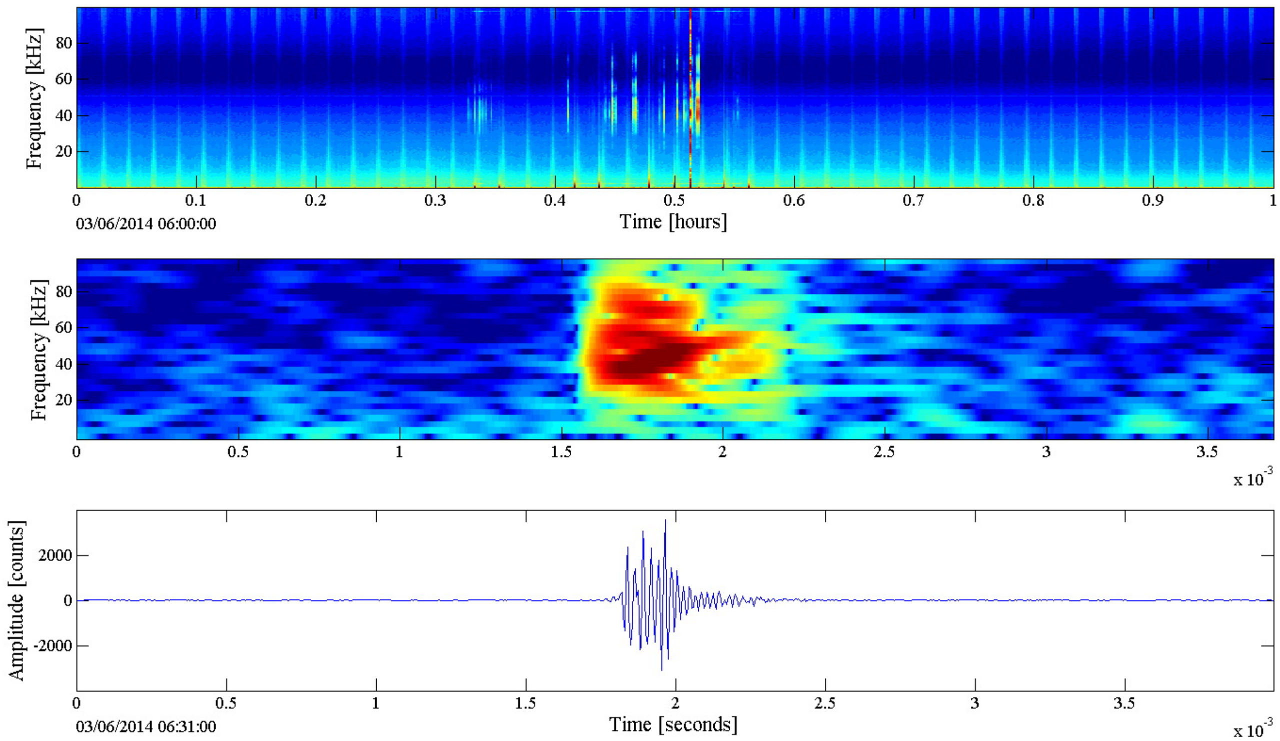

Figure 11. Echolocation sequence of Cuvier's beaked whale in LTSA (top) and example FM pulse in spectrogram (middle) and time series (bottom).

Baird's Beaked Whales

Baird's beaked whale is the most commonly visually observed beaked whale species within their range (>30° N, North Pacific Ocean and adjacent seas), likely because they are relatively large and travel in groups of up to several dozen individuals (Allen and Angliss 2010). Baird's beaked whale echolocation signals are distinguishable from other species' acoustic signals and, aside from dolphin-like clicks, one of their signal types demonstrates the typical beaked whale polycyclic, FM pulse upsweep (Figure 12) (Dawson *et al.*, 1998). These FM pulses and clicks are identifiable due to their comparably low-frequency content. Spectral peaks are notable around 9, 16, 25 and 43 kHz (Baumann-Pickering *et al.*, 2013b). Unlike other beaked whales in the area, Baird's beaked whales incorporate whistles and burst pulses into their acoustic repertoire (Dawson *et al.*, 1998).

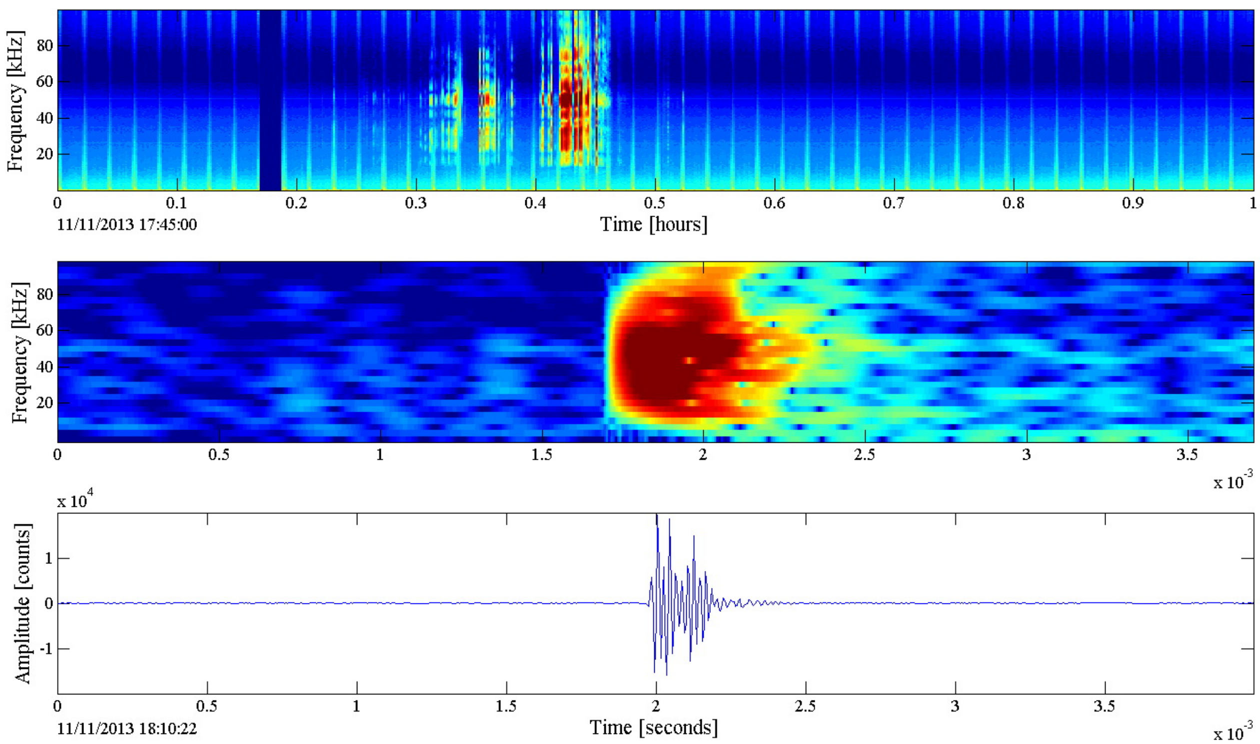

Figure 12. Echolocation sequence of Baird's beaked whale in LTSA (top) and example FM pulse in spectrogram (middle) and time series (bottom).

Unidentified Porpoises

Harbour porpoises (*Phocoena phocoena*) and Dall's porpoises (*Phocoenoides dalli*) were the most frequently sighted marine mammals during visual surveys in the area (Oleson *et al*., 2010; Oleson *et al*., 2009). Both Dall's and harbour porpoises produce echolocation clicks that contain energy from 115-150 kHz (Verboom & Kastelein, 1995). The HARP only records acoustic energy up to 100 kHz, and thus the peak energy of the porpoise clicks is above the upper frequency band recorded by the HARPs. However, the HARP anti-alias filter allows some spectral leakage from energy above 100 kHz, resulting in 120-140 kHz energy appearing at 60-80 kHz (Figure 13). Detection of porpoise clicks is therefore possible when the animals are close to the HARP (< ~1 km) and their received levels are high. Unidentified porpoise clicks were detected via manual scanning of the recordings.

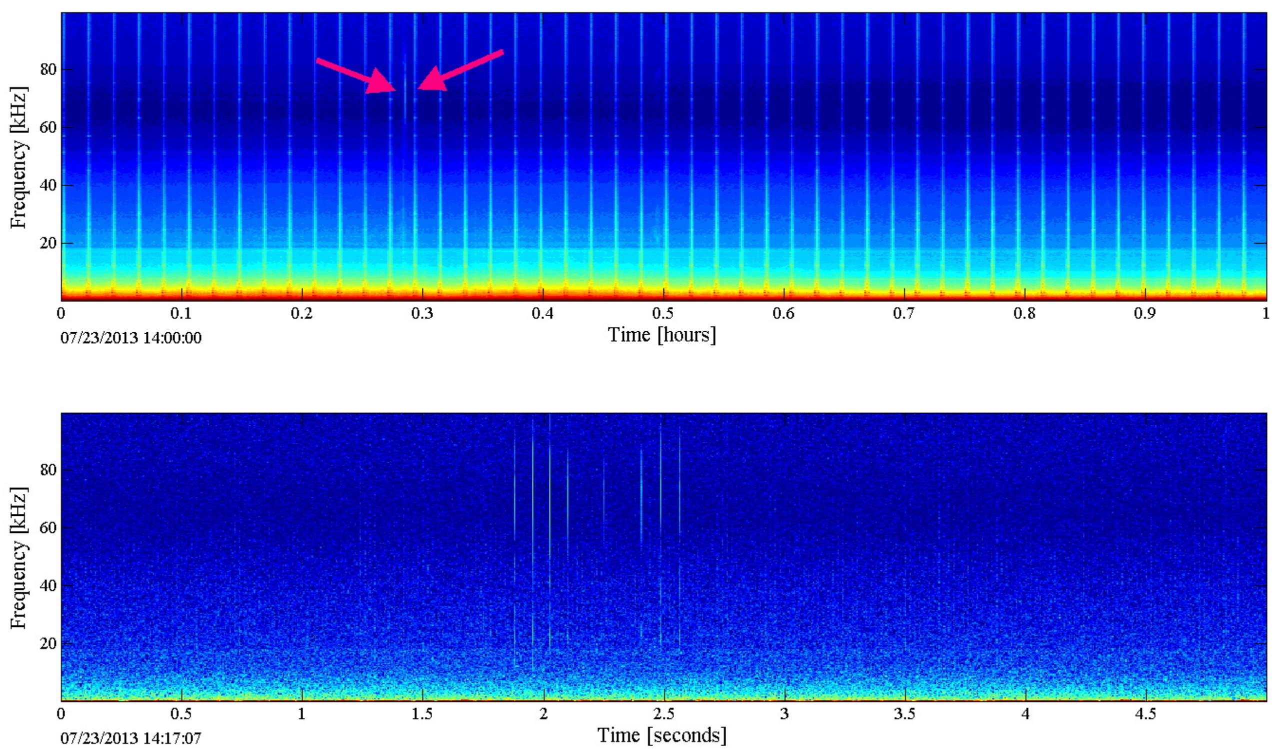

Figure 13. Example LTSA (top) and spectrogram (bottom), presumably produced by spectral aliasing of porpoise clicks (120-150 kHz frequency content).

Anthropogenic Sounds

Several anthropogenic sounds occurring at mid-frequency ranges (<5 kHz) were monitored for this report: mid-frequency active (MFA) sonar, low-frequency active (LFA) sonar, underwater communications, and explosions. Underwater communications, MFA sonar, and LFA sonar were detected by manually scanning the data, whereas explosions were detected by a computer algorithm. During manual examination of the data, the LTSA frequency was set to display between 10-5,000 Hz with a 0.75 hour plot length. To observe individual signals, the spectrogram window was typically set to display 1-5,000 Hz with a 30 second plot length. The start and end of each sound or session was logged and their durations were added to estimate cumulative hourly presence.

Mid-Frequency Active Sonar

Sounds from MFA sonar vary in frequency (1 – 10 kHz) and are composed of pulses of both frequency-modulated (FM) sweeps and continuous wave (CW) tones grouped in packets with durations ranging from less than 1 s to greater than 5 s. Packets can be composed of single or multiple pulses and are transmitted repetitively as wave trains with inter-packet-intervals typically greater than 20 s. Many MFA sonar packet signals are between 2 and 5 kHz and are known more generally as '3.5 kHz' sonar. Analysts manually scanned LTSAs and logged sonar wave train event start and end times in which inter-event-intervals were typically greater than 1 hour.

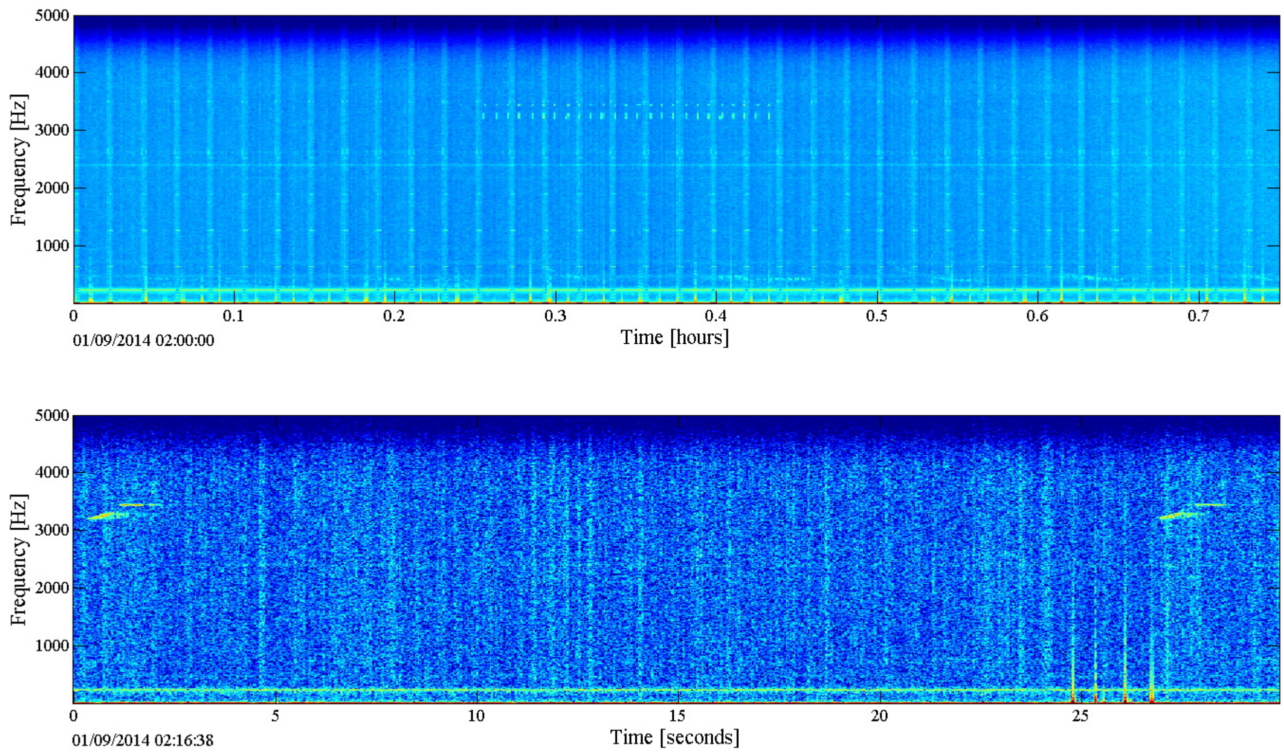

Figure 14. MFA sonar shown as a wave train event in a 45 minute LTSA (top) and as a single packet with multiple pulses in a 30 second spectrogram (bottom).

Low-Frequency Active Sonar 500 Hz – 1 kHz

Effort to detect low-frequency active (LFA) sonar between 500 Hz and 1 kHz was expended on these data (Figure 15). Analysts manually scanned LTSAs for LFA sonar bout start and end times.

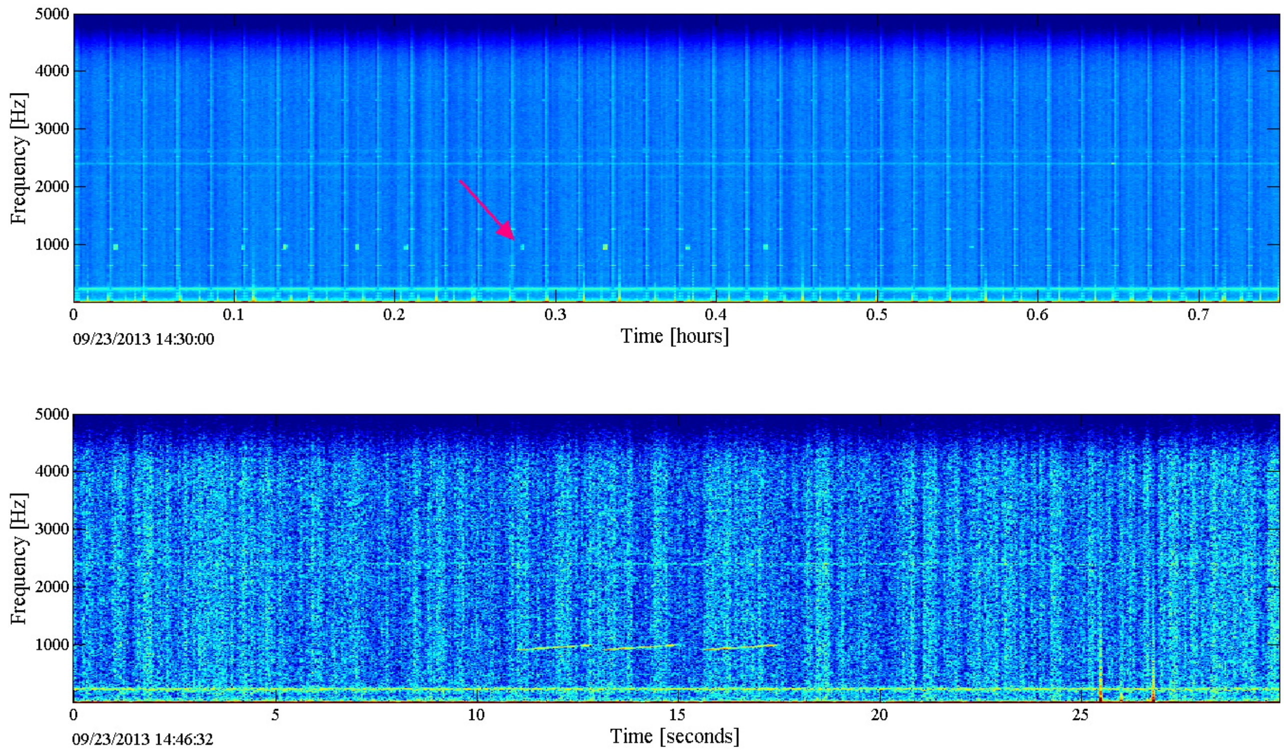

Figure 15. LFA sonar at 950 Hz in the LTSA (top) and spectrogram (bottom).

Underwater Communications

Underwater communications are used to transmit information. They can sound like distorted voices underwater (Figure 16) or electronic transmissions (Figure 17). Analysts manually scanned LTSAs for underwater communication signals, but none were detected in the data.

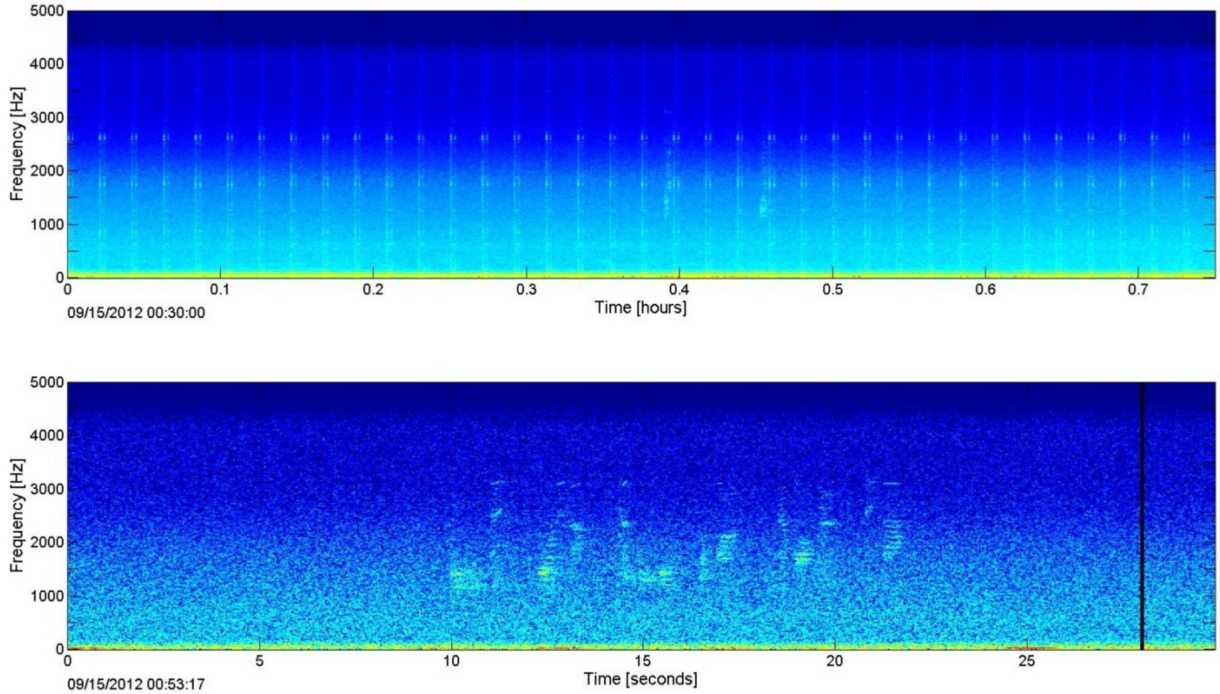

Figure 16. Underwater communications in LTSA (top) and spectrogram (bottom).

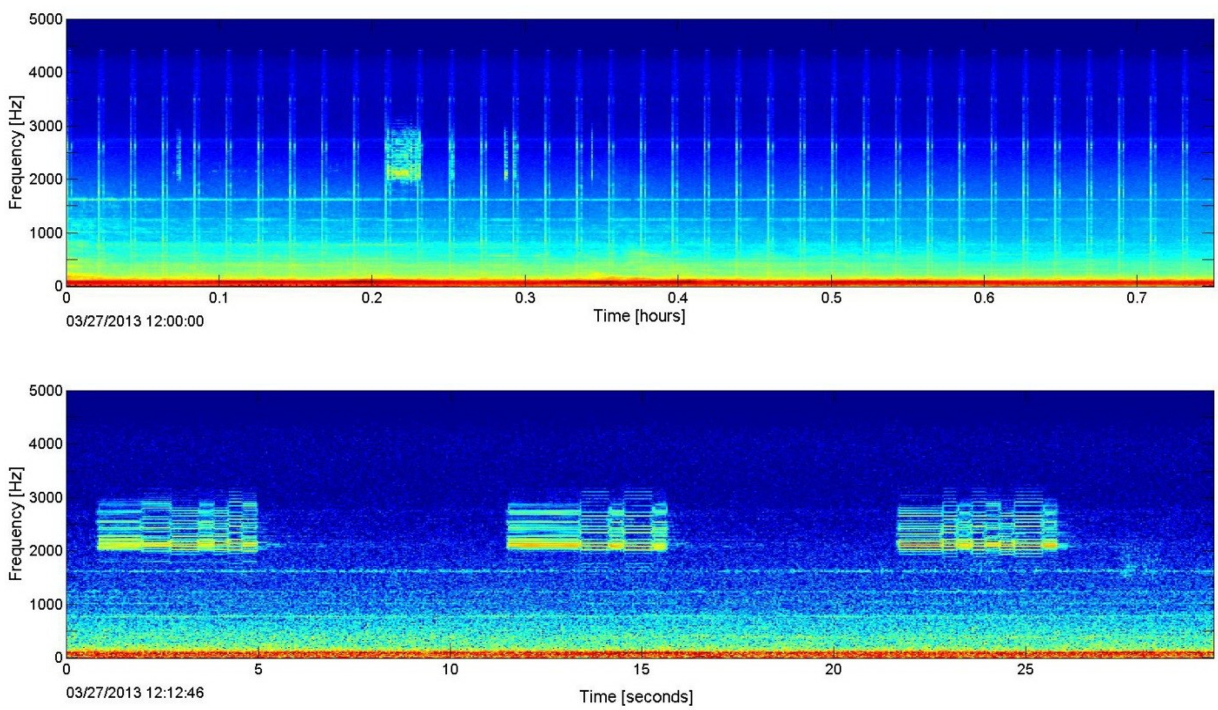

Figure 17. Electronic underwater communications in LTSA (top) and spectrogram (bottom).

Explosions

Effort was directed toward finding explosive sounds in the data, 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 18). Explosions were detected automatically using a matched filter detector on data decimated to 10 kHz sampling rate. The time series was filtered with a 10^{th} order Butterworth bandpass filter between 200 and 2,000 Hz. Cross correlation was computed between 75 seconds of the envelope of the filtered time series 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 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 above the median was set. When the correlation coefficient reached above threshold, the time series was inspected more closely. Consecutive explosions were required to be separated by at least 0.5 seconds to be detected. A 300-point (0.03 s) floating average energy across the detection was computed. The start and end above threshold was determined when the energy rose by more than 2 dB above the median energy across the detection. Peak-to-peak (pp) and rms received levels (RL) were computed over the potential explosion period and over a time series of the length of the explosion template before and after the explosion. The potential explosion was classified as false detection and deleted if: 1) the dB difference pp and rms between signal and time AFTER the detection was less than 4 dB or 1.5 dB, respectively; 2) the dB difference pp and rms between signal and time BEFORE 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. 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.

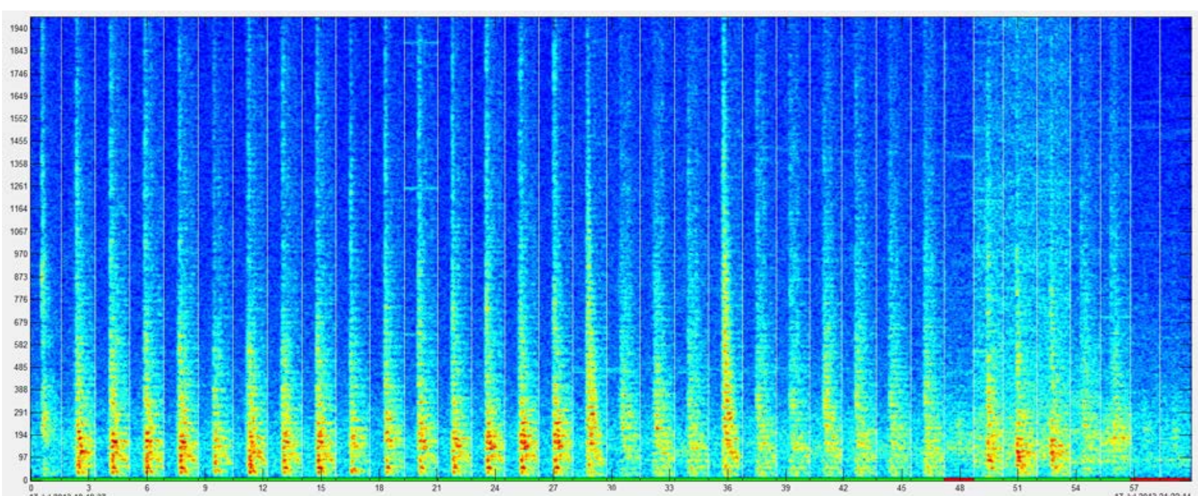

Figure 18. Explosions in the analyst verification stage of the detector. Green in the bottom evaluation line indicates true and red indicates false detections.

Results

The results of acoustic data analysis at sites CE and QC from July 2013 through April 2014 are summarized. We describe the seasonal occurrence and relative abundance of marine mammal acoustic signals and anthropogenic sounds of interest, as well as ambient noise.

Ambient Noise

Underwater ambient noise was only calculated for site CE from July 17-31, 2013 (Figure 19). Noise at site CE had a spectral shape with higher levels at low frequencies, owing to the dominance of shipping at frequencies below 100 Hz, as well as contribution from cable strumming. At frequencies above 100 Hz, local wind and waves dominated the noise (Hildebrand, 2009). Underwater ambient noise could not be calculated for site QC due to the reduced data quality.

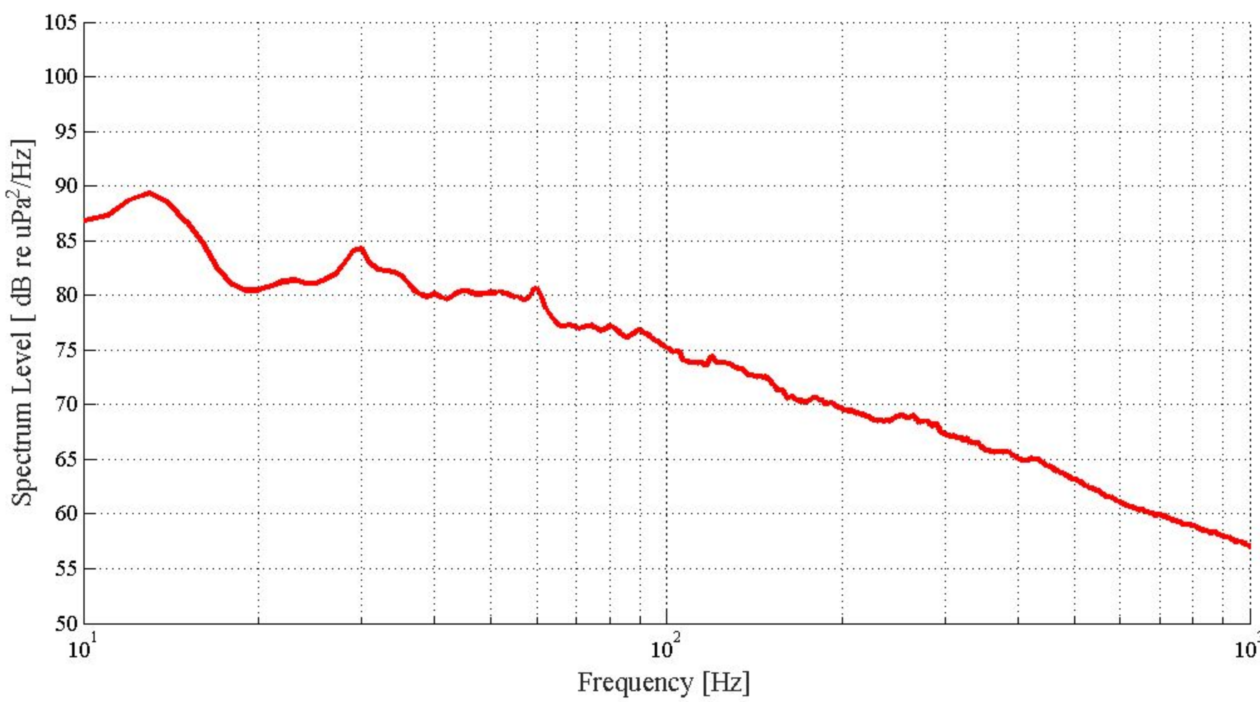

Figure 19. Average ambient noise at site CE from July 17-31, 2013.

Mysticetes

Three species of baleen whales were detected between July 2013 and April 2014: blue whales, fin whales, and humpback whales. The numbers of detections for these species at site QC may have been somewhat affected by the poor hydrophone performance at low frequencies.

Blue Whales

Northeast (NE) Pacific blue whale B calls, which are produced exclusively by males and are likely associated with mating behavior (Oleson et al. 2007), were recorded throughout much of the monitoring period at both sites. Blue whale D calls, associated with feeding animals (Oleson et al. 2007), were only detected at site CE in late summer.

- NE Pacific B calls were detected in July at site CE, and from July through February at site QC (Figure 20).
- Detections of NE Pacific B calls peaked at site QC in early January (Figure 20).
- The overall seasonal occurrence of NE Pacific B calls is consistent with earlier recordings, and suggests presence of blue whales in this area from summer through the winter (Kerosky *et al.*, 2013; Debich *et al.*, 2014).
- There was no discernable diel pattern in the NE Pacific B calls at either site (Figure 21).
- Blue whale D calls were only detected at site CE, and at relatively low levels (Figure 22).
- There were too few detections of D calls to determine a diel pattern at site CE (Figure 23).

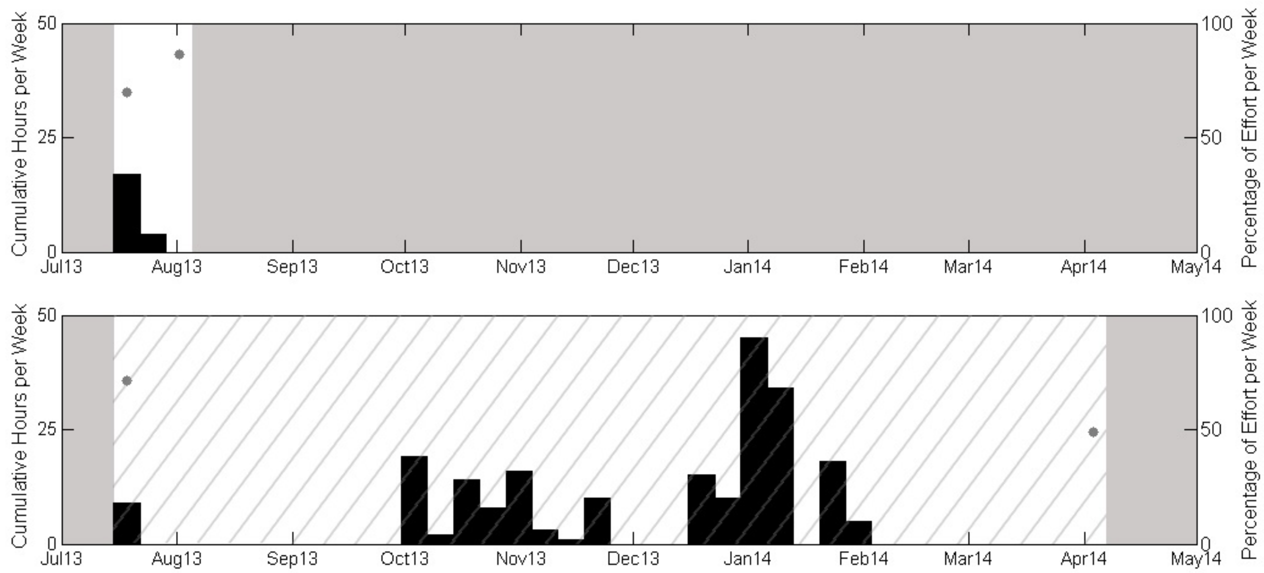

Figure 20. Weekly presence of Northeast Pacific blue whale B calls between July 2013 and April 2014 at sites CE (top) and QC (bottom). Gray dots represent percent of effort per week in weeks with less than 100% recording effort, and gray shading represents periods with no recording effort. Gray diagonal lines denote reduced data quality. Where gray dots or shading are absent, full recording effort occurred for the entire week.

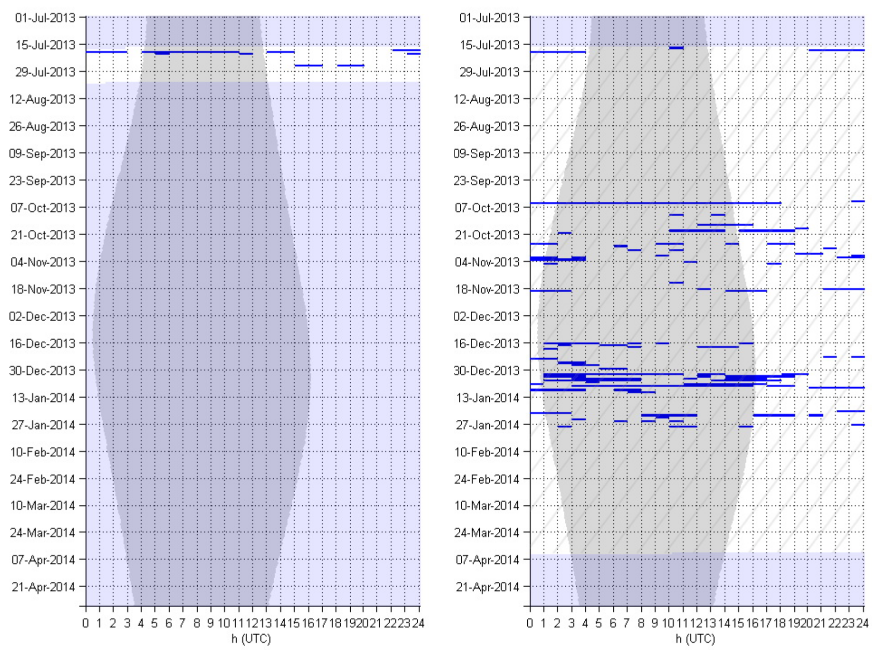

Figure 21. Northeast Pacific blue whale B calls in one-hour bins at sites CE (left) and QC (right). Gray vertical shading denotes nighttime, and light purple horizontal shading denotes absence of acoustic data. Gray diagonal lines denote reduced data quality.

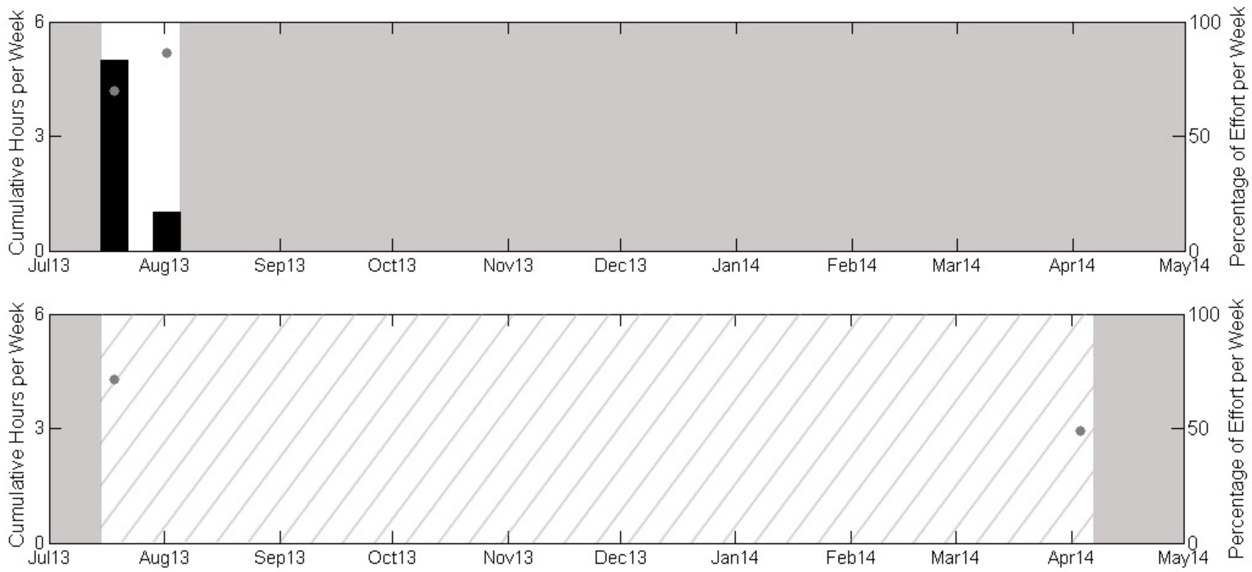

Figure 22. Weekly presence of blue whale D calls between July 2013 and April 2014 at sites CE (top) and QC (bottom). Effort markings are described in Figure 20.

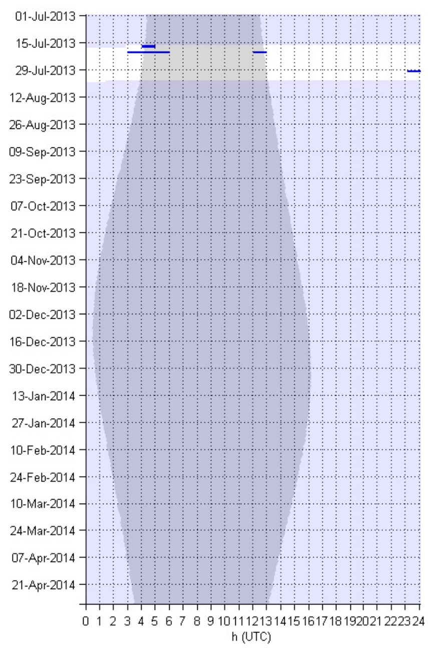

Figure 23. Blue whale D calls in one-hour bins at site CE. No blue whale D calls were detected at site QC. Effort markings are described in Figure 21.

Fin Whales

Fin whale 20 Hz calls, associated with singing and call-countercall among animals, were detected at both sites.

- Fin whales were detected in July at site CE (Figure 24).
- Fin whales were detected from July through February at site QC, although detection rates were highest in December and January (Figure 24). This pattern broadly corresponds to the generally reported seasonal occurrence of fin whale calls from October through April in the eastern North Pacific (Watkins *et al*., 2000).
- There was no discernable diel pattern for 20 Hz calls (Figure 25).
- Overall, this seasonal presence is consistent with previous reports (Kerosky *et al.*, 2013; Debich *et al.*, 2014).

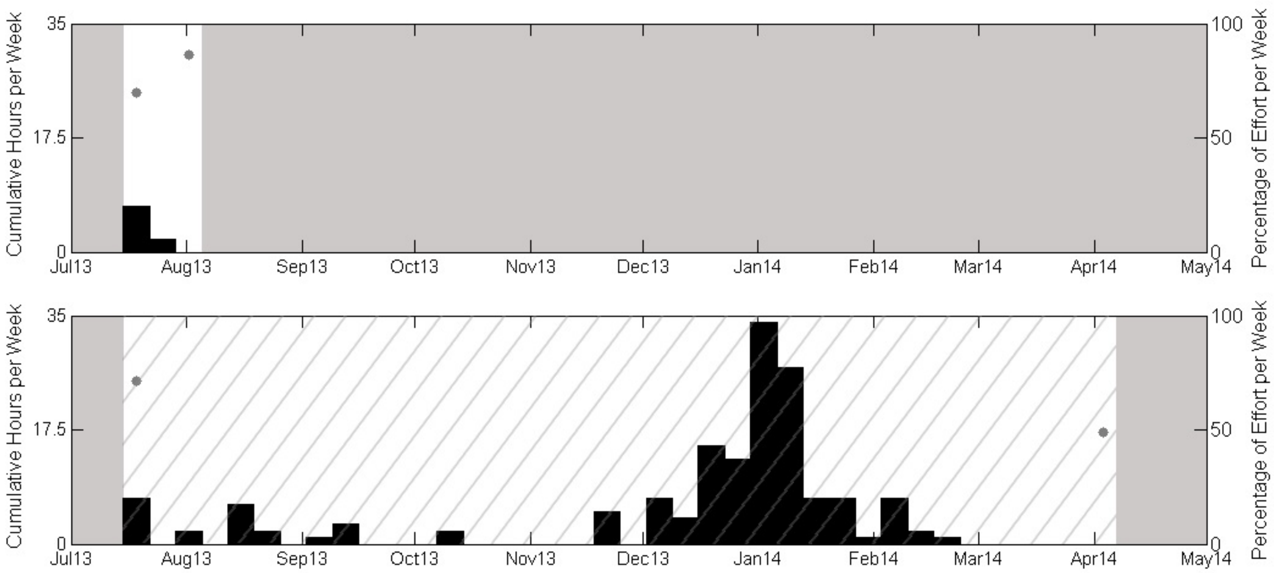

Figure 24. Weekly presence of fin whale 20 Hz calls between July 2013 and April 2014 at sites CE (top) and QC (bottom). Effort markings are described in Figure 20.

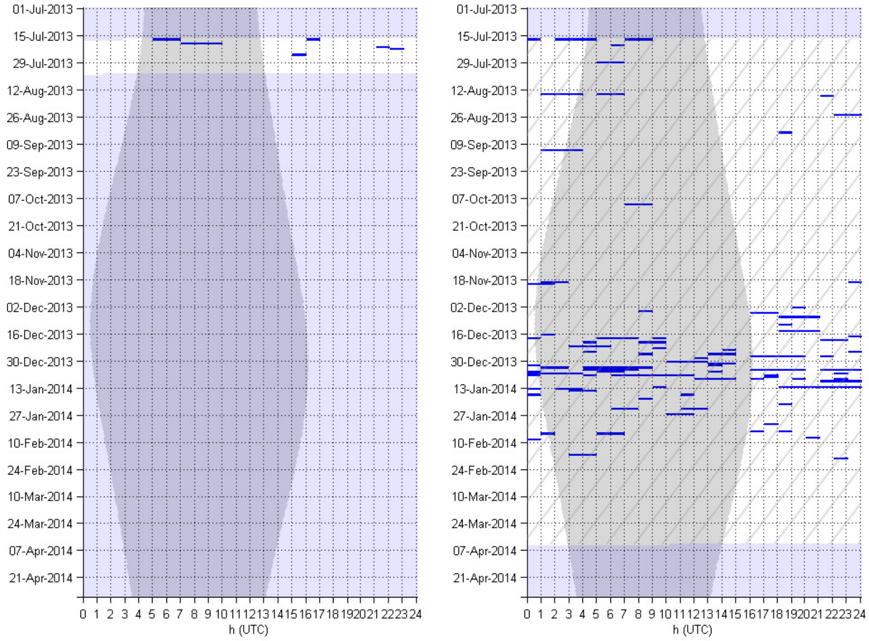

Figure 25. Fin whale 20 Hz calls in one-hour bins at sites CE (left) and QC (right). Effort markings are described in Figure 21.

Humpback Whales

Humpback whale calls were detected at both sites. The high rates of detection from December through February at site QC are consistent with previous recordings showing overwintering presence at this site (Oleson *et al*., 2009; Širović *et al*., 2012; Širović *et al*., 2011).

- Humpback whale calls were consistently detected throughout July and August at site CE (Figure 26).
- Detection rates at site QC were highest from November through January, and peaked in December (Figure 26). The substantial presence of humpback whales during the winter does not fit models of whale migration to subtropical or tropical waters. These data instead suggest that some humpback whales remain in temperate waters during the winter.
- Although song and non-song call types were grouped together for this analysis, peaks in calling during the winter months are likely due to increased singing, reflecting a possible shift in primary behavior from foraging to pairing and mating.
- The decline in calling beginning in February is consistent with previous findings (Oleson *et al*., 2009; Širović *et al*., 2011; Širović *et al*., 2012; Kerosky *et al*., 2013; Debich *et al.*, 2014)
- There was no discernable diel pattern at either site (Figure 27).

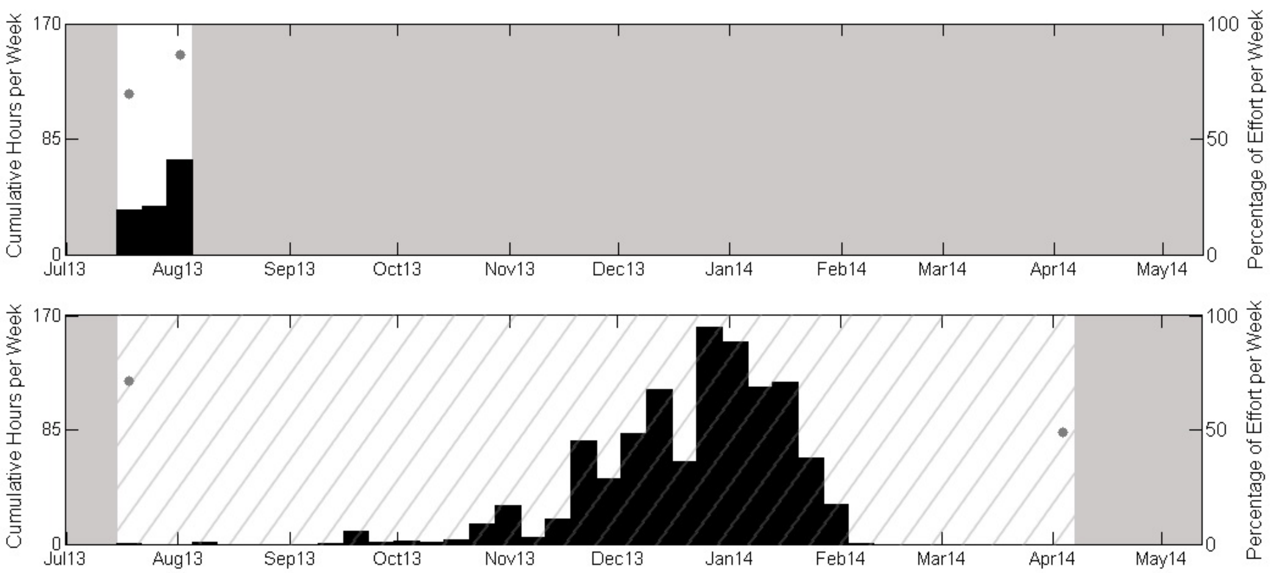

Figure 26. Weekly presence of humpback whale calls between July 2013 and April 2014 at sites CE (top) and QC (bottom). Effort markings are described in Figure 20.

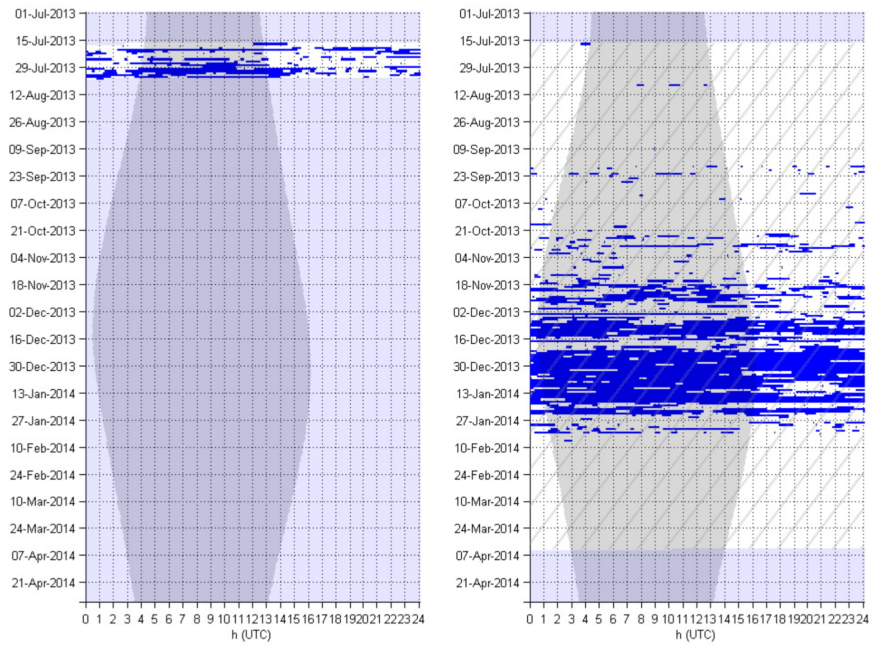

Figure 27. Humpback whale calls in one-minute bins at sites CE (left) and QC (right). Effort markings are described in Figure 21.

Odontocetes

Four known species of toothed whales were detected between July 2013 and April 2014: killer whales, Stejneger's beaked whales, Cuvier's beaked whales, and Baird's beaked whales. Unidentified porpoise clicks that were not classified to species were also detected. Beaked whales were only recorded at the deeper, offshore site QC.

Killer Whales

Killer whale calls were primarily recorded at site CE, with only a single daytime detection at site QC in September.

- There were no detections of killer whale echolocation clicks or HFM signals.
- Killer whale pulsed calls were recorded at both sites, and peaked in August at site CE (Figure 28).
- Killer whales were only recorded once at site QC, in a detection containing pulsed calls and whistles that occurred in September (Figure 30).
- There were too few detections to determine a diel pattern for killer whale pulsed calls (Figure 29) or whistles (Figure 31).
- These results differ from earlier reports, in that killer whales have typically been commonly detected at site QC in previous years, but were only recorded at site QC once during this monitoring period (Kerosky *et al.*, 2013; Debich *et al.*, 2014), likely a result of the poor hydrophone performance at site QC.

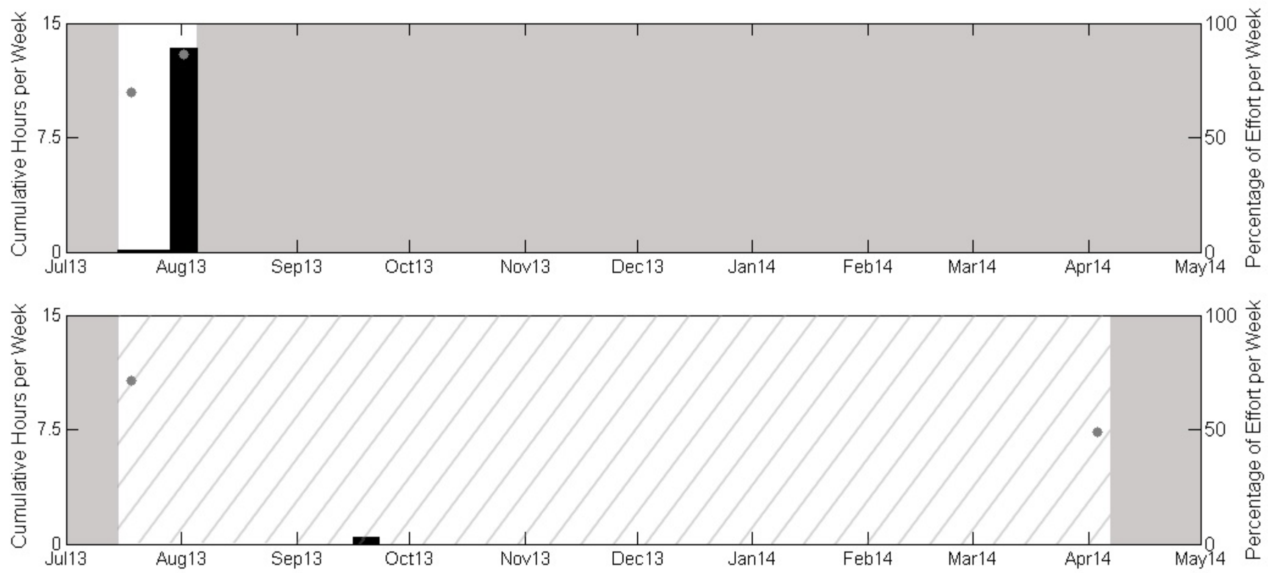

Figure 28. Weekly presence of killer whale pulsed calls between July 2013 and April 2014 at sites CE (top) and QC (bottom). Effort markings are described in Figure 20.

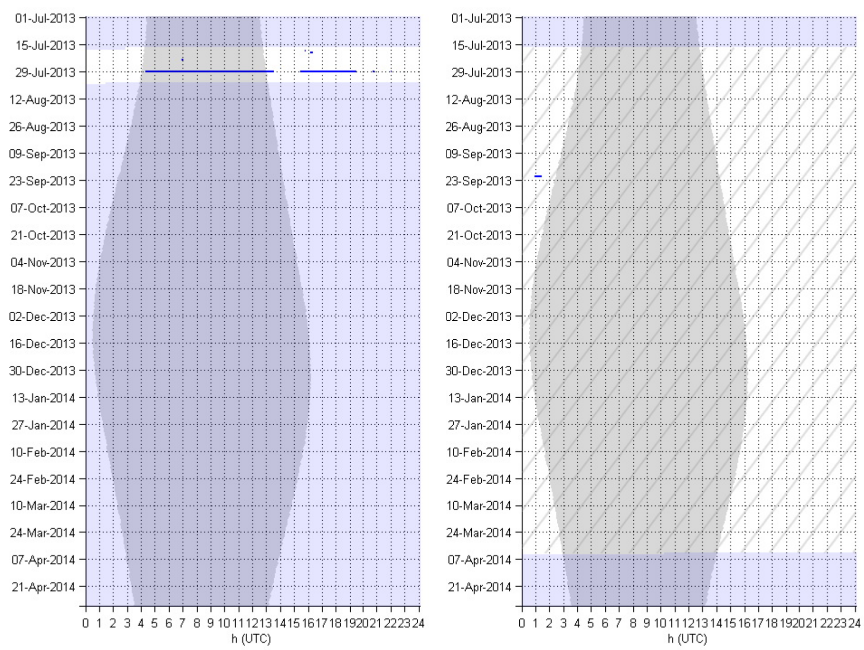

Figure 29. Killer whale pulsed calls in one-minute bins at sites CE (left) and QC (right). Effort markings are described in Figure 21.

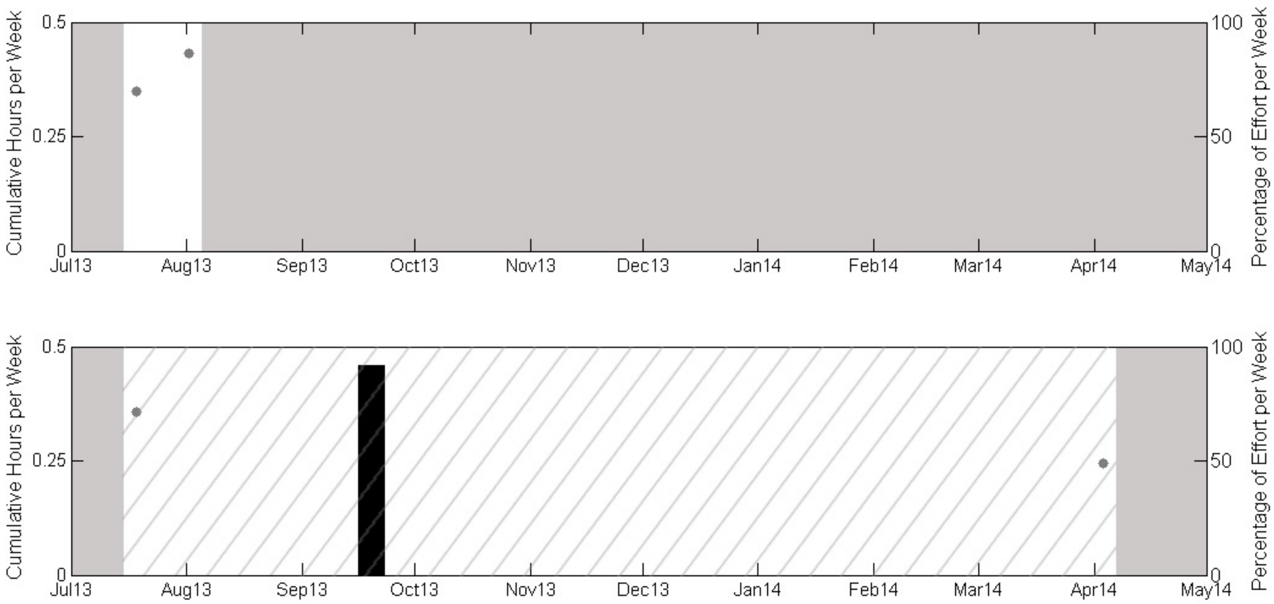

Figure 30. Weekly presence of killer whale whistles between July 2013 and April 2014 at sites CE (top) and QC (bottom). Effort markings are described in Figure 20.

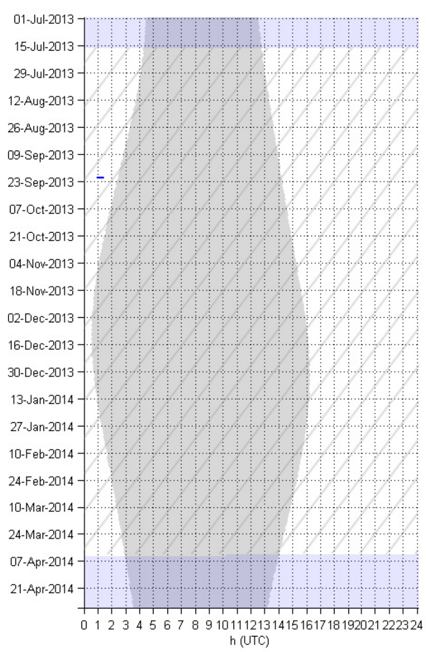

Figure 31. Killer whale whistles in one-minute bins at site QC. No killer whale whistles were detected at site CE. Effort markings are described in Figure 21.

Stejneger's Beaked Whales

Stejneger's beaked whales were the most consistently detected species of beaked whale at site QC.

- Stejneger's beaked whale FM pulses were detected from September through April (Figure 32).
- Detections peaked in January (Figure 32).
- There was no discernable diel pattern for Stejneger's beaked whale FM pulses (Figure 33).
- These results are similar to earlier reports (Kerosky *et al.*, 2013; Debich *et al.*, 2014).

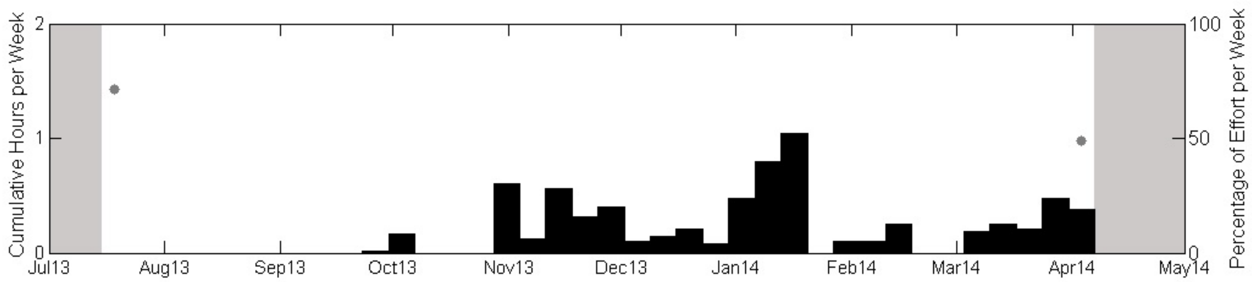

Figure 32. Weekly presence of Stejneger's beaked whale FM pulses between July 2013 and April 2014 at site QC. Effort markings are described in Figure 20.

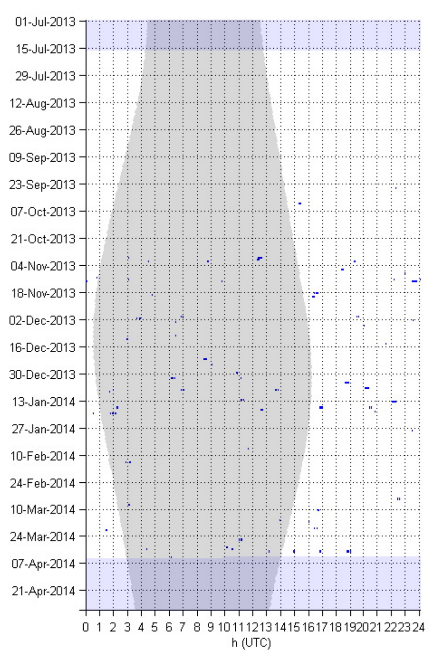

Figure 33. Stejneger's beaked whale FM pulses in one-minute bins at site QC. Effort markings are described in Figure 21.

Cuvier's Beaked Whales

Cuvier's beaked whales were sporadically detected at low levels at site QC during the winter.

- Detections of Cuvier's beaked whale FM pulses peaked in early January (Figure 34).
- There were too few detections to determine a diel pattern for Cuvier's beaked whale FM pulses (Figure 35).
- These results are similar to previous reports on the seasonality and acoustic presence of Cuvier's beaked whales at site QC (Kerosky *et al.*, 2013; Debich *et al.*, 2014).

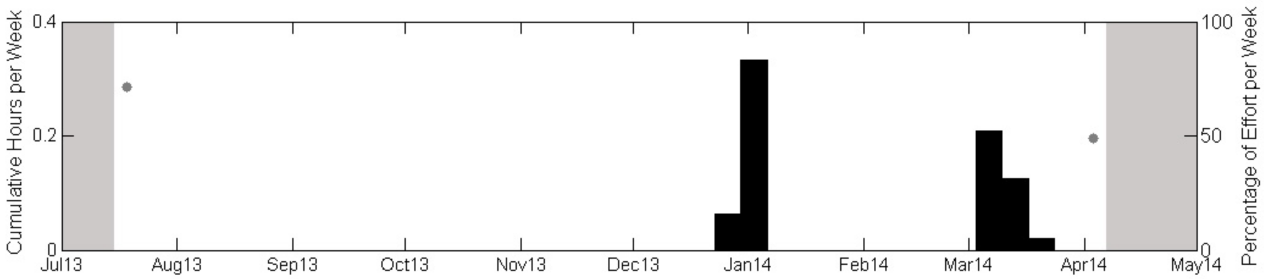

Figure 34. Weekly presence of Cuvier's beaked whale FM pulses between July 2013 and April 2014 at site QC. Effort markings are described in Figure 20.

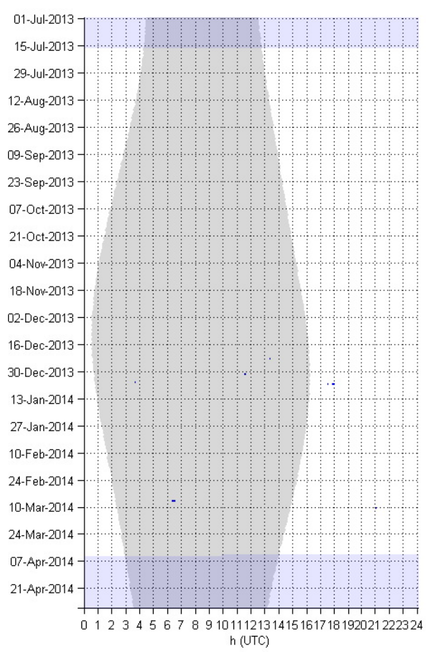

Figure 35. Cuvier's beaked whale FM pulses in one-minute bins at site QC. Effort markings are described in Figure 21.

Baird's Beaked Whales

Baird's beaked whales were intermittently detected throughout the fall and winter at site QC.

- Baird's beaked whale FM pulses were detected from August through January, with an additional single encounter occurring in March (Figure 36).
- Detections peaked in August, and again in November and December (Figure 36).
- All detections of Baird's beaked whale FM pulses in August occurred at nighttime, but there was no discernable diel pattern for the rest of the recording period (Figure 37).
- These results are similar to previously reported acoustic presence of Baird's beaked whales in the area (Kerosky *et al.*, 2013; Debich *et al.*, 2014).

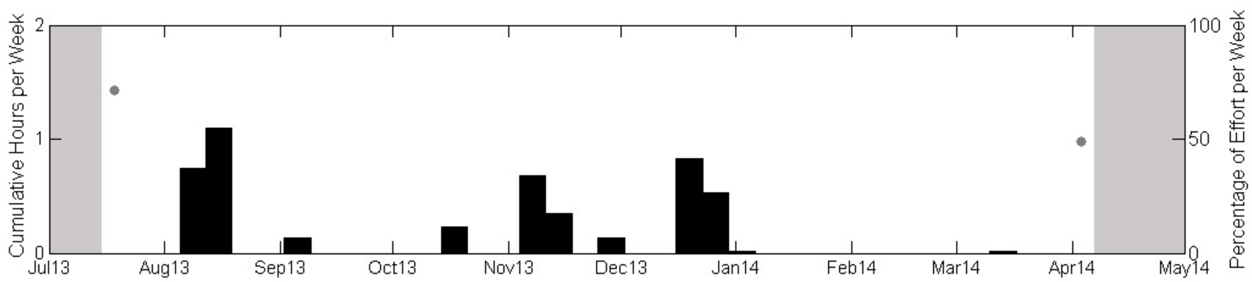

Figure 36. Weekly presence of Baird's beaked whale FM pulses between July 2013 and April 2014 at site QC. Effort markings are described in Figure 20.

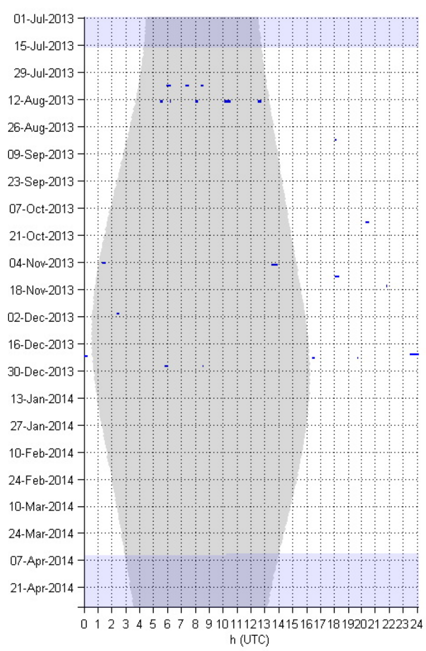

Figure 37. Baird's beaked whale FM pulses in one-minute bins at site QC. Effort markings are described in Figure 21.

Unidentified Porpoises

Narrow-band high frequency clicks belonging to unidentified porpoise were detected at site CE.

- Porpoise clicks were detected in low numbers in July at site CE only. There were no porpoise detections at site QC (Figure 38).
- There were too few detections to determine a diel pattern for porpoise clicks (Figure 39).
- The presence of porpoise clicks at site CE and lack of detections at site QC is consistent with previous recordings (Širović *et al.*, 2012; Kerosky *et al.*, 2013).

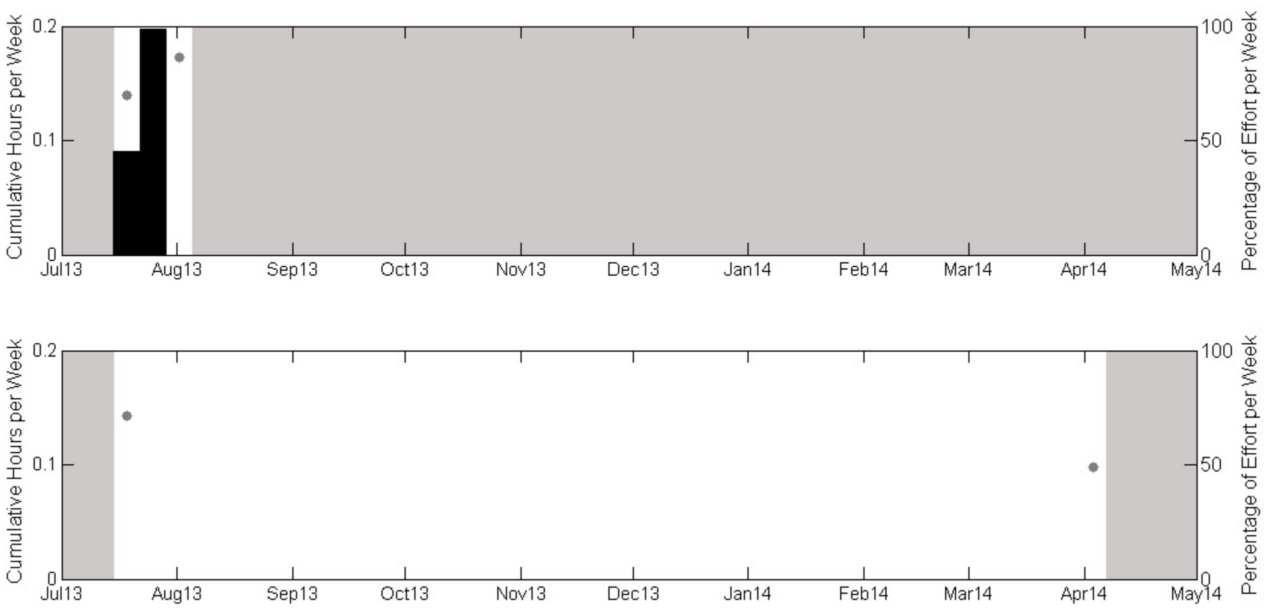

Figure 38. Weekly presence of unidentified porpoise clicks between July 2013 and April 2014 at sites CE (top) and QC (bottom). Effort markings are described in Figure 20.

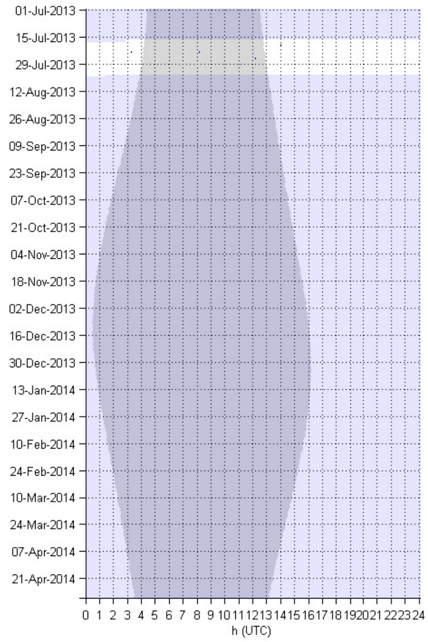

Figure 39. Unidentified porpoise clicks in one-minute bins at site QC. No porpoise clicks were detected at site QC. Effort markings are described in Figure 21.

Anthropogenic Sounds

Three types of anthropogenic sounds were detected between July 2013 and April 2014: MFA sonar (2.4 – 4.5 kHz), LFA sonar (500 – 1000 Hz), and explosions. The numbers of detections for these signals at site QC may have been somewhat affected by the poor hydrophone performance at mid-frequencies.

Mid-Frequency Active Sonar

There was a single detection of MFA sonar less than 5 kHz at site QC.

- A single nighttime detection of MFA occurred at site QC in January (Figure 40).
- There were too few detections to determine a diel pattern (Figure 41).
- The overall low acoustic presence of MFA in the area is consistent with previous reports (Kerosky *et al.*, 2013; Debich *et al.*, 2014).

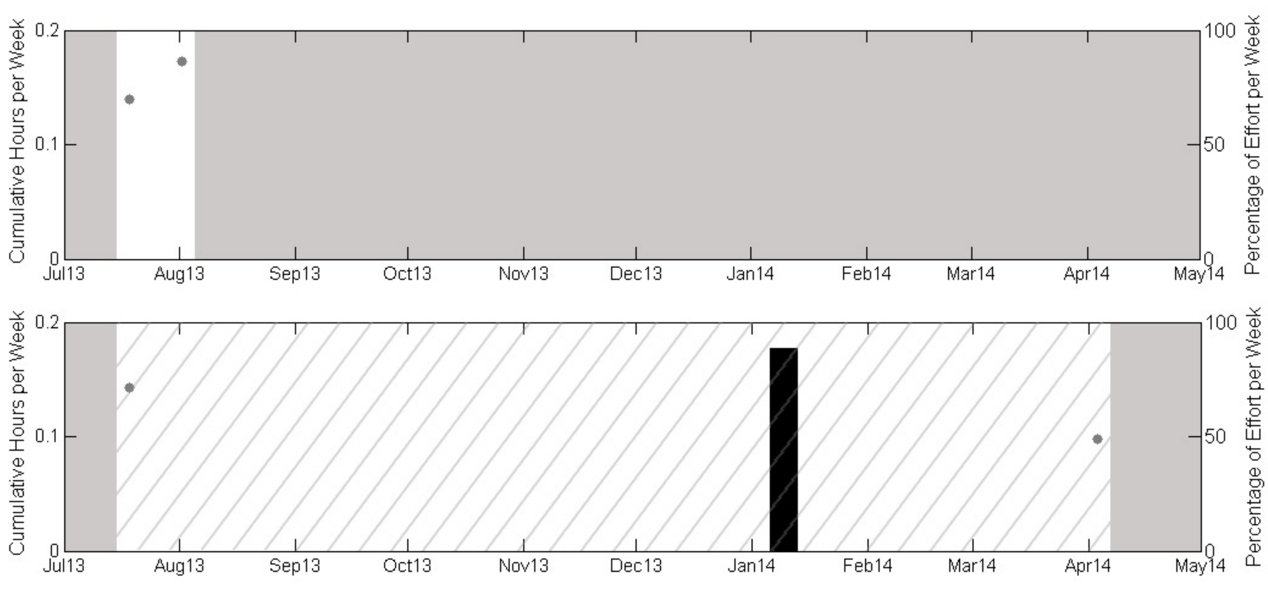

Figure 40. Weekly presence of MFA less than 5 kHz between July 2013 and April 2014 at sites CE (top) and QC (bottom). Effort markings are described in Figure 20.

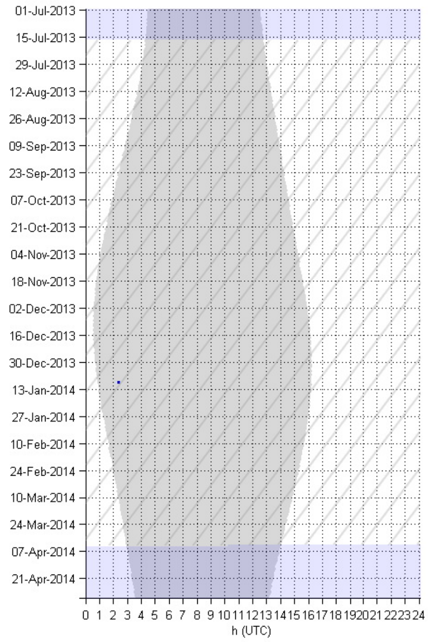

Figure 41. MFA less than 5 kHz signals in one-minute bins at site QC. No MFA was detected at site CE. Effort markings are described in Figure 21.

Low-Frequency Active Sonar

LFA sonar between 500 Hz and 1 kHz was detected only at site QC.

- LFA sonar between 500 Hz and 1 kHz was detected sporadically during the deployment at site QC (Figure 42).
- All detections occurred during daytime hours (Figure 43).

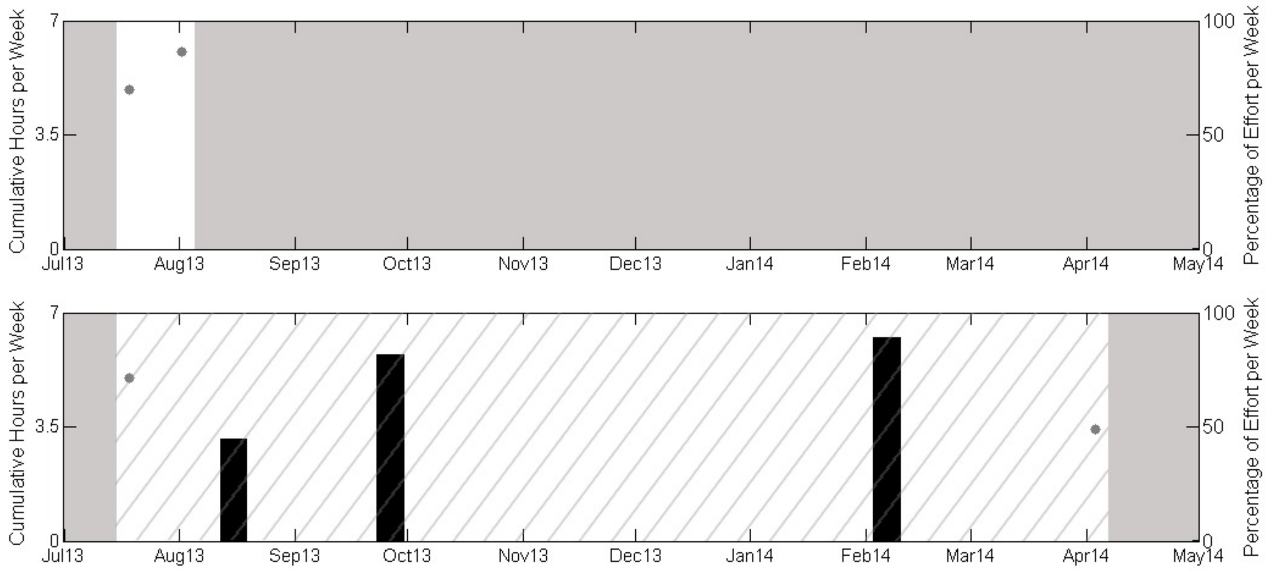

Figure 42. Weekly presence of LFA greater than 500 Hz between July 2013 and April 2014 at sites CE (top) and QC (bottom). Effort markings are described in Figure 20.

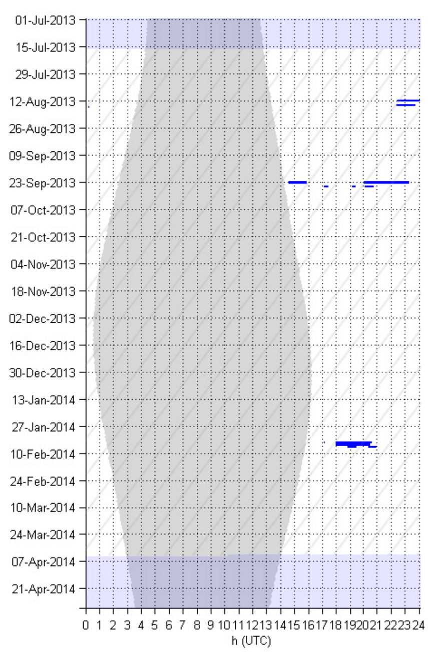

Figure 43. LFA signals between 500 Hz and 1 kHz in one-minute bins at site QC. No LFA was detected at site CE. Effort markings are described in Figure 21.

Explosions

Explosions were only detected at site CE.

- Explosions were detected throughout the July-August 2014 recording period at site CE (Figure 44).
- 837 explosions were detected at site CE.
- Almost all explosions occurred during daytime hours (Figure 45).
- The relatively short duration of the explosion reverberations and the moderate received levels suggest that these explosions might be seal bombs related to fishing activity. Furthermore, the occurrence of these explosions in late summer coincides with Coho and Chinook salmon season.
- These results differ from previous recordings, in that explosions were consistently detected at site QC in earlier deployments, while there were no detections at this site in these data, perhaps due to the poor performance of the hydrophone at site QC. However, the diel and seasonal trends of the detections at site CE are consistent with previously reported findings (Širović *et al.*, 2012; Debich *et al.*, 2014).

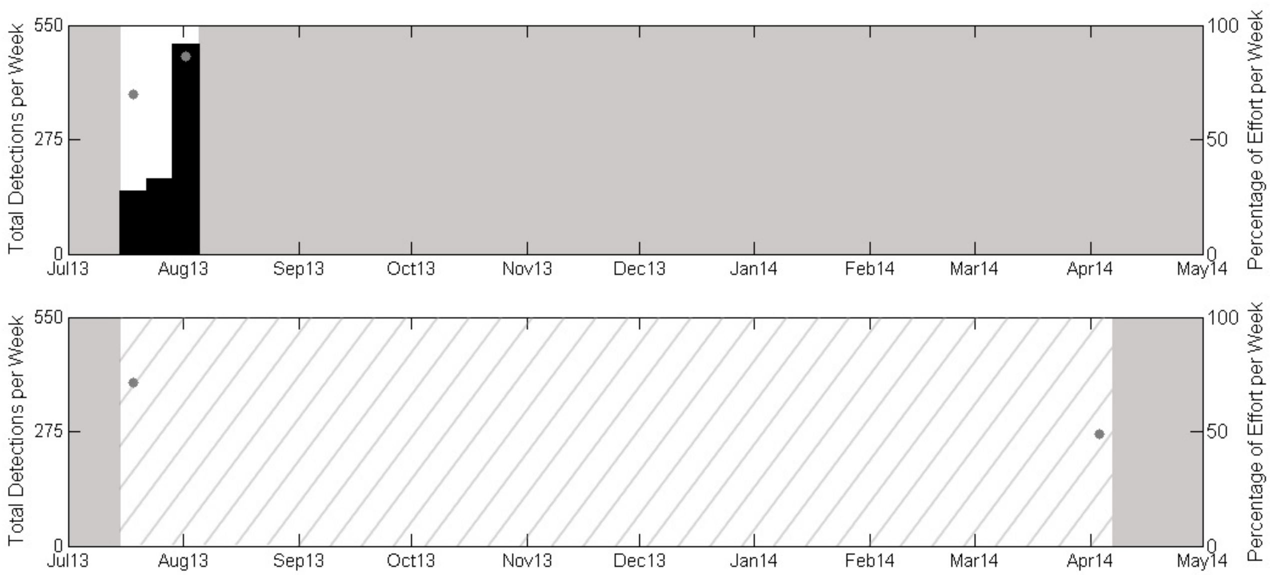

Figure 44. Weekly presence of explosions between July 2013 and April 2014 at sites CE (top) and QC (bottom). Effort markings are described in Figure 20.

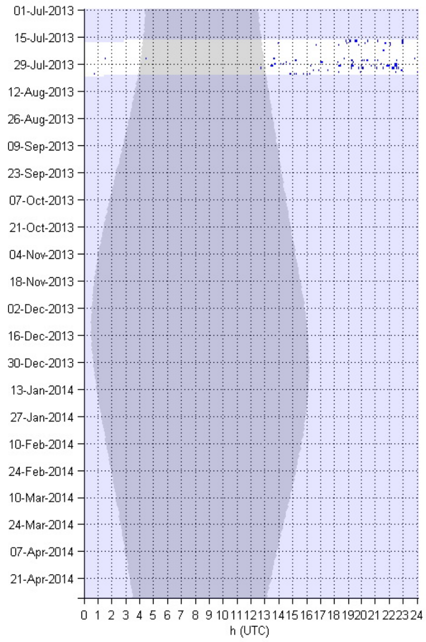

Figure 45. Explosion detections in one-minute bins at site CE. No explosions were detected at site QC. Effort markings are described in Figure 21.

Acknowledgements

We thank U.S. Pacific Fleet for providing support for this program. The HARP deployment at site CE was conducted under research permit OCNMS-2010-010 and OCNMS-2010-010-A1. We thank Liam Antrim of the Olympic Coast National Marine Sanctuary for assistance with permitting. This work also benefitted from members of the Scripps Whale Acoustics Laboratory who assisted with logistics support for instrument preparation, deployment and recovery including: Beve Kennedy, Ryan Griswold, and John Hurwitz. We also thank the captain and crew of the R/V Centennial, operated by the University of Washington, for assistance with instrument deployment and recovery.

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