Characteristics of echolocation clicks in southern resident killer whales (*Orcinus orcas*)

Sofia Chang[1,2]

Marine Birds and Mammals
Summer 2011

[1]Friday Harbor Laboratories, University of Washington, Friday Harbor, WA 98250
[2]Department of Integrative Biology, University of California – Berkeley, Berkeley, CA 94720

Contact Information:

Sofia Chang
Department of Integrative Biology
University of California – Berkeley
3060 Valley Life Sciences Building
Berkeley, CA 94720
swchang@berkeley.edu

Abstract

Odontocetes rely on echolocation clicks to navigate, forage and communicate. As such, understanding the characters of click shall help understanding whale communication. Southern resident killer whales of the North Pacific Ocean are recorded echolocating at Lime Kiln State Park and characteristics of the echolocation clicks are explored. This study aims to describe the nature of killer whale vocalization by analyzing their calls and echolocation characteristics. Click train duration, number of clicks and duration of individual clicks are measured and tested against the hypothesis that they should follow a normal curve. Results mostly confirmed previous studies of the echolocation click's predominant characteristics in terms of click train duration of (<10 seconds), number of clicks in a click train (0-50 clicks) and individual click duration (<2ms). However, results failed to accept the hypothesis that the characteristics should follow a normal distribution. Suspected reason for such result lies in limitations of the acoustic data's collection methods, such as immobility of the hydrophones and unknown location of the killer whales respect to hydrophones. In addition, factors of conducting a short-term bioacoustic study are discussed.

Keywords: *Orcinus orca* SRKW vocalization bioacoustics echolocation click lime kiln

Introduction

The southern resident killer whale population (SRKW) resides in the inland waterways of Washington State and British Columbia (Strait of Georgia, Strait of Juan de Fuca and Puget Sound). The population consists of three pods, designated J, K and L that follows a matriarchic lineage. As opposed to transient and offshore populations, resident killer whales occupy in costal habitats and live in relatively large and stable social groups (Hildebrand 2004). SRKW are particularly active in the San Juan Island channels where they feed on salmon species during the summer. SRKW are often found along the west side of San Juan Island where salmon are particularly abundant.

Common to many odontocetes, killer whales depend on auditory signals to navigate, forage and communicate intraspecifically. The three main types of sounds produced are pulsated calls, tonal whistles and echolocation clicks (Ford 1989). Pulsed calls are the most common and ubiquitous form of vocalization that sounds like squeaks, screams and squawks, often heard during traveling and foraging to maintain contact with other group members (Miller 2002, NOAA 2008). Pulsed calls may also develop dialects within different tribes of orcas since vocalization is not innate and requires learning. Tonal whistles are tonal sounds of a fundamental frequency with the addition of several harmonics (Thomsen et al. 2001). Whistles are produced for both long-range communication and social interactions. Echolocation clicks are brief pulses of ultrasonic sound that often form a series known as click trains. They are used for navigation and discriminating objects in the environment and can also be present during social interactions.

Echolocation clicks are of special interest because they are non directional, broadcasting into their space in order to create a spatial understanding of their surroundings. Individual clicks are highly variable. A single click can last from .1 to 25 ms, and the frequency can range from 4-18 kHz normally but reach up to 50-85kHz (Barrett-Lenard et al. 1996, Au et al. 2004). A click train may last 2-8 seconds and contain around 2-50 clicks. However, click numbers in a train has been as high as 300 clicks. Slower clicks are thought to function for navigation and orientation, and rapid clicks are used to investigate objects within 10m (Ford 1989). SRKW communicate and detected their prey through combining echolocation clicks and passive listening (Barrett-Lennard et al. 1996).

This study aims to gain a better understanding of the vocal nature of SRKW. I quantified characteristics of echolocation clicks based on 1) duration of a click train, 2) number of clicks in a click train, 3) duration of individual click. Also, I want to test the hypothesis that the characteristics should follow a normal distribution pattern, or a bell curve. Biological variables that resulted from interaction of different factors often fit the normal distribution fairy well (Sokal et al. 1995). Further, this paper reflects my personal goal of familiarizing with the unique whale calls as well as the hydro acoustic methods used to study cetacean vocalization.

Methods

Data collection

Behavioral and acoustic data were recorded from 1990 up to now (2011) during the summer months at Lime Kiln State Park, San Juan Island, Washington (B.Otis and L. Skates, unpubl.data). I obtained acoustic data only for the period 29 July, 2011 to 10 August, 2011. Acoustic recordings are made from the Lime Kiln hydrophone array, which are positioned southwest of the lighthouse, about 7 m below the water surface attached to the seafloor (see Appendix for map). They can receive both directional and non directional acoustic signals, but the directional signal can only be detected when the source is close to perpendicular to the hydrophone. Pulsated calls were heard throughout the recordings, but only echolocation clicks were quantified.

Data Analysis

Audacity 1.3.13-beta and RavenLite 1.0 from Cornell Lab of Orinithology's Bioacoustics research program were used to analyze raw acoustic data (See Appendix for screenshot). I counted the total duration of a click train, the number of clicks in a click train and the duration of a single click (Fig. 1a). I used Audacity 1.3.13 – beta to processes the raw acoustic data and filter background noises in order to determine periods of useful time. The same program was useful to determine the total click train duration and individual click duration.

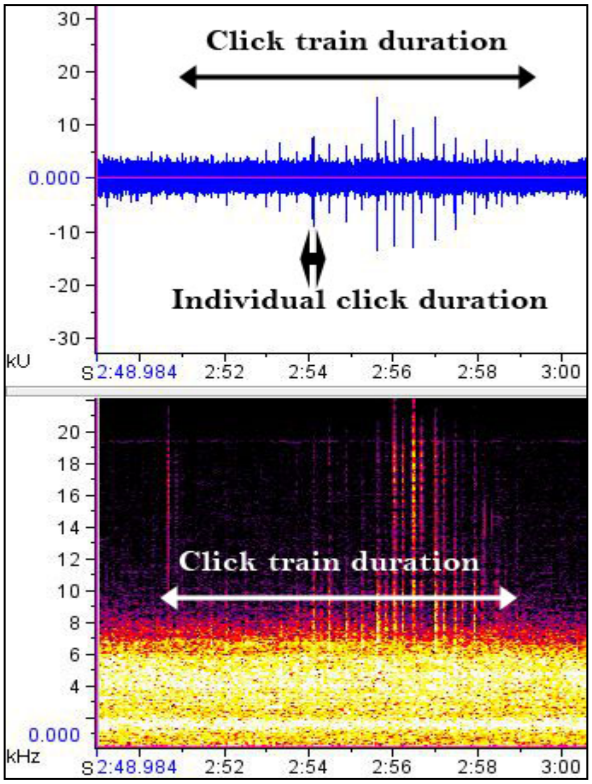


Figure 1a. Waveform of an acoustic sample. Lines surpassing the background noise are amplitudes that indicate individual clicks. Figure 1b. Spectogram of an acoustic data sample. Each line can be considered a click. Presence of a high amplitude line or frequency line does not always correspond to an audible click, but both can be used to aid click count.

RavenLite 1.0 generated spectrograms of the filtered audio file, allowing me to count the number of clicks in each click train by visualization. Noise that sounded like a quick pinch of a plastic bag was not used. Noises that clearly had a 'click' similar to plastic chopsticks striking each other, and noises that sound like lightly tapping the backside of a metal bowl were used. I mainly determined presence of a click train by listening to the audio. I counted the number of clicks with the aid of the waveform and spectrogram of the sound files because occasionally, even when the sound is present, the waveform does not necessarily show a peak, nor does the spectrogram necessarily display an energy line (Fig.1b). I organized the data in Microsoft Excel and summarized the results in histograms to look for predominance of click train duration, click number in a click train and duration of a single click. An additional Excel Add-in named "Analysis ToolPak" had to be installed before the generation of histograms from the raw data.

Results

Overall, the distributions of click train duration, individual click duration and number of clicks in a click train are weighted on the left. About 80% of most of their respective values are concentrated within the first thirds of the distribution.

The range of click train duration was 0.04 s - 53.717 s, with 55.17% of the clicks being less than 10 seconds and 79.31% of the clicks less than 20 seconds (Fig.2). The number of clicks in a click train ranged from 2-128 clicks, with 79.31% of the clicks between 0-50 clicks, and 93.10% between 0-75 clicks (Fig.3). Individual click durations ranged from 0.3ms - 15ms, with 75.86% of the durations being less than 2ms and 86.21% of the duration being less than 4ms (Fig.4). It is interesting to note that both click train duration and individual click duration have the same proportion of values in the first 1/6 of the distribution (see Appendix for Tables).

Figure 2.Click train duration are categorized in 10 second increments to see the distribution. The numbers on the x-axis denote the highest cut off number.

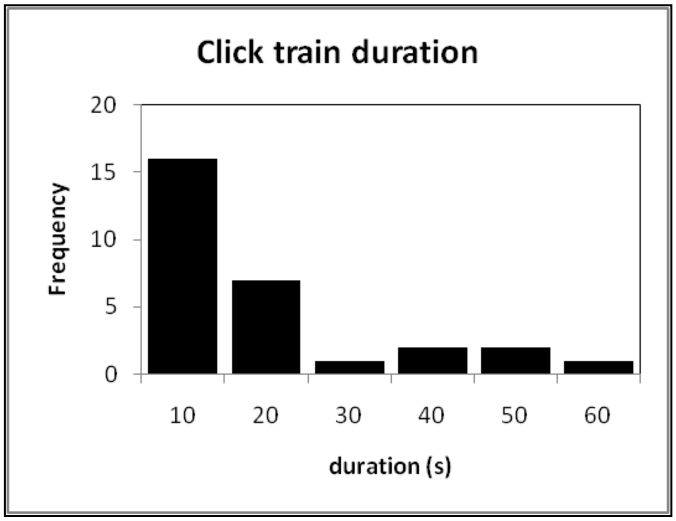


Figure 3. Number of clicks in a click train are categorized in 25 count-increments. The numbers on the x-axis denote the highest cut off number.

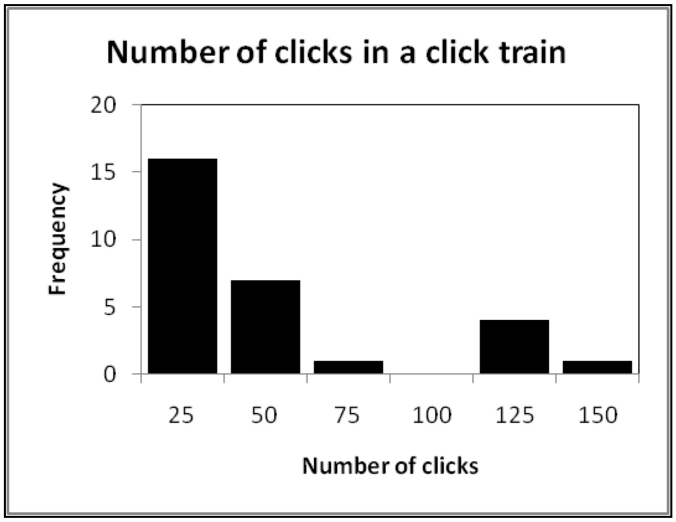
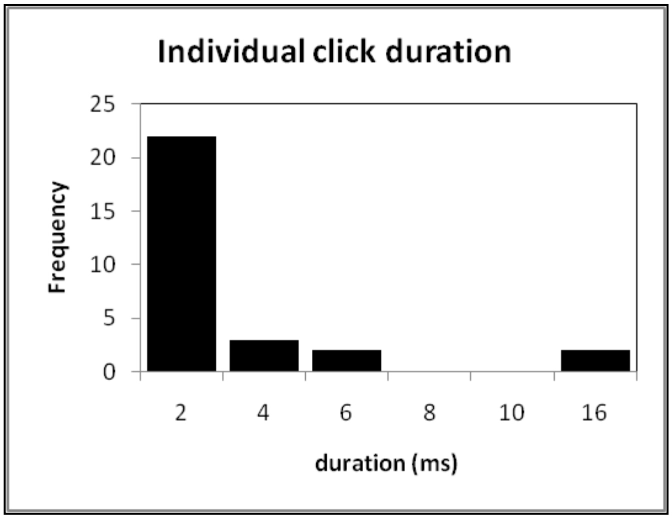


Figure 4. Duration of individual clicks are categorized in 2 miliseconds increments, except for the last category. The numbers on the x-axis denote the highest cut off number.



Discussion

Duration of a click train was predominantly less than 10 sec. Number of click per click train was predominantly less than 25 clicks. Duration of a single click was predominantly less than 2 ms. Short click train duration, fewer clicks per click train and short individual click duration has several behavioral implications. SRWK are known to echolocate during food foraging as well as socialization. Shorter click durations are used when their distance to their target is short or when the physical environment allows for good sound transmission. The whales may be close to an object, cutting short of the duration of click trains, lowering the necessity of using more clicks in a click train as well as using individual clicks of shorter duration.

Comparing the ranges of my measurement of previous measurements show some consistency once the confounding factors are identified. I measured, 0.5s – 54s for click duration, 2-128 clicks per click train, and 0.3-15ms for individual click durations. Barrett-Lenard et al. (1996), Au et al. (2004) and Ford (1989) measured ranges of 2-8 seconds for click train duration, 2-300 clicks for clicks per click train, and 0.1 to 25 ms individual click duration. The difference of the click train duration may be result of not knowing how many whales are echolocating at the same time. Although there is evidence of whales sharing the same click train produced by one whale (NOAA, 2004), whale may alternate echolocation time so that several click trains appears as one, explaining longer measured click train duration. In addition, previous studies used automated click-counting programs in Matlab (Beneze 2010; Kazuna 2009) while I counted the clicks through hearing them over headphones with the aid of spectrograms (Fig.1b). There may be more error associated with an automated process.

The lack of a normal distribution is apparent with visual inspection of the histograms (Fig.2, 3, 4). Since echolocation clicks depends on several factors such as presence/absence of an obstacle, a prey, a conspecific or a threat and properties of the water such as salinity, temperature, density and depth, combination of the effects of all the parameters should reflect a normal distribution (Sokal et al. 1995). However, the results appear to suggest that echolocation clicks are being made while being very close to a target. The limitations of the static hydrophone array in Lime Kiln may explain this observation. In previous studies, Beneze (2010) and Kazuna (2009) collected data by towing an array of four hydrophones behind a boat while making distance estimations and ensuring that the boat is oriented perpendicular to the path of the killer whales. The physical position of the hydrophones of Lime Kiln is fixed, and the position of the whales is unknown at the time of recording the sounds, so it is likely that most recorded sounds are made only when whales are relatively close to the hydrophone.

Nevertheless, failing to reject the hypothesis does not preclude the importance of detecting a normalcy in the echolocation characteristics. Proposing the normal distribution of clicking characteristics was inspired by a simple analogy to human speech: we whisper in a chapel or raise our voices at a bar; but most of the times, we have a set range of normal speaking volume. Systematically quantifying the speaking voices should reveal a normal distribution where the ‘chapel-tone’ and ‘bar-tone’ falls at the ends of the normal distribution and the ‘normal-tone’ would compose the dome of the bell-shaped curved. Similarly, whale vocalization may reveal a normal shaped curve with a range of most-used-characteristics. Prolonged usage of ‘bar-tone’ range, i.e. shouting constantly, may result in loss of vocalization whether vocalization is made in air or in water. Thus, characteristics where a normal range can be determined may serve as a proxy to identify acoustic pollution in the environment.

Effects of acoustic pollution have already been shown to be detrimental in odontocetes. Morton (2002) has shown that AHD deters killer whales from their original habitats, Holt (2009) shows that killer whales raise their call intensity 1 dB for every 1dB background noise increase, and Jepson (2004) suggested that sonar may cause direct physical damage in odontocetes. In addition, SRKW are listed as endangered in 2004 under the Endangered Species Act due to commercial and private vessel disturbance, decline in primary prey and exposure to high levels of chemical toxins (NOAA 2004). Studying how whales produce sound is part of Hildebrand (2005)'s vision where sources of acoustic sounds can be characterized and monitored. Understanding how anthropogenic noise sources affect marine life will aid protecting their environment from further degradation.

A project in bioacoustics will satisfy student's understanding of acoustic issues surrounding killer whales and the mechanics of studying sound in the water. However, caveats of the project should also be considered. Methodically, the acoustic data was collected very differently from previous studies since a static hydrophone is limited to capturing sounds that are close to its location. Logistically, there is a learning curve before one can start identifying the sounds of the ocean and analyzing the acoustic profiles with the programs Raven Lite or Audacity. If collaborating with another researcher, obtaining the data may be difficult since the researcher's availability may be unpredictable and the data files may be too large to be sent by email (An external hardrive proved to be very useful). Analytically, I found my previous familiarity with

Statistical package R, Matlab, and MS Excel helpful in navigating through SQLshare audio database and learning to use Ravenlite and Audacity. Five summer weeks is a relatively short time to learn the sounds of the ocean, familiarize with the background of sound propagation, learn the programming required to analyze the data and analyze the data. However, having the right contacts and spending more time with the data will result in good independent learning experience. Ultimately, identifying sounds in the ocean will contribute to our understanding of whale communication, and help protection of the marine environment for the marine animals endangered or threatened by anthropogenic soruces.

Acknowledgements

Breck W. Tyler, Eric M. Anderson and Connie Sullivan for the leading the summer course. Bob Otis and Lisa Skates for providing acoustic recordings from Lime Kiln State Park. Robin Kodner and Scott Veirs for providing an introduction to understanding the acoustic data and analysis.

Cited Literature

Au, W. W. L., Ford, J. K. B., Horne, J. K., and Allman, K. A. N. 2004. Echolocation signals of free-ranging killer whales (*Orcinus orca*) and modeling of foraging for Chinook salmon (Oncorhynchus tshawytscha). Journal of the Acoustical Society of America 115:901-909.

Barrett-Lennard, L. G., Ford, J. K. B., and Heise, K. A. 1996. The mixed blessing of echolocation: Differences in sonar use by fish-eating and mammal-eating killer whales. Animal Behavior 51:553-565.

Beneze, Erica. 2010. Echolocation use by southern resident killer whales (*Orcinus orca*) while foraging. Beam Reach Marine Science and Sustainability School. http://www.beamreach.org/091dir/final-paper-erica-beneze.pdf. 10 August 2011.

Hatch, L.T. and Wright, A.J. 2007. A Brief Review on Anthropogenic Sound in the Oceans. *International Journal of Comparative Psychology,* 2007, **20**, 121-133.

http://comparativepsychology.org/ijcp-vol20-2-3-2007/04.Hatch&Wright_PDF.pdf. 18 August, 2011)

Hildebrand, J. 2004. *Sources of anthropogenic sound in the marine environment.* International Policy Workshop on Sound and Marine Mammals, London.

Hildebrand, J. A. (2005). Impacts of anthropogenic sound. *Marine Mammal Research: Conservation Beyond Crisis* (pp. 101-124). Baltimore: Johns Hopkins University Press.

Holt MM, Noren DP, Veirs V, Emmons CK, Veirs S. 2009. Speaking up: Killer whales (Orcinus orca) increase their call amplitude in response to vessel noise. J Acoust Soc Am. 2009 Jan;125(1):EL27-32.

Horne, K.J. 2000. Acoustic approaches to remote species identification: a review. Fish. Oceanogr. 9:4, 356-371.

Kazuna, H.2009. Killer Whale (*Orcinus orca*) Echolocation click rates during various behavioral states and ambient noise levels. http://www.beamreach.org/wp-content/uploads/paper_hana102.pdf. 10 August 2011.

National Marine Fisheries Service. 2008. Recovery Plan for Southern Resident Killer Whales (*Orcinus orca*). National Marine Fisheries Service, Northwest Region, Seattle, Washington.

National Oceanographic Atmospheric Administration. 2004. Southern Resident Killer Whale Behavior Workshop. NOAA NMFS Northwest Fisheries Science Center. Seattle, Washington.

Miller, P.J. 2006. Diversity in sound pressure levels and estimated active space of resident killer whale vocalizations. *J Comp Physiol A Neuroethol Sens Neural Behav Physiol.* 192(5):449-59.

Miller, P.J. and Bain D.E. 2000. Within-pod variation in the sound production of a pod of killer whales, *Orcinus orca. Animal Behavior. Volume 60, Issue 5, November 2000, Pages 617-628.*

Morton, A.B. and Symonds, H.K. 2002. Displacement of *Orcinus orca* (L.) by high amplitude sound in British Columbia, Canada. *ICES J. Mar. Sci. (2002) 59 (1): 71-80.*

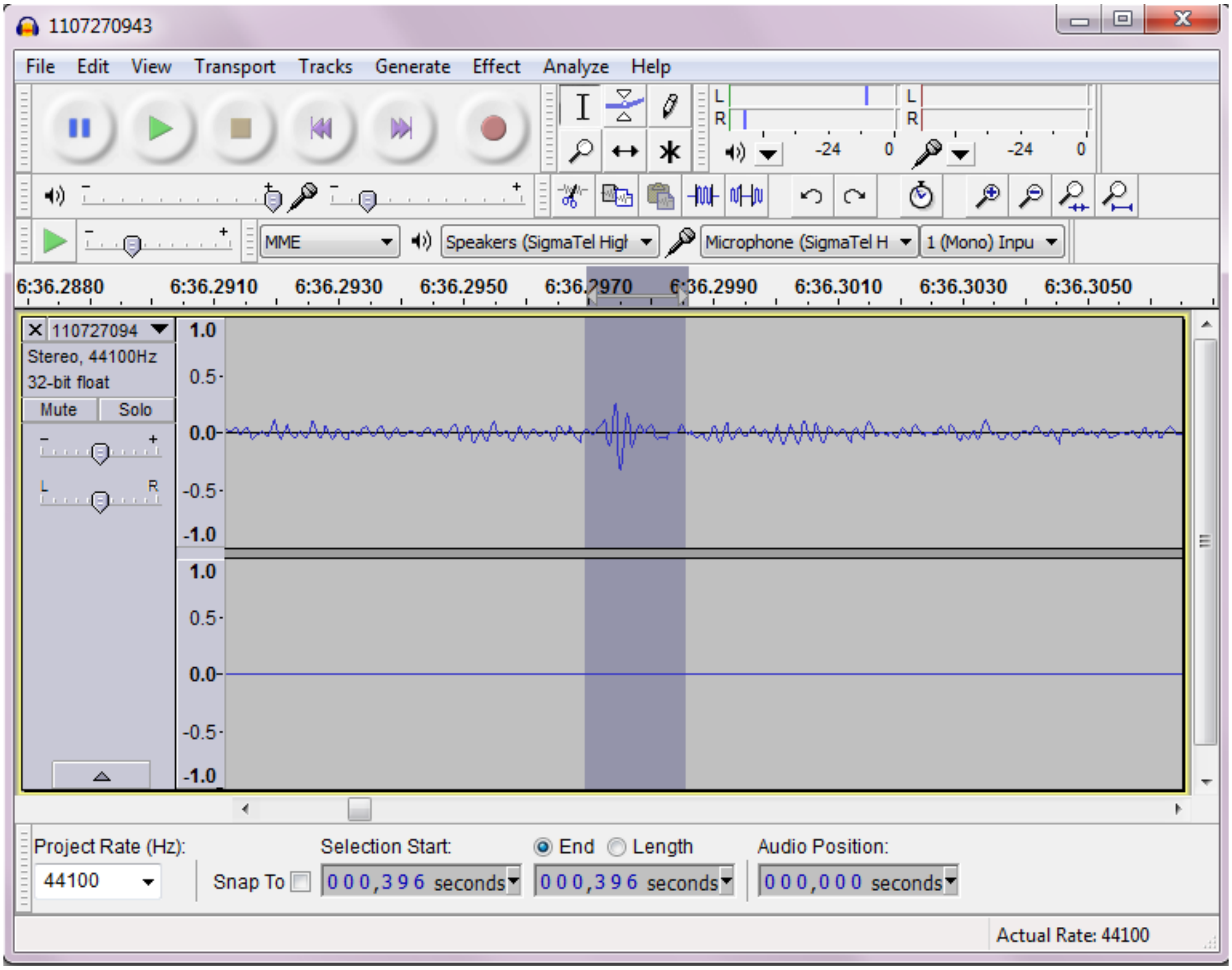
Thomsen, F., Franck D., and Ford J. K. B. 2001. Characteristics of whistles from the acoustic repertoire of resident killer whales (*Orcinus orca*) off Vancouver Island, British Columbia. *J. Acoust. Soc. Am. Volume 109, Issue 3, pp. 1240-1246.*

Sokal, R. R. and F. J. Rohlf. 1995. *Biometry: the principles and practice of statistics in biological research.* 3rd edition. W. H. Freeman and Co.: New York. 887 pp.

Soule, M.E. 1985. What Is Conservation Biology? *BioScience,* Vol. 35, No. 11, The Biological Diversity Crisis. pp. 727-734.

Soule M.E. Estes J.A. , Miller B., Honnold D.L. 2005.Strongly Interacting Species: Conservation Policy, Management, and Ethics. *BioScience*, Vol. 55, No. 2. 168.

Appendix I: Maps and Screenshots



Project Rate (Hz): 44100

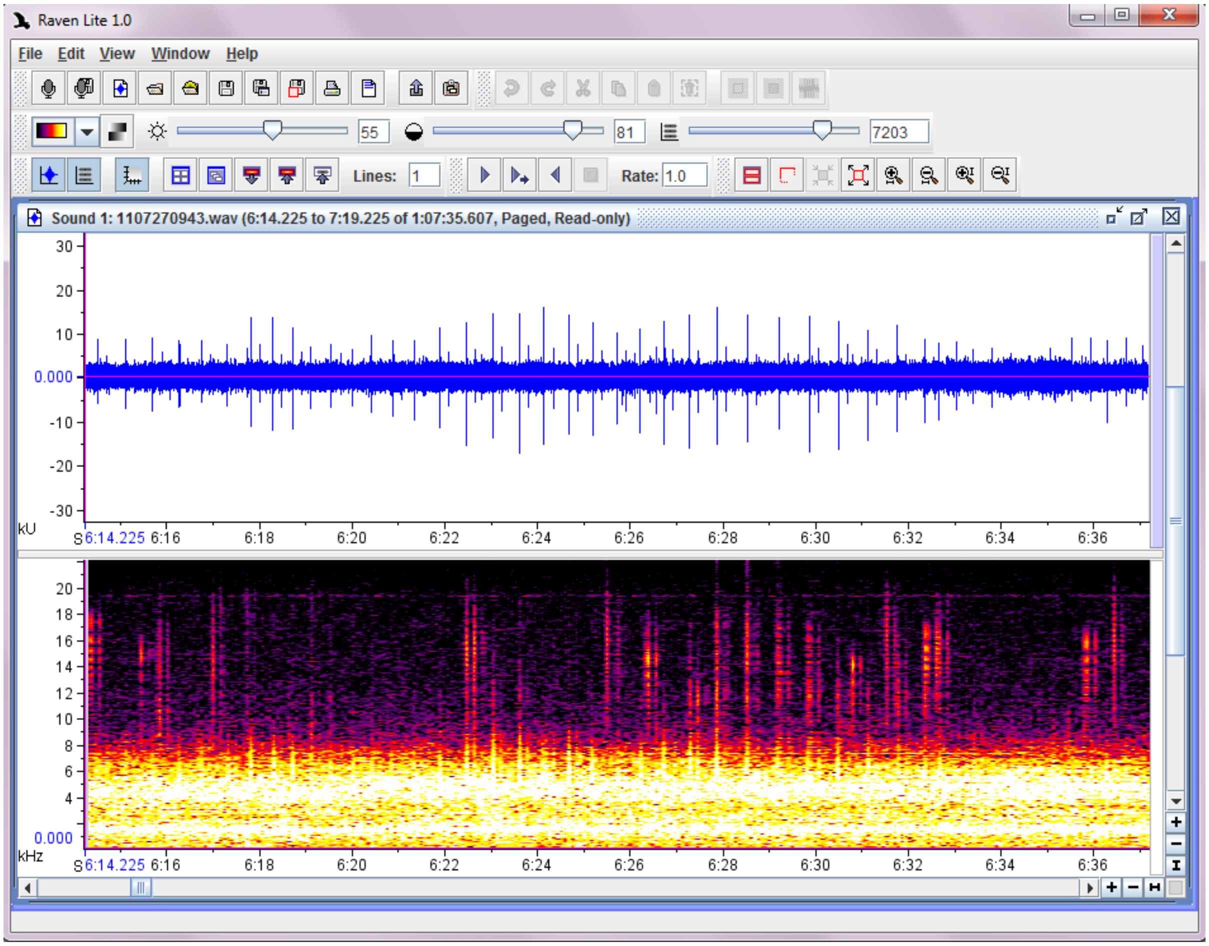
Selection Start: 000,396 seconds

● End ○ Length: 000,396 seconds

Audio Position: 000,000 seconds

Actual Rate: 44100

Figure 5: Screenshot of the program Audacity 1.3.14-beta. An individual click duration is being measured: zooming into the waveform very closely, I highlighted an estimated duration of the individual click duration and estimated the duration from the bolded numbers above the waveform.



Lines: 1

Rate: 1.0

Sound 1: 1107270943.wav (6:14.225 to 7:19.225 of 1:07:35.607, Paged, Read-only)

Figure 6. Screenshot of the program Ravenlite 1.0. A click train is shown in the viewing window with its corresponding spectrogram.

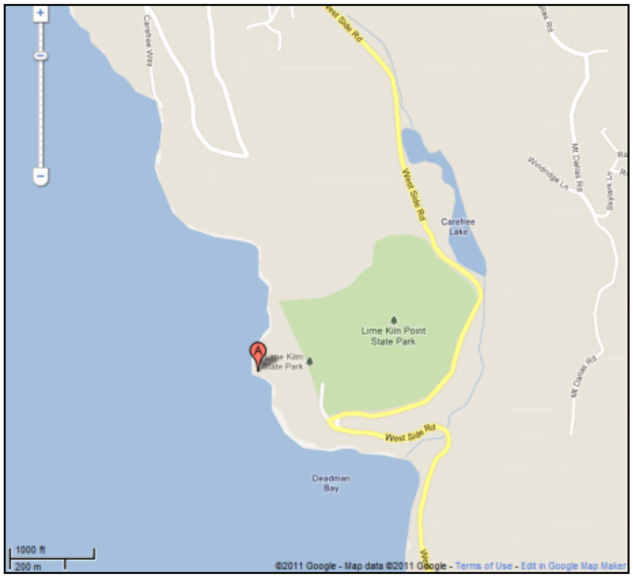


Figure 7.Map of the hydrophone location is under the lighthouse, marked (A) in map.

Behavioral observations by Otis and Skates span from the base of the Lime Kiln lighthouse (A), spanning the coastline from Deadman’s Bay up to one mile north. But behavioral observations are not used in this study because they were not received in time for adequate analysis.

(a) Click train Duration			
Bin	*Frequency*	*Cumulative %*	*Average*
10	16	55.17%	9.8
20	7	79.31%	11.3
30	1	82.76%	-
40	2	89.66%	9.5
50	2	96.55%	40.8
60	1	100.00%	-
More	0	100.00%	-
MAX	53.717	seconds	
MIN	0.498	seconds	

(b) Number of clicks in a click train			
Bin	*Frequency*	*Cumulative %*	*Average*
25	16	55.17%	24
50	7	79.31%	30
75	1	93.10%	-
100	0	96.55%	-
125	4	100.00%	103
150	1	100.00%	-
More	0	100.00%	-
MAX	128	number of clicks	
MIN	2	number of clicks	

(c) Individual click duration			
Bin	*Frequency*	*Cumulative %*	*Average*
2	22	75.86%	1.0
4	3	86.21%	3.0
6	2	93.10%	5.0
8	0	93.10%	-
10	0	93.10%	-
16	2	100.00%	13.0
More	0	100.00%	-
MAX	15.000	ms	
MIN	0.300	ms	

Table 1. Complementary tables that generated the histograms (Fig.2,3,4)

Table (a) are calculations for click train duration; table (b) for number of clicks in a click train; and table (c) for individual click durations.

Bin refers to the cut off for each bar in the histograms. Frequency is the number of cases occurring higher than the previous ‘Bin’ number, and less than or equal to the ‘Bin’ number in the corresponding row. For instance, first row of in (a), there are 16 clicks that are between 0-10 seconds, 10 sec included.

Cumulative percentage and average for each ‘bin’ category follow in the next two rows. No calculation is made where there is only one or no values

Maximum value and minimum values of the entire data set are identified in the last row.

Appendix II: Physics of sound and its characterization for starters

Preface: Personally, I struggled with understanding the concepts and terminologies related to sound transmission in water when I started this project. The following writings were originally included in the introduction assuming that the reader is in a similar position. However, as the subject of my research narrowed down to echolocation clicks, understanding the physics of sound ceased to be an obligation. As such, with the support of my course mentors, I decided to relocate my understanding of sounds in an appendix, in hopes that it should facilitate a future adventurous pioneer of bioacoustics in the ocean.

Sound travels in compression waves that cause particles in air or water to vibrate. If we were to track a particle vibrating, it will result in an oscillating waveform. Wavelength and amplitude characterizes a wave. Wavelength indicates how fast the particles are vibrating, and amplitude indicates how much energy the wave carries. Wavelength determines the pitch of the sound. Basic visualizations of sounds are waveforms and spectrograms. Waveforms are graphs of varying quantity against time or distance. They are commonly represented with sinusoidal waves, but sometimes the high resolution of the recording and the short duration of the signal may make the signal seem like a one-line peak. Spectograms are representation of varying frequency against time. Intuitively, it shows how the pitch of the sound changes throughout the recording.

'Loudness' of a sound results from a combination of the amplitude of the soundwave and the hearing thresholds of the listener. In sea water, sound travels approximately 15,000 ms^{-1} (although in air it only travels 340 ms^{-1}). Common methods to characterize one type of 'loudness' is looking at the amplitude and measuring peak-to-peak pressure, peak pressure and root mean squared (rms). Peak-to-peak pressure refers to the distance between highest peak and lowest trough; peak pressure is the maximum absolute amplitude and rms measures the average of the pressure of the sound signal over a given duration. The latter is preferred because it is directly related to the amount of energy carried by the sound wave. The unit decibels (dB) is a measurement of sound's intensity (or directional energy), usually relative to a relative measurement. In seawater, the standard reference is 1µPa, so that when the dB is reported, it is written as ###dB *re:* 1µPa. The reference in air is 20µPa, about the sound of a pin drop.