Measuring the Lengths of Sperm Whales of the Northern Gulf of Mexico by Wavelet Analysis of their Usual Clicks

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Measuring the Lengths of Sperm Whales of the Northern Gulf of Mexico by Wavelet Analysis of their Usual Clicks

A Dissertation

Submitted to the Graduate Faculty of the University of New Orleans
In partial fulfillment of the Requirements for the degree of

Doctor of Philosophy
In Engineering and Applied Science Physics

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December, 2023
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Abstract

Acoustic recordings of underwater sounds produced by marine mammals present an attractive alternative to costly and logistically complex ship based visual surveys for collecting population data for various species.

The first reported use of underwater acoustic recordings in the long term monitoring of sperm whale populations was by Ackleh et al. (Ackleh et al., 2012). The paper describes counting sperm whale clicks at different locations to track population changes over time.

Analysis of sperm whale clicks offers additional insight into sperm whale populations. The echo location clicks (usual clicks) of sperm whales can be used to give an estimate of the whale’s length. The acoustic axis of the whale must be aligned with the hydrophone for accurate length estimates to be made. Most previously reported work using acoustics to measure whale lengths has been done with surface hydrophones recording clicks from a diving whale. With that geometry the whale’s acoustic axis will be approximately aligned with the hydrophone. In the case of monitoring a diving whale it is usual that most of the recorded clicks are from a single whale reducing interfering clicks from other whales.

When recording clicks with bottom mounted hydrophones no whale/hydrophone orientation can be assumed. The vast majority of clicks recorded are from off axis whales and therefore produce inaccurate length measurements. It is also not unusual for several clicking whales to be recorded at the same time, producing incorrect whale length measurements due to interference between the clicks. Cepstrum Analysis is the favored technique for making acoustic whale length measurements from bottom moored hydrophones. If enough clicks are recorded from the same whale in enough different orientations, the spurious signals in off axis clicks are “averaged out”. It has been observed, however, that multiple whales clicking at the same time produced errors in the results from Cepstrum Analysis.
In this paper a new method for selecting on axis sperm whale clicks from which to determine repeatable length estimates will be presented. It uses wavelet decomposition and a unique quality control test to make better whale length estimates.

Keywords: Signal Processing, Underwater Acoustics, Sperm Whales, Wavelet Analysis, Cepstrum Analysis
Chapter 1 – Introduction

1.1 Background

During the summer of 2015 the Littoral Acoustic Demonstration Consortium – Gulf Ecological Monitoring and Modeling (LADC-GEMM) group launched an expedition to use passive acoustic monitoring (PAM) to survey the state of marine mammals in the northern Gulf of Mexico (GoM) after the Deepwater Horizon (DWH) incident in 2010. To this end bottom mounted hydrophones, automated surface vessels and undersea gliders were used to collect acoustic signals from dolphins, beaked whales, and sperm whales (Sidorovskaia, 2015).

The LADC-GEMM consortium was well positioned to do such a study having completed a two-week survey of marine mammals in 2007 just 9 nautical miles from the DWH site. The 2007 survey included visual and acoustical observations of the marine mammals as well as characterizing the background noise both natural and anthropogenic.

The bottom mounted hydrophones used in the 2015 survey (Environmental Acoustic Receiving System - EARS) were deployed in three areas of the GoM near the DWH site by the research vessel R.V. Pelican. The location of Buoys 3 and 4 (deployed in the most northern site) is shown in Figure 1-1. This site was the closest to the DWH site.
The Ears Buoys consisted of a hydrophone/recording package supported by a line of glass floats, and anchored by a 500 kg anchor. The buoy array was about 539 meters in length and was placed in water 1500 meters deep positioning it at the foraging depth of sperm whales. The data from the buoys were recorded on hard drives in the hydrophone/recording package. In order to recover the hard drives with the data at the end of the four months long survey an acoustic release mechanism was used to disconnect the anchor from the rest of the buoy assembly after receiving a specially encoded signal allowing the buoy to float the surface.
The objective of this study was to develop methods to estimate the lengths of sperm whales from the EARS recordings of their echolocation clicks. It is hoped that those methods will provide information on the size and perhaps the sex of the sperm whales allowing the monitoring of future trends in the sperm whale population of the GoM.

1.2 Introduction to the Sperm Whale

Sperm whales (*Physeter macrocephalus*) are some of the largest animals on earth. Male sperm whales can grow 16 to 18 meters in length with a mass of 60 tons. Female sperm whales grow to only about 11 or 12 meters in length and a mass of about 20 tons. This makes the sperm whale the most sexually dimorphic species of all whales (Whitehead, 2003). It is the largest of the toothed whales and possess the largest brain on earth (7.8 kg). Sperm whales are some of the ocean’s deepest divers. They have been tracked by sonar on dives deeper than 1000 meters. The head of the sperm whale, the largest head of any animal on earth, contains a very powerful sonar system which it uses for hunting for food as well as for communications (Whitehead, 2003). The echolocation click produced by the sperm whale used for foraging is the loudest animal produced sound on the planet with a source level of > 229 dB re 1uPa (Møhl, 2000).

1.3 Monitoring Sperm Whales

The GoM is a sperm whale nursey. For most of the year females, juveniles, and immature males make up the majority of the population living in mixed groups (Richter, 2008). Mature males are present in these groups only for a short mating season returning to their northern habitats at the end of the season. Observations of the GoM whales are difficult since most female/juvenile mixed groups live
offshore in waters that are typically 1000 meters deep. The mature females and older juveniles spend the majority of the time underwater foraging for food minimizing the opportunities for visual sightings.

Visual observations also require surveys by surface vessels or aircraft for extended periods of time making them expensive. Automated recording buoys (EARS buoys) placed on the seafloor of the GoM have demonstrated the ability to collect acoustic information for months at a time before being retrieved and the data analyzed. Acoustic data can be collected at night, and during inclement weather. Using acoustics to collect long term observations is useful in determining long-term population changes and their underlying causes (Sidorovskaia, 2017). Five ship based visual surveys of sperm whale populations performed by the National Oceanographic and Atmospheric Administration (NOAA) during the time period of 2003 to 2018 has documented an average 4.2% decline per year in the sperm whale population of the northern Gulf of Mexico (Whitehead, Shin, 2022). The largest declines occurred after the survey conducted in 2009. One of the first reports of using acoustics in a long term population monitoring survey of sperm whales was performed in the Gulf of Mexico (Ackleh, et.al, 2012). The number of sperm clicks were recorded at three sites in the GoM 9, 25 and 50 miles away from the DWH site. Baseline acoustical data had been recorded from those sites in 2007 prior to the oil spill. The number of clicks recorded at the 9 mile site during the 2010 survey was one half of the number recorded during the 2007 survey. Interestingly, there was an increase in the click activity at the 25 mile site. Perhaps the whale’s food supply moved and the whales followed. The most significant drawback to using an acoustic monitoring system is the lack of photo identified individual sperm whales.

1.4 Determination of the lengths of Sperm Whales from acoustic data

Sperm whales produce several major types of clicks. The most common click types are 1) Usual, 2) Creek, 3) Coda, and 4) Slow. The usual clicks are echolocation clicks used to locate food. The creeks are thought to be used by the sperm whales for terminal guidance to food as the whale approaches its
prey. Coda clicks are produced by sperm whales at or near the surface when the whales are in social
groups. They are thought to encode identity for a group and its members. Slow clicks have only been
associated with male sperm whales. These vocalizations may be useful in defining foraging areas for
male whales (Whitehead, 2003).

An explanation of how sperm whales produce echolocation clicks (usual clicks) was presented by
Norris and Harvey (N & H) in the 1970’s (Norris, Harvey, 1972). They proposed that the clicks were
produced by the phonic lips or museau de singe / monkey lips. They hypothesized that the acoustical
pulse produced by the phonic lips was directed rearward through the spermaceti organ and then
reflected forward from the frontal air sac. The pulse again traveled through the spermaceti to the distal
air sac in the front of the whale’s nose. It was hypothesized that the spermaceti organ was an acoustic
waveguide forcing the pulse to bounce back and forth between the two acoustic mirrors – the frontal
and distal air sacs. Norris and Harvey were uncertain as to where the pulses from the reverberations
exited the whale’s head. They proposed the exit location to be at the upper phonic lip of the whale. In
their model the time between emitted pulses was equal to the two way travel time through the
spermaceti organ.
Møhl (Møhl, 2003) proposed the “bent – horn” model of sperm whale usual click production. In this model a small portion of the click energy produced by the phonic lips is transmitted directly into the water in front of the whale. This pulse is the p0 pulse of the click. The majority of the click energy (99.6%, Møhl, 2003) is directed rearward through the spermaceti organ until it reaches the frontal sac. The energy reflects off of the frontal sac and passes through the junk on its path out of the front of the whale. This is the p1 pulse. The subsequent pulses of the click (p2, p3, etc.) are produced by the reflection of a portion of the p1 pulse forward directed to the distal air sac resulting in another round trip for the pulses (Figure 1-2). Each of the subsequent pulses being lower in amplitude than the preceding pulse (Madsen, 2002).
This set of uniformly spaced pulses is called the Norris-Harvey Set (N&H Set) (Figure 1-3). The phonic lips have been confirmed as the source of the clicks from data acquired from a neonate sperm whale in rehabilitation (Madsen, 2003, Zimmer, 2005 A).

Both the Norris-Harvey model and Møhl’s bent horn model show that the time between the pulses of a sperm whale click (the interpulse interval or IPI) is proportional to the length of the whale’s head. Data from whales harvested during whaling operations show that the head of a whale is approximately equal to 29% of a whale’s length (Nishiwaki, 1963). Measurement of the IPI of a whale click can therefore give an estimate of the whale length.

One of the first attempts to use the IPI to estimate the length of a sperm whale was made by Norris and Harvey (Norris, Harvey, 1972). In August, 1968, off the coast of Chile a single sperm whale approached a small boat in which they were recording underwater sounds. The whale was clicking while approaching the boat and bumped into the hydrophone. An estimate of the whale’s length was made by the crew as the whale traveled on the surface next to the boat. It was estimated that the whale was the same length as the boat, about 9 meters. Using the IPIs measured from the whale’s clicks as it approached the boat it was estimated that the whale was 9.18 meters long. That estimate was in good agreement with the crew’s estimate of the whale’s length.

One of the first researchers to publish an analysis of acoustic data to determine the length of sperm whales from recording of their usual clicks was Hilary S. Alder-Fenchel. Using a tape recorder, oscilloscope and filter she measured the interpulse interval (IPI) of sperm whale clicks in the western North Atlantic to be from 1.6 to 8 milliseconds. That IPI range corresponding to a length of 7 to 22 meters using the Norris and Harvey equation. The mean length of North Atlantic sperm whales determined by Adler-Fenchel was 15.6 meters as compared with a mean length of 14.4 meters reported

There is a problem determining the length of sperm whales from their IPIs. The spermaceti organ is not a perfect waveguide. Not all of the acoustic energy is contained within the organ and some leaks out. Figure 1-4 shows an example of paths taken by components of whale clicks to a hydrophone off of the acoustic axis of the whale. As can be determined from the figure the path length for the $p_{1/2}$ component is longer than that of $p_0$, but shorter than that of $p_1$. In this example the $p_{1/2}$ will arrive at the hydrophone between the $p_0$ and $p_1$ pulses. This additional pulse – or series of additional pulses – produces a complex waveform in which it is not possible to identify N&H set pulses (Figure 1-5). It is not possible to obtain accurate IPIs from off-axis pulses. In order to use IPIs to determine the length of sperm whales a method to identify which clicks were produced by on-axis whales is needed.

The goal of this research was to develop a method to select on axis whale clicks and use them to produce accurate length estimates of the sperm whales.
Figure 1-3: Usual Click from an On-Axis Sperm Whale with p0, p1 and p2 pulses

Figure 1-4: Paths taken by click components to a hydrophone from an off axis whale (Modified from Caruso, 2015, an open access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.)
Figure 1-5: Sperm Whale Usual click from an Off-Axis Whale
Chapter 2: Wavelet Method for Estimating Sperm Whale Lengths

2.1 Algorithm Development

The EARS Buoys deployed in the GoM recorded acoustic data for approximately four months (June to October, 2015). The signals were sampled at 192,000 samples per second by a 16 bit analog to digital converter and stored on four one terabyte drives located in each buoy. The hydrophone system consisted of a hydrophone with a sensitivity of -201dB re 1V/uPa (+/− 1dB) and an amplifier with a gain of 40dB (+/− 0.5dB). The output voltage range of the hydrophone system was 4V (+/− 2V) (Griffin, 2016).

Data from one of the terabyte drives on EARS Buoy Four were used in this study. That drive contained 119072 files each file being 21.3333 seconds long. Manually searching for sperm whale clicks in these files proved to be unworkable. It was decided that an automated method was needed to find files containing sperm whale clicks. A procedure using several computer programs was developed to search through the data files for sperm whale clicks and estimate the length of the whales from the inter-pulse intervals (IPIs) of the click pulses.

The first program was a custom Matlab program (Matlab programs are sometimes called scripts) written to locate the files containing sperm whale clicks and store them in a separate folder for further analysis. That code searched through the files looking for clicks with the following characteristics: 1) peak click voltage of 0.1V (141 dB re 1uPa) or greater, 2) maximum power frequency less than or equal to 20 KHz, and 3) a minimum bandwidth of 1.9 KHz (Madsen, et.al., 2002). A minimum bandwidth requirement was included to prevent signals from the sonar devices on the R.V. Pelican from being identified as sperm whale clicks. This program took 18 hours to scan through the 119,072 files on Buoy 4’s first hard drive. Of the 119072 files recorded on the hard drive, 3707 or about 3% where found to contain at least one sperm whale click.
The files selected by the first script were then processed by a second script. The second script determined the number of clicks in each file with peak magnitudes over 0.1 V. The number of clicks with peaks exceeding 0.1 V was recorded in a new file along with the clicks detected in that file. The individual clicks in the file were averaged and the average click was also recorded. The individual files were averaged to reduce background noise. A third program examined these newly created files searching for files with 6 peaks or more. Six clicks or more were found in 712 files. Those files were saved to a separate folder.

An additional Matlab script determined if the whales producing the clicks were facing towards the hydrophone or away from the hydrophone. A follow-up script then determined if the whale clicks were from whales with their acoustical axes aligned with the hydrophones. These scripts found 488 files that were on-axis with the whale aligned with the hydrophone.

![Average Click for file 51846CB3.040 (426.mat)](image)

Figure 2-1: Click from Sperm Whale heading towards a hydrophone
A final script was used to estimate the length of the whales classified as heading towards and on-axis with the hydrophone. A quality check for whale length was performed on these clicks. The locations of the p0, p1, and p2 clicks were determined. The p1 to p2 interval’s duration (p1_p2) was divided by the duration of the p0 to p1 interval (p0_p1). It will be shown later that a \( \frac{p1_p2}{p0_p1} \) ratio between 1.00 and 1.55 indicates that the estimate of whale’s length was not corrupted by extraneous sources of noise. An example of this is shown at the end of this chapter. This quality check was the reason to select whales pointing towards the hydrophone. For whales pointing towards or approaching a hydrophone the p0, p1, and p2 pulses of the N&H set were all present and the p0_p1 and p1_p2 intervals could be determined (Figure 2-1). For whales pointing away from or leaving the hydrophone the p0 and p1 peaks of the N&H set occurred at the same time so that a p0_p1 interval was not possible to determine (Figure 2-2). The lack of a p0_p1 interval prevented the quality check from being performed for whales facing away from or leaving the hydrophone.

Figure 2-2: Click from Sperm Whale Leaving a hydrophone
Ideally, the value of the p1\_p2/p0\_p1 ratio should be equal or close to one. The variation in the ratio is due to the variation in the measurement of the location of the p0 pulse. The p0 pulse is small in magnitude as compared with the p1 pulse (Figure 1-2). The location of the maximum low frequency energy (1 KHz to 4 KHz) is used as the location of p0. The location of p0 is not as precisely known as are the locations of the other click pulses due to the longer wavelength of the lower frequency.

The ratios for 575 approaching whales were calculated using p0, p1, and p2 pulse locations determined by a Matlab script (Figure 2-3). The ratio values arranged from smallest to largest formed a function with two “inflection points”. The first inflection point occurs at a ratio value of 1 while the second occurs at a value of about 1.55. Twenty-nine values were selected between ratio values of 1.0 and 1.55. Thirty-one ratio values less than 1.0 or greater than 1.55 were also selected for analysis. The length of the whales corresponding to the click ratios were calculated manually and compared with the lengths calculated by the code. The maximum error between manually calculated and code calculated whale lengths for the 29 clicks with ratios between 1.0 and 1.55 was 1.45 meters (Figure 2-4). The maximum calculated error for click ratios less than 1.0 was -3.5 meters and for ratios greater than 1.5 the maximum error was 9.0 meters (Figure 2-5).

The whale clicks that were submitted for length estimation had already been determined as coming from whales which were approaching the hydrophone and on axis with the hydrophone. Manual calculation of whale length estimates found errors in length estimation due to extraneous noise occurring in the same file as the click under study. The major source of this sound was other whales clicking in the same file as the subject whale. A second source of noise were signals know as reverberations which occur between the p1 and p2 pulses of the whale (Zimmer A, 2004). More will be presented concerning these noise sources at the end of this chapter.
Figure 2-3: p1-p2/p0-p1 ratio

Figure 2-4: Length Error versus p1-p2/p0-p1 Ratio for 1.0< Ratio < 1.5
2.2 Description of Matlab Scripts

The purpose of the first Matlab script was to read a data file from hard drive storage into the memory of a computer to determine if the file contained at least one sperm whale click. Once the file was read into the computer it was scanned for the largest voltage peak equal to or exceeding 0.1V. If no such peak was found the file was discarded and the next file was read. A threshold voltage of 0.1V was selected as that voltage is about 40 dB above peak noise voltage observed. That provided a buffer against mistaking noise for a click. It also inherently selected for peaks from whales acoustically aligned with or nearly aligned with the hydrophone.

If a possible click was detected the peak of the click was located and a section of the data 17.2 mS in length centered around the peak was used to determine the frequency content and half-power bandwidth of the click. The value 17.2 mS was used since that would allow the measurement of an IPI from an adult male sperm whale (~16.5 m). A Fast Fourier Transform (FFT) of the data snippet was
calculated as well as its power spectrum (Bracewell, R., 2000). The maximum power frequency and the -3dB bandwidth for the snippet were determined. The click was determined to be from a sperm whale if the maximum power frequency was less than or equal to 20 KHz and if the bandwidth was greater than 1.9 KHz (Madsen, et.al., 2002).

All of the files containing at least one possible sperm whale click where scanned by a second program which counted the number of clicks per file and produced an average click from all of the identified clicks. The number of clicks found in the file, the clicks found in the file and the average click where stored in a newly created folder. A third program then searched through the folder for files containing six or more clicks. Files containing six or more clicks were passed to a fourth script that determined if the whale producing the clicks was heading toward or away from the hydrophone.

The fourth script performed a continuous wavelet transform (cwt) on the average click (Figure 2-6) in each of the files. The signal was filtered by retaining the cwt coefficients corresponding to frequencies between 1 KHz to 4 KHz (the LF frequency band) and between 30 KHz to 60 KHz (the HF frequency band) while zeroing out the remaining coefficients. Inverse continuous wavelet transforms (icwt) were then used to reconstruct the filtered signals corresponding to the LF and HF frequency bands. The signals in the LF band are produced during the p0 pulse (Figure 2-7) and are omnidirectional in nature. The signals in the HF band occur in the p1 pulse (Zimmer, 2005 A) (Figure 2-8).

The low frequency and the high frequency signals contained in the average click begin at different times (Figure 2-9). The low frequency component of a sperm whale’s usual click is produced at the start of the click interval. It is the portion of the signal that is directed into the sea from the front of the whale’s nose when the click is initiated by the phonic lips (monkey lips) (Møhl, et. al., 2003).
Figure 2-6: Average click of a sperm whale pointing toward a hydrophone

Figure 2-7: Low Frequency (LF) Component of average click of a sperm whale pointing toward a hydrophone
The high frequency energy of the click is contained in the p1 pulse for whales heading toward a hydrophone (Zimmer, 2005 A). Zimmer uses the term “forward click” to describe a click produced by a whale when the whale is facing toward a hydrophone. The term “backwards click” is used to indicate
that the whale is facing away from the hydrophone. The upper end for high frequencies in Zimmer’s paper was 16 KHz (Zimmer, 2005 A) as seen in Figure 7 of that paper. The upper frequency limit for the EARS buoys was 96 KHz (sampling frequency 192 KHz). It was thought that higher frequencies might be more directional, so a high frequency band from 30 to 60 KHz was investigated. A signal in that frequency band was found to be associated with the p1 pulse of forward clicks. In a whale’s forward click the p0 pulse always precedes the p1 pulse. If one could detect a p0 pulse followed by a p1 pulse it would be an indication that the whale was pointed towards the hydrophone. If the whale is facing away from the hydrophone a backwards click would be received by the hydrophone. In the case of a backwards click the low frequencies of the p0 pulse and the high frequencies of the p1 pulse would be detected almost simultaneously. As seen in Figure 7 of Zimmer’s paper the low frequencies and high frequencies are both present in a backwards click.

A method was developed to determine if the low frequencies and high frequencies arrived at a hydrophone at different times or at the same time. Different frequencies would arrive at different times for forward clicks, and they would arrive at the same time for backwards clicks. This method makes it possible to determine if the whale was facing (approaching) or not facing (leaving) the hydrophone. The method calculates the normalized cumulative power (ncp) of the low and high frequency signals. It does this by squaring the voltage at each time point and then consecutively adding the squared terms together dividing by the sum of all of the voltages squared. If a signal consisted of three values v1, v2, and v3 recorded at times t1, t2 and t3 then the ncp of the signal would equal (t1, (v1²/(v1² + v2² + v3²)), (t2, ((v1² + v2²)/(v1² + v2² + v3²)), (t3, (v1² + v2² + v3²)/(v1² + v2² + v3²)). A moving average filter of length 10 was applied to both the low and high frequency normalized cumulative power functions. The plots of the normalized cumulative power function for the Low Frequencies from Figure 2-7 (ncpLF) and the normalized cumulative power for the High Frequencies from Figure 2-8 (ncpHF) are shown in Figure 2-10. The method searches the ncpLF function for the time point when its value is closest to 0.2
and for the time point when the value of the ncpHF function is closest to 0.2. If the difference in time is
greater than or equal to 1.90625 mS the click is a forward click and the whale is facing the hydrophone.
If the time difference is less than or equal to 7.8125 uS the click is a rearward click and the whale is
facing away from the hydrophone (Drouant, G., Ioup, J., 2020). The click shown in Figure 2-10, with a
time difference of 2.44 mS is obviously a forward click.

Figure 2-10: Normalized cumulative power functions for the Low Frequency and High Frequency (red) Bands
of file 51846CB3.040 (426.mat)

A script was written to determine if the clicks selected as forward clicks were or were not
acoustically aligned with the hydrophone. It is important to use acoustically aligned clicks due to the
corrupted click structure of the non-aligned clicks (Schulz, 2009). The corrupted click structure can give
rise to incorrect whale lengths since it interferes with the determination of the locations of the p0, p1,
and p2 pulses in the click. The difference between on and off-axis clicks is illustrated in Figures 2-11 and
2-12. It was thought that such great differences in the appearance of the on and off axis clicks would
also be seen in the normalized cumulative power of the mid frequency band (8 KHz to 12 KHz) of a click.
The mid band frequencies were selected since those frequencies have the largest amplitudes of the frequency bands used in this study. Figures 2-13 and 2-14 show the amplitudes of three frequency bands (1 to 3 KHz, 8 to 12 KHz, 30 to 60 KHz) and their occurrence in the clicks.

Figure 2-11: Average Click from file 5205B3F6.040 – On Axis

Figure 2-12: Average Click from file 51962E08.040 – Off-Axis
Figure 2-13: Magnitude of Frequencies Present in Average Whale Click file 5205B3F6.040 – On-Axis

Figure 2-14: Magnitude of Frequencies Present in Average Whale Click file 51962E08.040 – Off-Axis
As expected, the normalized cumulative power for the mid band frequencies (ncpMF) were different in on-axis clicks and off-axis clicks as is shown in Figures 2-15 and 2-16. In Figure 2-15 the ncpMF is nearly zero from the start of the click until the middle of the click. This is because signals in the mid frequency band are not present in the p0 pulse. Mid frequency band signals occur in the p1 pulse of a forward directed click from an on-axis whale. The p1 pulse is located in the middle of the click so the ncpMF increased very rapidly at the start of the p1 pulse and “breaks over” to a value close to one at the end of the p1 pulse. The p2 pulse following the p1 pulse has a very small amount of mid frequency band energy and it produced a very small “bump” in Figure 2-15 which is difficult to see at the scale presented. The ncpMF shown in Figure 2-15 is used as the template to judge if clicks are on or off-axis.

The ncpMF for an off-axis click is shown in Figure 2-16. Differences were seen when comparing the graphs of ncpMFs from the off-axis click (Figure 2-12) to that of the on-axis click (Figure 2-11). The ncpMF for off-axis clicks started to increase before the beginning of the p1 pulse. This was due to the presence of mid band energy before the middle of the click due to the off-axis orientation of the whale. A small area of Mid band energy (green in color) can be seen in Figure 2-14 before the larger amount of mid band energy in the center of the click (the p1 pulse). That misplaced energy produced the increase in the ncpMF before the middle of the click. If the click had been on-axis, mid band energy would not have occurred in the click until the p1 pulse.
It seemed logical to use the ncpMF function from an on-axis whale as a template with which to determine if a given whale click was on or off-axis. Two methods were tried to see if one or both of
them could determine if a given whale’s ncpMF was similar enough to the template to declare it to be on-axis. The two methods were 1) normalized cross correlation, and 2) the summation of differences squared.

The built in Matlab cross correlation function “xcorr” with an input argument of ‘normalized’ was used to perform the normalized cross correlation of the template with that of the ncpMF of a given click (Weeks, M., 2015). The value of the xcorr function at a lag of zero was used as a metric to determine if the click was on or off-axis. Twelve clicks manually determined to be on-axis and twelve determined to be off-axis from their average clicks were selected and their ncpMF functions were compared with the template from file 5205B3F6.040. The results are shown in Figure 2-17. A value (0.99973) was chosen as the limit between the on and off-axis groups by taking the average of the lowest xcorr value from the on-axis clicks and the largest value from the off-axis clicks. Figure 2-17 shows that all 24 clicks were correctly identified as to which group they belonged.

The second method used to determine if a click was on or off axis was the difference squared method. In this method each value of the template ncpMF function for an on-axis click is subtracted from the corresponding value of the click under test and the difference is squared. All of the squared difference values are then added together. As can be seen in Figure 2-18 a decision boundary can be constructed between two groups of clicks that correctly separates the 24 clicks into 2 groups of 12 clicks each – one group for on-axis clicks and the second groups for off-axis clicks. A value of 0.276 was selected as the boundary limit by adding three times the standard deviation of the on-axis clicks’ summation of differences squared (sods) to the average value of the on-axis sods. It should be noted that the ordinate of the sods chart is displayed as a log axis due to the small variation in the sods values of the on-axis clicks compared to much larger variations of the off-axis clicks.
Data from both the normalized cross correlation method and the summation of differences squared method were sent to the code written to determine whale lengths. Both methods produced
very similar results as can be seen in Figure 2-19. There were 575 files with forward sperm whale clicks directed towards a hydrophone. Of those 575 files, 488 of them were judged to contain on-axis average clicks by the sum of squared differences method with 403 of the average clicks used to calculate length estimates. The normalized cross correlation method selected 557 files as containing on-axis average clicks with the average clicks from 493 files used to calculate whale length estimates. A quality control test – the ratio test – was used to select which on-axis clicks were selected for whale length calculations. More will be said about the ratio test, shortly.

Figure 2-19: Estimates of Whale Lengths using Normalized Cross Correlation and Sum of Differences Squares to Select On-Axis Clicks.

The Matlab code that provides an estimate of the length of a whale from its average click performs a Continuous Wavelet Transform (cwt) on an average click judged to be on-axis (Strang, G, Nguyen., T., 1997), (Weeks, M., 2015), (van Drongelen, W., 2018). The cwt produces a matrix of complex wavelet coefficients. The matrix is an m x n matrix with m = 94 and n = 4967. The number of rows
(m=94) corresponds to the number of frequencies (frequency bands) used by the transform to deconstruct the signal and n is the number of samples (times) contained in the average click. The values in the matrix “wt” are squared to give the magnitudes of the coefficients. Each column of wt_mag is scanned to find the largest value. That value is the largest magnitude frequency component present in the signal at that sample time. A vector (max_mag_p1) is created using the maximum amplitudes found at each time point. The vector is searched for the largest entry. The largest entry corresponds to the peak of the p1 pulse – the largest pulse in the whale click. The location of the p1 peak in the vector gives the time that the p1 peak occurred in the click. Figure 2-20 shows a generalized schematic diagram of matrix wt_max and vector max_mag_p1.

![Figure 2-20: Schematic of matrix wt_mag and vector max_mag_p1](image)
A similar process was used to find the location of the p2 pulse in the click. Most sperm whale clicks exhibit what Zimmer calls “reverberations” (Zimmer, 2005 A) between the p1 and p2 pulses. Steps were taken to prevent the reverberations from interfering with detection of the p2 pulse. An offset in time of 1.04 ms after the p1 is used to avoid confusing a reverberation peak with the peak of p2. This delay prevents the code from producing incorrect measurements of whales 6.34 meters long or shorter by identifying the reverberations as p2 pulses. Whales of that length are too young to be foraging so they would not have been recorded. A second step was taken to avoid confusing reverberations for p2 pulses. It was observed that most of the reverberation energy was above 12 KHz. The search of the wt_mag matrix of coefficient magnitudes was limited to frequencies between 3.4 KHz and 10 KHz. With those two limitations a scanning process of matrix wt_mag was performed to locate the time of occurrence for the peak of the p2 pulse.

The location of the p0 pulse was determined by finding the largest magnitude value in the wt_mag matrix in columns starting with column 1 up to the column 200 steps before the column containing the p1 peak. This deadband in time (column number) prevents clicks from other whales from being selected as the p0 peak of the subject whale if the second whale clicked between the subject whale’s p0 and p1 pulses. As in the determination of the p2 pulse location a frequency limitation is used to reduce interference from other whales in the area. Frequencies between 1718 Hz and 4231 Hz (rows 44 to 57 of the wt_mag matrix) are scanned to find the p0 pulse location.

In order to estimate the length of a whale the time difference between the p1 and p2 pulses was determined to obtain the interpulse interval (IPI). The IPI was then used in either Gordon’s Equation or Growcott’s equation to estimate the whale length. The length estimate for the sperm whale was calculated using Gordon’s Equation if the whale was under 11 meters in length or by Growcott’s Equation if the whale is longer than 11 meters.
Gordon’s equation is:

\[ TL = 4.833 + (1.453 \times IPI) - (0.001 \times IPI^2) \]  

*equation 2 – 1*

Where \( TL \) = total length in meters  
IPI = interpulse Interval expressed in milliseconds

Growcott’s Equation is:

\[ TL = (1.257 \times IPI) + 5.736 \]  

*equation 2 – 2*

Where \( TL \) = total length in meters  
IPI = interpulse Interval expressed in milliseconds

Gordon’s Equation was developed from acoustic and photogrammetric measurements of 11 individual whales in sperm whale nursery areas (Sri Lanka and the Azores) so the measured whales were females or juveniles. The equation tends to underestimate the lengths of longer whales (Gordon, 1991).

Growcott’s Equation utilized acoustic and photogrammetric measurements of 54 individual whales of the east coast of the South Island of New Zealand. Male sperm whale predominate in this area so Growcott’s Equation gives a better length estimate for longer whales (Growcott et.al. 2011).

The time intervals between the \( p_0 \) and \( p_1 \) pulses and the \( p_1 \) and \( p_2 \) pulses should be approximately equal due to the anatomy of the whale’s head (Schulz, Whitehead, Rendell, 2009). A quality control test using that fact was developed as a final check on the validity of the length estimate. This test determines the time interval between the \( p_0 \) and \( p_1 \) pulses (\( p_0 \_p1 \)) and the time interval between the \( p_1 \) and \( p_2 \) pulses (\( p1 \_p2 \)). It then forms the ratio \( (p1 \_p2)/(p0 \_p1) \). If the ratio falls between 1.0 to 1.55 (inclusive) the length estimate was determined to be valid as discussed in section 2.1 (Figures 2-3, 2-4, 2-5).

The average click from file 5202B3F6.040 (an on-axis average click) is shown in Figure 2-21. The \( p_0 \), \( p_1 \), and \( p_2 \) pulses are shown in the figure in the locations found by the whale length estimating code. A small signal at about 3 mS was the \( p_1 \) pulse of a distant whale. The energy of that pulse was not
great enough in the frequency band defined for a p0 pulse to be misidentified as the p0 pulse of the subject whale. This can be better seen in the scalogram of the click’s cwt as shown in Figure 2-22.

The highest magnitude wavelet coefficient in the scalogram was selected as the location for the peak of the p1 pulse. This peak occurred at 12.96 mS as seen in Figure 2-22. The largest magnitude wavelet coefficient occurring within the time/frequency bounds established for the p2 pulse was selected as p2. The p2 pulse location was determined to be 16.03 mS. Likewise, the location for the p0 pulse was determined by locating the largest magnitude wavelet coefficient within the time/frequencies bounds for the p0 pulse. The location for p0 was 10 mS. The distant whale is much more apparent in the scalogram than in the time series. The shape and frequency content of the pulse from the distant whale identifies it as a p1 pulse.

By using the p0, p1 and p2 times of occurrence the ratio test can be used to determine if the click was measured correctly. It can be seen in both Figures 2-21 and 2-22 that the distance in time between the p0 and p1 pulses is about equal to the time between the p1 and p2 pulses. The ratio of those time differences was determined to be about 1.04. That value is well within the acceptable range of 1.0 to 1.55. The 3.07 mS between the p1 and p2 pulses indicates a whale length of 9.28 meters by Gordon’s equation (Gordon, 1991). What would have happened if the distant whale’s click would have been loud enough to have been mistaken for the p0 pulse? The location of p0 would have been misidentified as 3.0 mS instead of 10.0 mS and the ratio would have been equal to 0.44 – a value well outside of the acceptable range. Multiple whales clicking in the same file is not unusual. The ratio test is a good way to address that problem.

The need for the frequency restrictions and the ratio test can be seen by the presence of the reverberations between the p1 pulse and the p2 pulse in the scalogram of Figure 2-22. These reverberations can have amplitudes greater than the p2 pulse amplitude outside of the frequency band (3.4 KHz to 10 KHz) used to search for the p2 pulse. Sometimes the reverberations are strong enough in
the p2 pulse frequency band to be misidentified as the p2 pulse. In those cases the ratio test detects that something is wrong and prevents a length estimate from being calculated for that click. It may be that the reverberations contain information that would make it possible to identify individual whales turning a problem into an information rich feature. If they are unique to a given whale perhaps they contain information beyond the identity of the whale maybe even indicating the sex of the whale.

Figure 2-21: Average click of File 5205B3F6.040 with a Distant Whale and members of the N&H Set (p0, p1, and p2) identified.
An example of a click in which the reverberations between the p1 and p2 pulses were misidentified as the p2 pulse is given in Figures 2-23 and 2-24. The locations for the p0, p1, and p2 pulses as determined by the code were 9.5677 mS, 12.9531 mS, and 14.4635 mS respectively. These locations are indicated in Figure 2-23 and 2-24. The locations determined by visual inspection of the figures were that p0 and p1 were the same as calculated by the code, but that p2’s location was determined to be 16.59 mS. Using the program derived locations the estimated length of the whale was 7.03 meters. The ratio test; however, produced a value of 0.4462 which is below the lower limit of the acceptable range (1.0 to 1.55). The length estimate of this click was not recorded because the ratio value was out of bounds. If the manually estimated value for p2 was used, the whale would be 10.11 meters in length. The ratio value for the manual analysis was equal to 1.07 which is inside of the acceptable range for the ratio. Since the ratio value is within the acceptable range, the manual length estimate of 10.11 meters is very likely correct.
Another situation in which the ratio test prevents incorrect whale lengths from being estimated is the case of multiple whales clicking in the same file. This occurrence is illustrated in Figures 2-25 and
In these figures two other whales were clicking besides the whale who produced the very large p1 pulse. The p1 pulse from the first whale was located at 1.83 mS in the file. This pulse is very small in the time series representation (Figure 2-25), but becomes more visible in the cwt’s scalogram (Figure 2-26). The shape and frequency content of the pulse identifies it as the p1 pulse of a whale. The click’s p0 and p2 pulses are not seen while the p1 pulse is detected because the p0 and p2 pulses have less energy content than the p1 pulse. The p1 pulse from the second whale is located at 12.95 mS with its p0 pulse at 10.04 mS determined both by the program and confirmed manually. Its p2 pulse was manually located at 16.27 mS. The p2 pulse location was located by the program at 23.83 mS. This was not the p2 pulse of the second whale. It was the p1 pulse of the third whale. It was selected as p2 of the second whale because that location had the largest magnitude wavelet coefficient after the p1 pulse for the subject whale within the frequency range designated for p2. Again, the shape and frequency content of the third whale’s pulse identifies it as a p1 pulse. If the value of 23.83 mS was used to estimate the length of the whale producing the click the estimate would be 19.4 meters – a very large whale. The ratio test calculated a ratio of 3.74 using 23.83 mS as the location of p2. That ratio value was outside the 1.0 to 1.55 range for ratio values and the length estimate for that click was recognized as not valid. Using the manually acquired value of 16.27 mS a length estimate of 9.65 meters was produced with an acceptable ratio value of 1.14.
Figure 2-25: Time series for a file containing clicks from three different whales.

Figure 2-26: The cwt scalogram of a file containing clicks from three different whales.
Chapter 3: Other Methods used to Estimate the Lengths of Sperm Whales from their Usual Clicks

3.1 Background

One of the first attempts to determine the length of a sperm whale from its usual clicks was by Norris and Harvey (1972) from forward clicks recorded as a whale approached a small boat from which they were recording underwater sounds. The whale swam alongside the boat for a short time. The whale was estimated to be the same length as the boat – 9 meters. Manual analysis of the recorded clicks estimated the whale’s length at 9.18 meters.

Manual IPI measurements like those made by Norris and Harvey are considered to be very useful, but are very time consuming to perform. However, in a study by Antunes (2010) of three different methods used to estimate IPIs (manual, autocorrelation, and cepstrum methods) manual measurements of IPIs from the same whales on different days produced the most consistent length estimates.

In his comparison of the use of autocorrelation and cepstrum analysis Antunes stated, “Averaging of autocorrelation data seemed to require fewer clicks than averaging of cepstra to converge on an IPI estimate, as well as producing more consistent estimates. This method may therefore be preferable for automated IPI estimation, although there were a few cases where cepstrum averaging converged while autocorrelation did not.”

Goold (1996) and Rhinelander and Dawson (2004) have also used autocorrelation to estimate sperm whale IPIs. In both studies the clicks were recorded from the rear of the whale after the whale had fluked. Recording clicks from a diving whale gives some assurance that the recorded rearward clicks
will be on the acoustic axis of the whale. The IPI from an on axis rearward directed click will be the same
duration as the IPI from a forward directed click as indicated by Teloni (2007).

Goold (1996), Teloni (2007) and Caruso (2015) have experimented with the use of cepstrum
analysis to determine the IPIs of sperm whales. Teloni used cepstrum analysis to determine the IPIs for 6
individual whales. Caruso used a single hydrophone at a depth of 2,100 m in the central Mediterranean
Sea to analyze sperm whale clicks from 93 days of observations using cepstrum analysis.

3.2: Use of Autocorrelation to Determine Sperm Whale IPIs

Rhinelander (2004) performed a study to determine the answers to several questions
concerning whale click IPIs. The first question was were the IPIs of a given whale stable over different
dives in a given day. Data from 4 individual whales (two dives each on a single day) indicated that
although the average IPIs of two of the individuals changed between dives the change was less than 1%
of the IPI’s duration. This result indicated that the change in IPI would change the length estimate of a
15 m long whale by 15 cm. It was determined that although the IPIs could change during a single dive,
they didn’t change much.

A second question was did the value of a sperm whale’s IPI change over a period of days. It was
determined that the IPIs did not change if the IPI data were collected less than 2 months apart. IPI data
collected more than two months apart did show statistically different IPIs consistent with growth of the
whale. Whether or not a whale’s IPI varied over a period of years was investigated with data from 6
whales having at least two years of data. In five of the 6 whales increases in their IPIs were observed.
Autocorrelation was used in Rhinelander’s study. A discrete form of autocorrelation is given by:

\[
 r(\tau) = \sum_{i=-\infty}^{\infty} x(i) x(\tau + i) \tag{equation 3-1}
\]

where \( r \) = autocorrelation of \( x \)
\( \tau \) = lag

Autocorrelation was well suited for use in that study due to the known orientation of the whale with respect to the hydrophone. The whales in the study were recorded by hydrophones near the surface while the whales were diving. That orientation makes it very likely that the recorded clicks will be on or near the acoustical axis of the whale. The p0 and p1 components of the Norris & Harvey set are received at the same time in this orientation with the p2 click received after the p0/p1 combination. The length of the IPI (the length of the p1 to p2 interval) determined by autocorrelation was the distance between the large central peak and the largest peak following that central peak. The use of autocorrelation in Rhinelander’s study also benefited from the study being performed off the South Island of New Zealand. The sperm whales in that region are mostly males and tend to be widely separated when searching for food thereby minimizing the risk of clicks from multiple whales being recorded at the same time. Clicks from multiple whales occurring close in time can corrupt whale length estimates produced by autocorrelation.

A file recorded by EARS Buoy 4 on Day 196 of 2015 (file 2803.mat, hard drive file 519632B2.040) was analyzed manually and by autocorrelation (Figures 3-1 and 3-2). The average click in that file was composed of 9 rearward directed clicks. A file containing rearward directed clicks was used in order to simulate a hydrophone recording the whale clicks from the surface as was done in Rhinelander’s experiment. The IPI of the average click was manually determined to be 3.2083 mS (16.1406 mS – 12.9323 mS from figure 3-1) by locating the p0/p1 peak, the p2 peak and then determining the distance between them. That IPI corresponds to a length of 9.484 meters.
A short Matlab script was written to perform the autocorrelation on the rearward directed average click (Figure 3-2). A large peak at lag zero can be seen in the center of the figure with a smaller peak located 616 lags to the right of the central peak. The IPI was determined by dividing 616 (the number of lags) by the sample frequency (192 KHz) to obtain a value of 3.2083 mS as the length of the IPI. The manual method and the autocorrelation method produced the same results for the IPI, and therefore the same length for the whale. It is seen in this example that autocorrelation can produce answers that agree with answers obtained by manual methods.
The use of autocorrelation with an average click produced from 8 forward directed clicks recorded by Ears Buoy Number 4 was performed in order to determine how well autocorrelation would work with forward directed clicks. The average click of the 8 forward directed clicks is shown in Figure 3-3 and the autocorrelation is shown in Figure 3-4. Manual analysis of the average click (Figure 3-3) determined that the IPI was equal to 3.1667 ms (9.424 meters). The autocorrelation indicated a lag of 608 between the two largest magnitude peaks and therefore an IPI of 3.1667 ms. The manually determined IPI was in very good agreement with the IPI determined by autocorrelation.
Figure 3-3: Average Click Composed of 8 Forward Clicks

Figure 3-4: Autocorrelation of an Average Click Composed of 8 Forward Directed Clicks
There are certain circumstances under which autocorrelation experiences difficulties. If extraneous clicks from other conspecifics occur in the file containing clicks from the subject whale, large errors can be encountered. Off axis clicks also present problems for determining IPIs with autocorrelation.

An average click derived from 9 forward directed clicks recorded by EARS Buoy Number 4 is shown in Figure 3-5. The IPI for the p1 to p2 interval can be seen to be 3.2187 mS by visual inspection of the figure. The p0 to p1 interval is about 3.1458 mS. A click from a second whale occurs at 23.849 mS or 10.9167 mS after the p1 click. The IPI of 3.2187 mS determined by visual inspection corresponds to a whale length of 9.4994 meters. Dividing the p1 to p2 interval by the p0 to p1 intervals produces a ratio value of about 1.02 which is within the acceptable ratio range indicating that the estimate length is valid.

Figure 3-5: Average Click Composed of 9 Forward Clicks
The autocorrelation of this average click from Figure 3-5 is shown in Figure 3-6. The autocorrelation mistakenly selected the click from the second whale as the p2 peak. The calculated p1 to p2 interval is 10.9167 mS according to the autocorrelation results. That time interval gives an estimate of 19.4583 meters for the length of the whale. That length estimate is more than twice the length estimate of the manual method. The autocorrelation estimate is in error. Since the autocorrelation method does not generate a time of occurrence for p0, the ratio test cannot be used to identify clicks that have been corrupted with clicks from other whales.

Figure 3-6: Autocorrelation of an Average Click Composed of 9 Forward Directed Clicks
3-2: Use of Cepstrum Analysis to Determine the IPI of Sperm Whales

An underwater neutrino observatory named The Ocean noise Detection Experiment (OvDE) was placed on the seafloor of the Mediterranean at a depth of 2100 meters off the eastern coast of Sicily. It operated from January 2005 until November 2006. Caruso (2015) described the observatory as recording acoustical signals produced by the interaction of neutrinos with water as well as the vocalizations of sperm whales in the vicinity.

A single hydrophone was used to record sperm whales clicks. The click signals were sampled at 96 KHz with 24 bits of resolution. Five minutes of recording were done once an hour with the data relayed to a shore based laboratory connected to the observatory via a 28 km long undersea fiber optic cable. The orientation of the clicking whales could not be determined as the whale clicks were recorded by a submerged hydrophone not from a ship at the surface (as is the case for rearward directed clicks). In the case in which a surface hydrophone is used to monitor a clicking whale after it flukes and begins its foraging dive the orientation of the whale to the hydrophone is such that the rearward click will very likely be on axis. When the hydrophone is anchored to the seafloor there is no way to insure that a clicking whale is acoustically aligned with the hydrophone. As described in Teloni’s paper (2007) a method was needed that could use clicks generated by whales from a wide range of different orientations to determine the IPIs of the whales.

Cepstrum Analysis was used to address the problem of off axis whales (Childers, D.G., Skinner, D.P., Kemerait, P.C., 1977) (Teloni, V., Zimmer, W.M.X., Wahlberg, M., Madsen, P.T., 2007). As shown in Chapter 1 of this work, clicks from whales aligned with the recording hydrophone display a stable structure with stable IPIs known as the Norris and Harvey set of pulses. That set of pulses consists of the p0, p1, and p2 pulses (Figures 1-1 and 1-2). Clicks from off axis whales do not display a regular stable structure (Figures 1-3 and 1-4), but rather a click structure which changes as the orientation of the
whale changes with respect to the hydrophone. Other whales clicking at the same time as the subject whale also contribute to the problem of unstable click structure. Even clicks from off axis whales contain the p1 and p2 pulses of the Norris and Harvey set as noted in Teloni’s (2007) work. The additional pulses created by the whale’s acoustical axis not being aligned with the hydrophone would mix with the p0, p1, and p2 pulses at the hydrophone and obscure the true IPI.

One use of cepstrum analysis is the detection and cancellation of echoes as described in Bogert (Bogert, 1963). The p1 pulse in a click from an on axis whale can be thought of as a sharp acoustical event such as a clap in a large room with sound reflecting walls. The p2 pulse can be thought of as the echo of the clap. Cepstrum analysis of the click will return the time difference between the clap and the echo except what it is actually returning is the IPI between p1 and p2. It will also return the time intervals between the off axis pulses in a click. If the cepstrum of enough clicks in different orientations are combined the IPI between p1 and p2 will become apparent and the IPIs from the off axis generated pulses will be averaged out. Teloni (2007) empirically determined that between 200 to 1000 clicks were need to calculate an accurate IPI (p1 to p2) with cepstrum analysis. In Caruso’s (2015) work a 5 minute long file was required to have at least 50 clicks for the clicks in that file to be analyzed. The real cepstrum function (rceps) in Matlab’s Signal Processing Toolkit (MathWorks, 2022) was used to process the square of the click time series (power signal) as done by Caruso. The minimum phase results were used to determine the IPIs of the clicks. The rceps function implements the following equation:

$$y = \text{real}(\text{ifft}(\log(\text{abs}(<f f t(x^2)>))))$$  \hspace{1cm} \text{equation 3} - 2.

The data recordings from EARS Buoy 4 were used to simulate the method used by Caruso. In Caruso’s paper five minutes of data were recorded once an hour. For the data to be analyzed at least 50 clicks had to occur in that five minute period. Two sections of data approximately 5 minutes long were selected from the EARS buoy data. Each five minute data selection contained at least 50 clicks. Unlike
the length measuring procedure based on continuous wavelet (cwt) analysis described in Chapter 2, individual clicks – not average clicks – were used to keep the simulation more like Caruso’s method. The data sections were selected so that one section came from a time when little click activity was recorded (Day 178) while the second data section was chosen from a time period in which many clicks were recorded (Day 190).

The data section from Day 178 was 5.33 minutes in length and contained 96 clicks. The clicks were from files not tested to see if the clicks were forward clicks or on axis clicks. The clicks selected only met the 0.1 volt amplitude and the frequency requirements for a sperm whale click. This was in keeping with the methods of Caruso (2015). The clicks in files 74.mat through 85.mat contained the clicks in this five minute time segment. Figure 3-7 shows the cepstrum of the clicks. The cepstrum was limited to a quefrency of 12.0 mS, and as in Caruso’s paper the range of valid quefreniciencies was taken to be from 2.0 mS to 10.0 mS corresponding to whale lengths of 7.74 meters to 18.3 meters. The largest peak between 2 and 10 mS occurred at 3.08333 mS. The largest peak within the 2.0 to 10.0 mS quefrenency range gave the IPI between p1 and p2. An IPI of 3.08333 mS indicates a 9.3036 meter long whale.
The continuous wavelet method for whale length determination presented in Chapter 2 was used as a check on the cepstrum analysis estimate for the lengths of whales in the “five” minute interval. Four files in the time interval were found to have clicks that met the requirements of the cwt method (forward clicks and on axis). The length data presented in Tables 3-1 a) and 3-1 b) shows the results for the cwt methods which were in general agreement with the result of the cepstrum method. The cwt method indicates that there may be two whales clicking in the time interval based on length estimates of 9.1 to 9.2 meters long for one whale and about 9.4 meters long for a second whale. The cepstrum method produced a single length estimate for the entire five minute period.

Figure 3-7: Cepstrum of 96 Sperm Whale Clicks in a 5.33 minute period
## Table 3-1 a) Results of CWT Analysis Method – First Five Minute Section - pulse locations

<table>
<thead>
<tr>
<th>file.mat</th>
<th>Day</th>
<th>p0 location (mS)</th>
<th>p1 location (mS)</th>
<th>p2 location (mS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>74</td>
<td>178.3335</td>
<td>10.573</td>
<td>12.958</td>
<td>15.911</td>
</tr>
<tr>
<td>79</td>
<td>178.3353</td>
<td>10.375</td>
<td>12.969</td>
<td>16.109</td>
</tr>
<tr>
<td>82</td>
<td>178.3362</td>
<td>10.339</td>
<td>12.953</td>
<td>15.938</td>
</tr>
<tr>
<td>85</td>
<td>178.3372</td>
<td>10.25</td>
<td>12.953</td>
<td>15.964</td>
</tr>
</tbody>
</table>

## Table 3-1 b) Results of CWT Analysis Method – First Five Minute Section – Length and ratio

<table>
<thead>
<tr>
<th>file.mat</th>
<th>Day</th>
<th>p0_p1 interval (mS)</th>
<th>p1_p2 interval (mS)</th>
<th>Length (meters)</th>
<th># of clicks</th>
<th>ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>74</td>
<td>178.3335</td>
<td>2.385</td>
<td>2.953</td>
<td>9.11517</td>
<td>7</td>
<td>1.237991</td>
</tr>
<tr>
<td>79</td>
<td>178.3353</td>
<td>2.594</td>
<td>3.141</td>
<td>9.386465</td>
<td>7</td>
<td>1.210843</td>
</tr>
<tr>
<td>82</td>
<td>178.3362</td>
<td>2.615</td>
<td>2.984</td>
<td>9.16039</td>
<td>10</td>
<td>1.141434</td>
</tr>
<tr>
<td>85</td>
<td>178.3372</td>
<td>2.703</td>
<td>3.010</td>
<td>9.198073</td>
<td>7</td>
<td>1.11368</td>
</tr>
</tbody>
</table>

The data section from Day 190 was 4.62 minutes long with a total of 127 clicks. As in the data described above, the clicks were from files not tested to see if the clicks were forward clicks or on axis clicks. The clicks selected only met the 0.1 volt amplitude and frequency requirements for a sperm whale click. Figure 3-8 shows the cepstrum of the clicks. The largest peak between 2 and 10 mS occurred at 6.31771 mS. The value should indicate the IPI of the whale click. An IPI of 6.31771 mS is equivalent to a whale length of 13.68 meters. No click having an IPI of 6.3177 mS could be found reviewing the 127 clicks.
clicks manually. What was found was an interfering click from a second whale in click 5 of file 767.mat (Figure 3-9). The time interval between the interfering peak and the p1 peak for click 5 was 6.3073 mS.

The time interval is very close to the interval determined by cepstrum analysis. The cepstrum analysis mistook the interference click for the p2 pulse in click 5 of file 767.mat and an incorrect value of 13.68 meters was calculated for the length of the clicking whale.

Figure 3-8: Cepstrum of 127 Sperm Whale Clicks in a 4.62 minute period.
Clicks from the file 767 were analyzed by the cwt analysis of Chapter 2. That method also mistook the interference peak as the click’s p2 pulse. It calculated an IPI of 6.2917 mS and a length of 13.64 meters very similar to the estimate produced by the cepstrum method. However, the algorithm also calculated the (p1 to p2 / p0 to p1) ratio to be 2.5272 which was greater than the ratio’s upper limit of 1.55. The file containing that click was not used to calculate a whale length avoiding the reporting of a 13+ meter long whale when one was not there. The cepstrum method does not locate individual pulse locations. It determines the distances between the pulses. It is not clear how a ratio check could be carried out using cepstrum analysis.
The largest peak in the cepstrum (Figure 3-8) was located at 1.28646 mS, corresponding to a 6.70 meter long whale. Even though that click was outside of Teloni’s valid measurement range an effort was made to see what produced the click. As in the previous case, no 6.70 meter long whale was found in the click set during a manual inspection of the clicks. An interfering click from a second whale was found in click 7 of file 774.mat between the p0 and p1 locations of the subject whale. Figure 3-10 shows that the interfering peak occurred at 11.6667 mS or 1.28646 mS before the p1 peak for that click. The cepstrum method measured the time between the interfering click and the p1 pulse of the subject whale instead of calculating a valid IPI. It should be noted that when the cwt method was used to analyze the clicks in file 774.mat the interfering click did not corrupt the length measurement (8.972 meters), the location of p0 (10.5104 mS), or the ratio calculation (1.1660). This was because the frequency content of the interfering click was outside of the frequencies scanned for p0 (1.7 KHz to 4.2 KHz). The scalogram of the average click for the clicks contained in file 774.mat presented in Figure 3-11 shows that the lowest frequency components of the interfering click is about 5.6 KHz which is above the 4.7 KHz upper limit for the p0 pulse scan.
Figure 3-10 Eighteen clicks in file 774.mat
The second highest peak in the quefrency range above 2.0 mS in Figure 3-8 was located at 10.974 mS. The peak was also outside of the 2.0 to 10.0 mS measurement range of Caruso, but an interest in the source of the peak motivated a search for its origin. An IPI of 10.974 mS is indicative of a 19.530 meter whale. As with the prior two searches a whale of the indicated length was not found. An interfering whale click in click 6 of file 772.mat was found at 23.849 mS as seen in Figure 3-12. The cwt method also misidentified the interfering peak as the p2 peak. A length of 19.4086 meters was calculated from the click data. The algorithm computed a ratio value of 3.737 which was greater than the upper limit of the ratio test. The incorrect whale length of over 19 meters was therefore not reported by the cwt method since the click didn’t pass the ratio test.
The cwt method was used to analyze 8 files found in the five minute interval in which clicks meeting the amplitude, frequency, forward click, and on-axis requirements for the cwt method were satisfied. The average click for each of the files was generated and searched for the locations of p0, p1, and p2. The average clicks with ratio values falling between 1.0 and 1.55 were used to calculated whale lengths. From the lengths listed in Tables 3-2 a) and 3-2 b) at least three whales can be seen – a small whale of about 8 meters, a whale (possibly two) of about 9 meters and a whale over 9.5 meters in length. These length measurements were confirmed by visual analysis of the cwt scalograms of the average clicks.
From the above study cepstrum analysis is seen to work when not many whales are clicking in the local area. Cepstrum analysis may be able to compensate for the detrimental effects on IPI measurements from off axis whales, but seems to have trouble with interference from nearby whales as is the case when whales are foraging for food.

<table>
<thead>
<tr>
<th>file.mat</th>
<th>Day</th>
<th>p0 location (mS)</th>
<th>p1 location (mS)</th>
<th>p2 location (mS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>762</td>
<td>190.8272</td>
<td>11.3385</td>
<td>12.9531</td>
<td>15.1563</td>
</tr>
<tr>
<td>768</td>
<td>190.8289</td>
<td>10.6927</td>
<td>12.9531</td>
<td>15.7292</td>
</tr>
<tr>
<td>769</td>
<td>190.8291</td>
<td>10.1094</td>
<td>12.9635</td>
<td>16.3073</td>
</tr>
<tr>
<td>774</td>
<td>190.8304</td>
<td>10.5104</td>
<td>12.9583</td>
<td>15.8125</td>
</tr>
</tbody>
</table>

Table 3-2 a) Results of CWT Analysis Method – Second Five Minute Section – pulse locations

<table>
<thead>
<tr>
<th>file.mat</th>
<th>Day</th>
<th>p0_p1 interval (mS)</th>
<th>p1_p2 interval (mS)</th>
<th>Length (meters)</th>
<th># of clicks</th>
<th>ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>762</td>
<td>190.8272</td>
<td>1.6146</td>
<td>2.2032</td>
<td>8.0293</td>
<td>6</td>
<td>1.3645</td>
</tr>
<tr>
<td>768</td>
<td>190.8289</td>
<td>2.2604</td>
<td>2.7761</td>
<td>8.8589</td>
<td>12</td>
<td>1.228145</td>
</tr>
<tr>
<td>769</td>
<td>190.8291</td>
<td>2.8541</td>
<td>3.3438</td>
<td>9.6803</td>
<td>7</td>
<td>1.171578</td>
</tr>
<tr>
<td>774</td>
<td>190.8304</td>
<td>2.4479</td>
<td>2.8542</td>
<td>8.972</td>
<td>18</td>
<td>1.165979</td>
</tr>
</tbody>
</table>

Table 3-2 b) Results of CWT Analysis Method – Second Five Minute Section – Length and ratio
The clicks in this “five minute” selection of data (Day 190 data) were used to determine the measurement errors associated with the continuous wavelet transform (cwt) method and the cepstrum method of whale length estimation. The difficulty of quantifying error in this effort was that the true length of the whales was not known. Manual whale length estimates were the best available proxies for the length of the whales recorded. They were used as the “true” whale lengths.

In the five minute selection of Day 190 data 13 files containing 127 clicks were found. All 127 clicks were used by the cepstrum method to determine the lengths of whales present (Figure 3-8). This was in keeping with Caruso’s methodology. Eight of the 13 files were found to conform to the selection criteria of the cwt method – files containing at least 6 clicks each click having a minimum peak amplitude of 0.1 Volts, from whales whose acoustical axes were aligned with the hydrophone. Those eight files contained 76 clicks, 46 of which met the ratio test requirements. The difference between the cwt length estimate and the manual length estimate was calculated for each of those 46 clicks. The average value of those “errors” was calculated as was the standard deviation of the errors. The same analysis was performed for the cepstrum length estimates made for the same 46 clicks. A 95% confidence interval was calculated for the error in each method

\[
\text{confidence interval} = \mu \pm t \times \left( \frac{S}{\sqrt{n}} \right) 
\]

where: \( \mu \) = average of the errors
\( t = t \text{ statistic for 0.025 one tail, 45 degrees of freedom} \)
\( t = 2.0141 \)
\( s = \text{sample standard deviation} \)
\( n = \text{number of paired data samples} \).

The 95% confidence interval for the average errors with the cwt method equals [-0.0001, 0.1324] meters while the confidence interval for the cepstrum method equals [0.1600, 0.7423] meters.
Chapter 4 – Future Efforts

4-1 Introduction

Based on the apparent successful estimation of whale lengths through the application of wavelet analysis to the average of at least 6 whale clicks the question arose “Could an accurate whale length estimate be obtained from a single click?” The answer appears to be yes - if “good” clicks are used in the analysis. What are good clicks? Good clicks are clicks from whales whose acoustical axis is aligned with the recording hydrophone, who are approaching the hydrophone (forward clicks), and whose p0, p1 and p2 pulse locations meet the ratio test discussed previously. If these conditions are met it is highly likely that the estimate produced will be accurate. The reason for attempting to produce length estimates on the basis of a single click is to increase the number of measurements per unit time. That would allow the detection of more than one whale per file and produce a better estimate of the sizes of the whales present.

It would be helpful to the understanding of social ties within groups of whales if the sex of the whales were known. A method for determining the sex of whales through their click characteristics is proposed.

Initial investigation on both of the above topics are covered in the next two sections. It should be noted that in order to verify that the methods described produce accurate results, data from photogrammetrically measured whales of known sex would be required.
4-2 Estimating Sperm Whale Length from Single Clicks

It was observed that if clicks from a given file were displayed with their p1 pulses time aligned, but with the clicks offset from one another along the y-axis, the presence of whales of different lengths in the same file became apparent. This was seen as a time shift in the occurrence of the p0 and p2 pulses. The seven clicks in file 769.mat illustrate this phenomena (Figure 4-1). The p0 and p2 pulses of the lower three clicks occurred closer to the central p1 pulse than the p0 and p2 pulses of the upper four clicks in Figure 4-1. This produced a shorter p1_p2 interval for the lower three clicks; therefore, the lower three clicks were produced by a shorter whale. Could those clicks from different length whales within a file be analyzed on an individual basis to determine the lengths of multiple whales in a 21 second time interval instead of determining just one length estimate – the length estimate of the average click of the file? A preliminary investigation was carried out. It was found that if an individual click passed the ratio test (1.0 <= [length of p1_p2 interval / length of p0_p1 interval] <= 1.55) it was possible to produce an accurate length estimate from that click.
The seven clicks in file 769.mat were analyzed by both the cwt method described in Chapter 2 and the cepstrum method described in Chapter 3 (Table 4-1). Manual length estimates were made from the time series of each click. The majority of cwt and cepstrum estimates were close to the estimates produced by hand. The one click for which the cwt method’s estimate failed was a click that also failed the ratio test. The click failed the test due to interference from an additional whale clicking in the 25 mS window of the subject whale’s click. The cwt algorithm mistook the interference as the p2 pulse of the subject whale. This longer than normal p1-p2 interval produced the out of range ratio value. The value being out of range prevented the length estimate from being reported. The length estimate for this click produced by cepstrum analysis corresponded with the manually derived estimate for click number 7.

The length of the whale producing click 3 was accurately calculated by the cwt algorithm. That estimate corresponded to the manually determined length. The cepstrum method overestimated the whale’s length due to the interference (p1 pulse) of a second whale clicking (Figure 4-3). The cwt algorithm was
not affected by the second whale’s interference because the frequency range used to search for the p2 pulse in the cwt algorithm is limited on the high end to below 10 KHz. Most of the frequency content of the second whale’s p1 pulse was above 10 KHz. The algorithm produced an estimate close to that of the manual estimate.

<table>
<thead>
<tr>
<th>click #</th>
<th>Length from manually measured time series (meters)</th>
<th>Length from cepstrum of individual click (meters)</th>
<th>Length from cwt method of individual clicks (meters)</th>
<th>ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8.88150</td>
<td>8.95688</td>
<td>8.85134</td>
<td>1.16667</td>
</tr>
<tr>
<td>2</td>
<td>8.90410</td>
<td>8.73071</td>
<td>8.88904</td>
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</tr>
<tr>
<td>3</td>
<td>8.90400</td>
<td>11.44488</td>
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<td>9.73302</td>
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<tr>
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<td>9.62000</td>
<td>9.59742</td>
<td>9.55222</td>
<td>1.10035</td>
</tr>
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<td>6</td>
<td>9.73300</td>
<td>9.76315</td>
<td>9.72548</td>
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<tr>
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<td>9.73300</td>
<td>9.81587</td>
<td>19.90998</td>
<td>6.52108</td>
</tr>
</tbody>
</table>

Table 4-1: Length Estimates from Individual Clicks from file 769.mat

Figure 4-2: Scalogram of Click 7 in file 769.mat
The seven clicks in the file were combined to produce an average click (Figure 4-4). An average click was formed in an attempt to reduce noise and inferences from other whales. Comparing the scalogram of the average click of file 769.mat (Figure 4-5) to the scalograms of clicks 3 (figure 4-3) and 7 (Figure 4-2) it can be seen that averaging did in fact reduce the background noise and interferences from other whales.

A manual determination of a whale length estimate was performed on the average click from 769.mat. Length estimates were also performed with the cwt and cepstrum algorithms. The results in Table 4-2 indicate that the estimates compare favorably with those for clicks 4 through 7 in the file, but not the first 3 clicks. It was interesting to note that the length estimates for the average click corresponded to the IPIs of actual clicks (in this case clicks 4 through 7) and not to an average value of all clicks present. When the method determined that there was a 9.7 to 9.8 meter whale clicking in the file there was a whale of that length actually clicking. It was not the case that there were two whales of
different lengths - 9.3 meter and a 10.3 for instance - clicking in the same file whose lengths were averaged together. It is desired to obtain a length estimate of a “real” whale not a “composite” whale if using estimated lengths for other purposes such as to count the number of whales present.

What about the first three clicks in file 769.mat? Were they “real” clicks? Yes they were real. An 8.8 to 8.9 meter long whale produced those clicks. They were measured manually, and the manual measurements agree with the estimates produced by the cwt and cepstrum algorithms for the individual clicks.

![Average Click of 7 Clicks in file 769.mat](image)

Figure 4-4: Average Click from Seven Clicks in file 769.mat
The approximately 5 minute long data segment from Day 190 used in Chapter 3 to investigate the use of cepstrum analysis contained 127 clicks in 13 files. In order to simulate the manner in which cepstrum analysis was used by Caruso to estimate IPIs (and therefore whale lengths) from whale clicks, all 127 clicks where used to produce the cepstrum estimate of an IPI equal to 6.31771 mS corresponding to a whale length of 13.68 meters. No whale of that length was found in those clicks. What was found
was a second whale which produced an interfering click causing the error. The same files were used with the cwt method to estimate whale lengths. The cwt method did not use all 127 files in the time period. Part of the cwt method selects files that have a minimum of 6 clicks with p1 pulse peak of 0.1 Volts or higher, with the average click being on-axis with the hydrophone. The average click must also have an acceptable ratio value. Of the 127 clicks in the time period, 8 files containing 46 clicks met the requirements of the cwt method.

The results from one of the eight files (file 769.mat) are summarized in Table 4-1. Of the seven clicks in file 769.mat, six of them passed the ratio test. The click that failed the test (Click 7) was interfered with by a different whale clicking at the end of the subject whale’s click. The cwt algorithm was also fooled by the interfering click, but since the ratio test indicated a problem, data from that click was not used for a length estimate. Cepstrum analysis for Click 7 was correct. Click 3 passed the ratio test and the cwt length estimate agreed with the manually produced estimate. The cepstrum length estimate for Click 3 was in error due to an interfering whale click. These results suggest that a whale length measuring system that can determine the length of a whale from a single click rather than from an average of clicks may be possible. A combination of the two systems is proposed. Using the cwt method with its ability to perform the ratio test and calculate IPIs along with the cepstrum method’s of calculating IPIs may produce a more robust system in the presence of interfering whale clicks. A requirement that the calculated ratio value must be within the valid range for each click and that the IPIs (length estimates) from both the cwt and cepstrum methods applied to each click produce comparable results could give assurance that clicks are free from interfering whale clicks and that the length estimates are reasonable. Those requirements applied to file 769.mat would have produced 5 whale length estimates from seven clicks instead of just one length estimate from the average click of the file.

The cwt method would have normally produced 8 length estimates during the approximately 5 minute long data segment reported on above — one estimate for the average click from each file. By
using the proposed method, forty-one whale length estimates would have been calculated during the
time period instead of just eight.

4-3 Determining the Sex of Sperm Whales from Their Clicks

In the 1990’s Goold and Jones reported on the time and frequency properties of sperm whale
usual clicks (Goold, Jones, 1995). In that paper clicks from a large (~ 18 meter) male sperm whale and a
smaller female sperm whale were analyzed using a bank of FIR bandpass filters. The filters separated the
frequencies present in the clicks into several frequency bands (0 to 500 Hz, 500 to 1500 Hz, 1500 to
3000 Hz, and 3000 to 6000 Hz.). The signal content in several of the bands differed markedly between
the male and female clicks. In the lowest frequency band the male’s clicks exhibited a structure of a
dampened sinusoid while the female’s click had little or no energy. The dampened sinusoid shape
appeared in the female’s click in the 500 to 1500 Hz band with the male’s click exhibiting a random noise
like pattern. The typical multipulse structure of the sperm whale clicks appeared in the 1500 Hz to 3000
Hz frequency band of the male while it appeared in the female’s click in the 3000 to 6000 Hz frequency
band. The whales in this study were 2 of eight whales visually identified as male or female. All of the
clicks were recorded from the surface, while the whales were diving (rearward directed clicks).

A short study was done to see if differences in spectral content could be found in the recorded
clicks. Since all of the clicks were recorded by a bottom anchored hydrophone, it was not possible to
determine which clicks were produced by male whales and which clicks were produced by females since
the clicking whales were at the bottom of the Gulf of Mexico. Clues to the sex of the clicking whales can
be found in the length of the whales and in the number of clicks per unit time.

Female sperm whales can attain a length of up to 12.3 meters. The usual upper length for
females 25 to 45 years old is in the range of 10 to 11 meters. Younger females (7 to 13 years old) are
usually 8.2 to 9.2 meters in length. On the other hand, maximum male sperm whale length in the post-whaling period is approximately 18 meters. The lengths of thirty-five to sixty year old males is typically in the range of 15.2 to 16.1 meters. Young male sperm whales (7 to 11 years of age) range between 8.7 and 10.3 meters in length with 18 to 21 year old males averaging approximately 11 to 12 meters in length (Rice, 1989).

Sperm Whales produce usual clicks when searching for food. Females and juveniles forage together while males tend to forage alone. Juvenile males have been known to live and forage in small bachelor pods (Whitehead, 2003). It should be expected that the number of whale clicks per unit time would be higher when juvenile and female whales are foraging. Foraging male whales should produce fewer clicks per unit time since males usually hunt individually or in small groups. Since the Gulf of Mexico is a sperm whale nursery it was expected that clicks would be recorded from juvenile male and female whales with the possibility of recording clicks from mature females.

![Figure 4-6: Plot of Sperm Whale Length versus Day](image-url)
A plot of recorded clicks is shown in Figure 4-6. Two clicks were selected from the plot for further analysis. One click was from a whale with an estimate length of 11.64 meters from an area of the plot with low density clicking. That length corresponded to a possible male 18 to 21 years of age. A second click was selected from an area of the plot with a high density of clicks consistent with the foraging of juveniles and female whales. The estimated whale length for the whale producing the click was 10.77 meters in keeping with the range of lengths for 25 to 45 year old females.

Figure 4-7 contains the average click from the whale with an estimated length of 11.64 meters. The click energy was broken into three frequency bands using continuous wavelet transforms. The 8 to 12 KHz frequency band (green line, mid frequency band) gives the outline of the p1 pulse of a sperm whale click. The amplitude of the 1 to 4 KHz signal (blue line, low frequency band) is much smaller than that of the signals in the mid frequency band and is difficult to see in the figure. A magnified view of the p1 pulse section of the click is shown in Figure 4-8. In that view the low frequency component of the click (blue line) can be seen in the p1 pulse. The amplitude of the low frequency component is larger inside of the p1 pulse than it is outside of the pulse. The normalized cumulative power of the low frequency band (1 to 4 KHz) calculated for the click is given in Figure 4-9. A small “bump up” in cumulative power occurs just before 0.01 seconds with the occurrence of the p0 pulse. The p1 pulse (~ 12.9 mS) produced a very large change in the normalized power. Approximately 80% of the normalized power in the 1 KHz to 4 KHz frequency band was contained in the p1 pulse. The reconstructed time series of the low frequency portion of the click is shown in Figure 4-10. In that figure one can see most of the power in the low frequency band of the average click resides in the p1 pulse. This is very likely a characteristic of a male whale – most of the cumulative power of the low frequency signal components is inside the p1 pulse.
Figure 4-7: Average Click (file 3549.mat) separated into three frequency bands.

Figure 4-8: Magnified View of the Average Click (file 3549.mat) separated into three frequency bands.
Figure 4-9: Normalized Cumulative Power of Low Frequency Band (1 to 4 KHz) of Average Click

Figure 4-10: Reconstruction of the Average Click for Signal Components in the 1 KHz to 4 KHz Frequency Band
As in Figure 4-7, Figure 4-11 contains the average click of a whale but with an estimated length of 10.77 meters. Wavelets were again used to decompose the energy in the click into 3 frequency bands. The 1 KHz to 4 KHz frequency band signal (Figure 4-12) is seen to be of much smaller amplitude inside the p1 pulse than prior to the p1 pulse. The normalized cumulative power of the 1 to 4 KHz band (Figure 4-13) shows that only a small portion of the cumulative power resides in the p1 pulse (the p1 pulse limits are indicated by the data taps on the curve at 12.44mS and 13.47 mS). The reconstruction of the average click using only the frequencies between 1 KHz and 4 KHz (Figure 4-14) illustrates that most of the energy in that band occurs within or slightly after the p0 pulse.

The length of the whale, the fact that the whale was feeding at the same time as several other whales, and the low value of the cumulative power within the p1 pulse suggests that this click is from a mature female sperm whale.

One reason why the p1 pulse of a male sperm whale may contain more low frequency energy than the p1 pulse of a female sperm whale is the size of the whale’s frontal sac. A sperm whale’s click is produced by a wideband impulsive event produced in the front of the whale’s head by air forced through the monkey/phonic lips. Part of the energy is coupled into the water and the majority of the click’s energy is directed through the spermaceti organ to the frontal air sac in the back of the whale’s head. The click reflects off of the frontal air sac, travels through the junk and exits the whale nose as the p1 pulse. The larger male whales have larger frontal air sacs than the smaller females. The larger frontal sacs of the males are better reflectors of lower frequencies than the small frontal sacs of the females. This may contribute to the p1 pulses of male sperm whales containing more of the low frequency energy of the click than the female sperm whales (Goold, Jones, 1995).
Figure 4-11: Average Click (file 1643.mat) separated into three frequency bands.

Figure 4-12: Magnified View of the Average Click (file 1643.mat) separated into three frequency bands.
Figure 4-13: Normalized Cumulative Power of Low Frequency Band (1 to 4 KHz) of Average Click

Figure 4-14: Reconstruction of the Average Click for Signal Components in the 1 KHz to 4 KHz Frequency Band
Conclusions

The goal of this research was to determine if lengths measurements could be made of sperm whales in the Gulf of Mexico from their clicks recorded by bottom moored hydrophones. The main obstacle in achieving this goal was the problem of determining which clicks recorded by the hydrophone were produced by a whale whose acoustical axis was aligned with the hydrophone. Received clicks from off axis whales do not display the regular multipulse structure displayed by on axis clicks. The use of off axis clicks to estimate whale lengths will lead to erroneous length estimates.

Clicks that had peak amplitudes over 0.1 V and frequency content consistent with that from a sperm whale were selected. The use of continuous wavelet transforms enabled the energy in the selected clicks to be broken into several frequency bands. This information allowed the selection of clicks from whales approaching the hydrophone. Clicks from approaching whales made it possible to develop a “ratio” test that could determine if the click was interfered with by a second clicking whale. Using the normalized cumulative power in the 8 to 12 KHz band enabled a determination if the click was on or off axis. Different frequency bands were used to determine the locations of the p0, p1, and p2 pulses in the clicks of the on axis, approaching whales thereby enabling sperm whale length estimates closely matching length estimates made by hand.

Two additional methods for estimating sperm whale lengths were evaluated – autocorrelation and cepstrum analysis. Both methods produced good estimates when presented with “good” clicks – on axis clicks without interfering clicks from additional whales clicking at the same time as the subject whale. Both methods were found to be sensitive to interfering whale clicks. Even though cepstrum analysis is used by other researchers to overcome the off axis click problem, it appears that it is susceptible to clicks from interfering whales. The use of the ratio test in the continuous wavelet method helps prevent the problem of interfering whale clicks.
A short study was done to see if lengths estimates could be made from a single click. If it is possible to make a length estimate from a single click instead of multiple clicks more length estimates could be made in a given time interval perhaps revealing the presence of additional whales.

The continuous wavelet transform method and the cepstrum method are based on the use of more than a single click to produce a length estimate. The wavelet method presented requires at least 6 click in a file to meet the requirements of a “good” click to produce an estimate. It uses the ratio test to detect and discard clicks contaminated by other whales. The cepstrum method uses somewhere between 50 and 1000 clicks that just meet the minimum amplitude requirement. The large number of clicks used by the cepstrum method enables that method to overcome the off axis click problem. The method seems to still be vulnerable to interfering clicking whales.

It is proposed that a combination of the wavelet and cepstrum methods be developed. In that method the clicks will be selected by the selection criteria of the wavelet method and the ratio test employed to detect interfering whale clicks. A length would be estimated by the wavelet method if the click passes the ratio test. The click data would then be sent for cepstrum analysis. The results of the cepstrum analysis would be compared to the wavelet length estimate, and if the two results agreed the length estimate would be recorded.

It is also proposed to determine if initial findings indicating that male and female sperm whales can be sexed by the frequency content of their clicks be further investigated.
References


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Vita

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