JOHNS HOPKINS
UNIVERSITY

Applied Physics Laboratory
Laurel MD 20723-6099

FPS-T-14-0338
January 28, 2015

To: Distribution

From: Manwei Chan

Statistical Simulation of Whale Vocalizations with Application to Sonar

Manwei Chan

July 2014

Abstract

Using the Marine Mammal Movement and Behavior software to simulate sperm whale movements, as well as the ray trace and eigenray capabilities of the software CASS (Comprehensive Acoustic System Simulation), I estimate the availability of sperm whale vocalizations (clicks) by a submerged receiver array in deep open ocean environments. These results will help define a statistical model to describe the spatial and temporal biologic clutter characteristics on the under water noise field.

1 Introduction

1.1 Sound Propagation

The speed of sound in water is a function of temperature, salinity, and pressure. Our research is based in the Sargasso Sea and the Pacific Ocean, both of which have mid-latitude, deep ocean sound-speed profiles. The specific profiles I used are seen in Figure 1. The decline of velocity beginning at the surface is attributed to the decrease in temperature as depth increases. The surface layer (water layer closest to the surface) is influenced by the sun and other surface effects such as the wind. Underneath is the seasonal thermocline which is too deep to be affected by surface effects, and is mainly influenced by seasonal heating and cooling. Below the seasonal thermocline and above where the minimum sound speed occurs, lays a permanent feature called the main thermocline, where temperature decreases regardless of what is happening above the surface of the ocean. The minimum sound speed is called the deep-sound channel axis. Below the deep-sound channel axis is the deep isothermal layer. At this depth, the water temperature is more or less constant at 4°C, and the sound speed increases because pressure increases as depth increases [1].

The propagation of sound through water is dictated by Snell's law. Snell's law states that sound bends towards areas where the sound speed is lower through the equation:

$$\frac{cos\theta_1}{c_1} = \frac{cos\theta_2}{c_2} \tag{1}$$

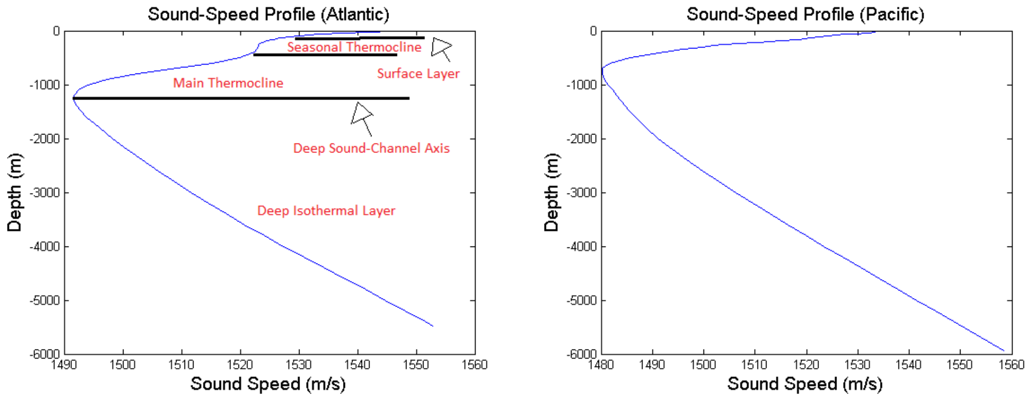

Figure 1: Historical, deep water sound speed profiles in the Atlantic and Pacific. The Atlantic SVP is annotated with the different water layers.

The equation describes the refraction of sound when it travels from an area with one sound speed to an area with another sound speed. In the equation, θ_1 corresponds to the grazing angle of an incident ray in an area with sound speed c_1. The subscript 2 corresponds to an area with a different sound speed [2]. Due to this phenomenon, sound traveling above the deep-sound channel is refracted down, with the opposite effect happening to sound traveling below the channel. This propagation can be tracked by a ray tracing software. An example can be seen in Figure 2.

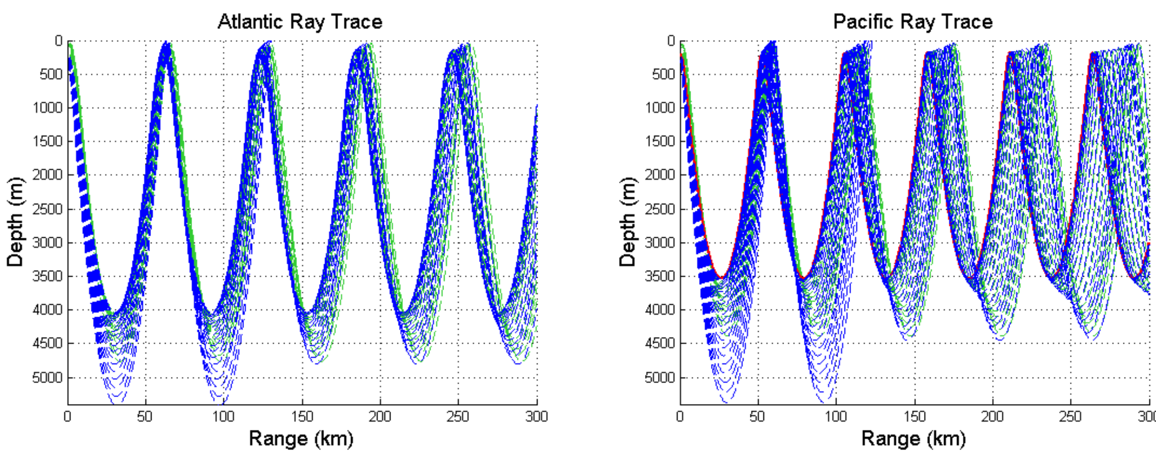

Figure 2: These Ray Traces were created by CASS using the sound-speed profiles in Figure 1 and a sound source at 180m. The green traces are the rays that had a starting angle above the horizontal, the blue rays had initial angles below the horizontal, and the red line in the Pacific ray trace is the ray that was initially horizontal. An important aspect of these ray traces is the refocusing of the rays when they return to the surface, leading to high sound intensity. These are referred to as convergence zones (CZ) and the first is roughly at 60km.

1.2 Sperm Whales

Sperm whales are the largest of the extant toothed whales. Sperm whales dive to depths of more than 2000m in order to forage for prey such as giant squid. In their search for food, sperm whales utilize echolocation by producing clicks that originate in their head. These clicks turn into buzzes at certain times, and it is believed that whales buzz when homing in on their prey [3]. For my simulations, we will not be worrying about the buzzes, but the clicks. In the Atlantic Ocean, sperm whales start clicking at a depth of 222.7 ± 107.5m [3]. I did not have information on the depth Pacific whales start clicking at, so I just assumed the same depth as the Atlantic whales in my simulations. The clicks are broadband transient signals; however, the power magnitude is greater at specific frequencies. Male sperm whales produce more powerful clicks at 400Hz and 2kHz while females produce more powerful clicks at 1.2kHz and 3kHz [4]. At these frequencies, the clicks are less susceptible to attenuation due to ionic relaxation than clicks at higher frequencies. The ionic relaxation of magnesium sulfate ($MgSO_4$) is the dominant cause of absorption in seawater at frequencies between 10-200kHz and boron-borate relaxation is dominant below 10kHz according to the Francois-Garrison model [10]. Because low frequencies are attenuated less than high frequencies, hydrophone receivers can detect the low frequency part of sperm whale clicks at very large distances.

2 Software

2.1 Marine Mammal Movement and Behavior (3MB)

3MB allows users to simulate the movements of virtual mammals within a given bathymetry. In this case, we use the Atlantic and Pacific sperm whales, and 3MB simulates the sperm whale's behaviors such as dive duration, dive depth, location, horizontal rate of travel, etc. The specific behaviors in the sperm whale files are based on references [9], [3], [8], and [7], and the values can be seen in Table 1. 3MB also allows simulations to be run for different time durations of up to 24 hours and provides multiple ways to seed the animals into a certain bathymetry. Figure 3 has an example of the data 3MB can provide.

2.2 CASS

CASS is a computer program designed to investigate undersea acoustic propagation and acoustic systems. For my purposes, I use CASS's ray trace and eigenray functions. From the ray trace program, I simulate the propagation of sound to find locations in the ocean where sound can be easily detected. This function is useful because it allows me to determine when whales are within the rays, which allows their clicks to be heard by a hydrophone located at the source. From the eigenray function, I obtain the transmission loss at various frequencies at different locations. This is useful since it allows me to determine if the whale clicks are insignificant compared to the inherent noise of a hydrophone.

	Atlantic Sperm Whale	Pacific Sperm Whale
Travel Rate (m/s)	$0.88 \pm .27$	$0.88 \pm .27$
Ascent Rate (m/s)	$1.4 \pm .2$	$1.2 \pm .2$
Descent Rate (m/s)	$1.2 \pm .1$	$1.2 \pm .2$
Depth of Dive (m)	683.7 ± 83.1	616.6 ± 217.9
Reversals	8.2 ± 4.2	8.2 ± 4.2
Reversal Dive Rate (m/s)	$1.8 \pm .5$	$1.8 \pm .5$
Time in Reversals (min)	2.4 ± 1.4	2.4 ± 1.4
Time Spent at Surface (min)	9.3 ± 2.8	8.5 ± 2.2

Table 1: The foraging behavior of the sperm whales is defined in terms of reversals, which are the number of times a whale may dive up and down after reaching maximum depth. The time spent foraging is effectively the time the whales spend performing all their reversals. Most parameters between the Atlantic and Pacific sperm whales are similar. However, the biggest difference is the depth that the whales dive. I suspect this will contribute to longer intersections with the ray traces for the Atlantic sperm whale.

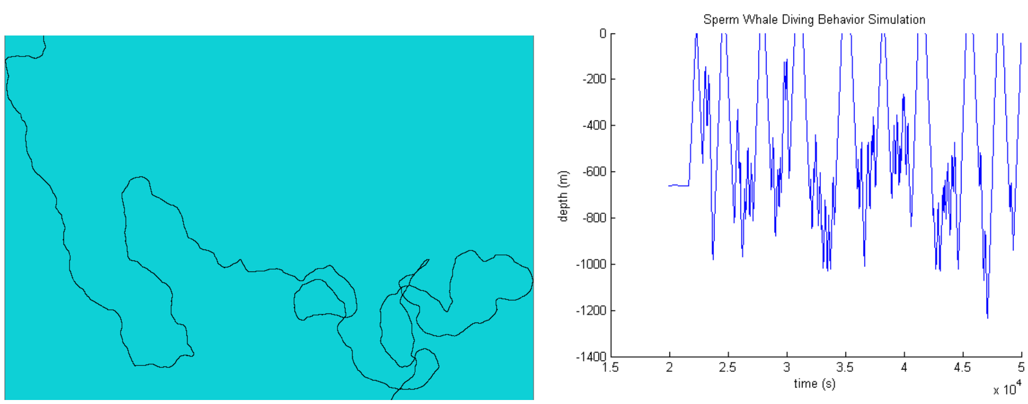

Figure 3: The image on the left is the top down view of a simulated sperm whale over a 24hr period within a 250km by 250km box with a depth of 5300m. The image on the right is the dive data taken from the same simulation. Only data from hours 5.5 - 13.9 are shown so the details of the dive can be seen. The whales dive and hover around certain depths where they forage before coming back to the surface for air.

An important thing to note is that CASS runs using a sound source and then models how the sound will travel outward. My goal in this project is to find out how the whales will affect hydrophone readings, effectively making the whales the source, and CASS's sound source effectively a receiver. However, due to reciprocity, I take the simulations to be valid since if an emitted ray in CASS travels to a whale, a whale's clicks will be able to travel back to the source following the same ray.

3 Data Analysis

3.1 A Problem with 3MB

There is a problem associated with the initial conditions that 3MB seeds the whales. The 3MB program seeds whales with very similar initial properties, so the whales all behave similarly for the beginning of the simulation. Technically, the default animal behavior file for the sperm whale that was included with 3MB has an 80% chance of initializing in the deep foraging behavior. At this behavior, the distribution of depths is 683.7 ± 83.1m. For future reference, this initializing state can be adjusted by changing the behavior file in 3MB. A visual of this behavior can be seen in Figure 4. To account for this behavior, I started all data analysis at 15,000 seconds, which is when the depth distribution of the whales is finally stochastic.

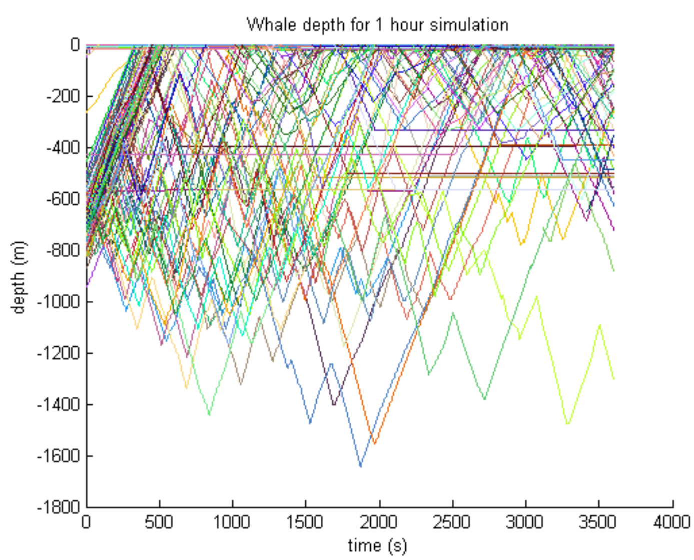

Figure 4: This image depicts the dives of the whales of a 1 hour 3MB simulation. It can be seen that the whales exhibit very similar behavior at seconds 0-500. During this time there are almost no whales at depths of 0-400 meters. From the plot, it can also be seen that many whales return to the surface right after the simulation starts. This would cause many whales to begin their surface phase together. It takes until 15,000 seconds into a 10 hour simulation for the behaviors to fully randomize.

3.2 Determining the Intersection

The first step in analyzing the data is to determine when and where the whales are producing clicks and if these times also coincide to times when the whale is within the rays trace. To do this, I ran 10 hour 3MB simulations in a 500km by 500km box with a depth of 5300m for the Atlantic Ocean and 5942m for the Pacific Ocean. The box had a side length of 500km to ensure that we would reach out to the 3rd CZ at around 180km in the Atlantic (the 3rd CZ is closer in the Pacific) if we put our virtual hydrophone at the center of the box. Sperm whales were seeded using the method that allows us to randomly disperse virtual sperm whales around the box using a given density per square kilometer. Refer to Table 2 for the densities we used in our simulations. This form of seeding does not account for the pod behavior that sperm whales can exhibit. The CASS ray trace was run in the Atlantic and Pacific Oceans.

	Number of Whales	Whale Density (whales per square kilometer)	Density Spread (whales per square kilometer)
Atlantic (Sargasso Sea)	1930	0.007888	0.006276 – 0.009500
Pacific ($27°N, 148°W$)	38	0.000156	0.000116 – 0.000196

Table 2: The density spread is the range of densities at the specific location. The whale density is the average of the density spread and was the value used in the 3MB simulations. The Atlantic density is from [6] and the Pacific density is from [5].

To determine the intersection, I placed a hydrophone array at the center of our box. Since 3MB outputs whale positions in latitude and longitude, I then calculated the distance between each whale position and the hydrophone array using a program that converts two pairs of latitude and longitude coordinates into a distance in meters, while assuming the Earth is a sphere.

Lastly, the data gathered from the 3MB simulation on whale distances from the hydrophone and depths was superimposed onto the data from the ray traces. I did not include any of the rays that were reflected by the ocean surface or bottom because the transmission loss of these rays would be too great to have a significant effect compared to the unreflected rays. To determine the intersections, I set a threshold that only counted an intersection if a whale was within 0.5km distance-wise and 20m depth-wise of a ray. Another constraint that was added was the fact that whales start clicking at a depth of 222.7 ± 105.4m [3]. To account for this, each whale was assigned a random depth where they started clicking based on this distribution. An example of an intersection can be seen in Figure 5.

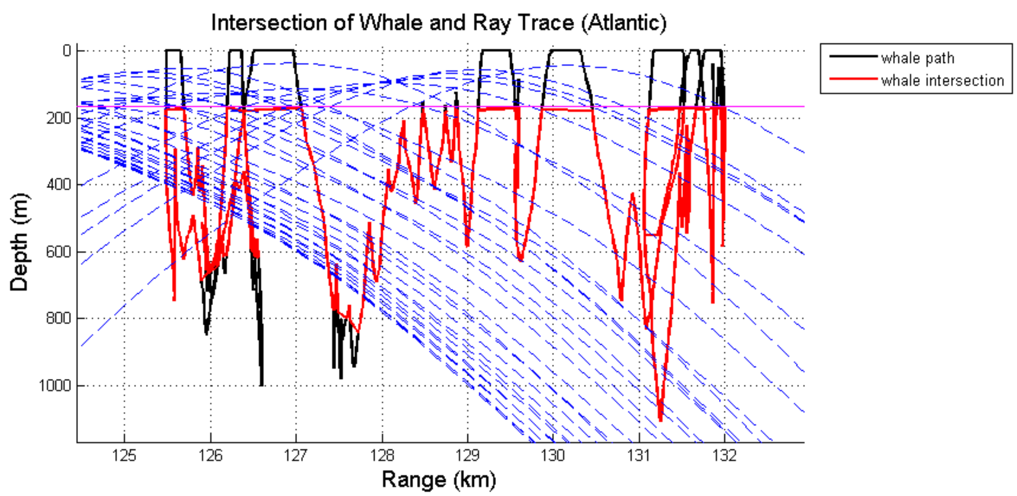

Figure 5: Here is the whale intersection at an Atlantic ray trace at the 2^{nd} CZ. The blue-dotted lines are the rays and the red path indicates what whale data we will be using in our intersections. The magenta line is the randomly assigned depth at which whales start clicking.

3.3 Duration of Intersections

A useful metric I can extract from these simulations is the duration that whales are within the ray trace and are clicking. I defined an intersection as each time the whale entered and exited the ray trace, so a particular whale can produce multiple intersections throughout the simulation if it goes in and out of the ray trace. The data is best described by a gamma distribution, specifically the exponential distribution where the probability density function is:

$$y = \frac{1}{\mu} e^{\frac{-x}{\mu}}$$

Here μ is the scale parameter. See Figure 6 for histograms of the durations obtained from the simulations. The specifics of the distributions can be seen in Table 3. Additionally, to achieve a better understanding of the distribution of the durations, a sample cumulative distribution function is displayed in Figure 7.

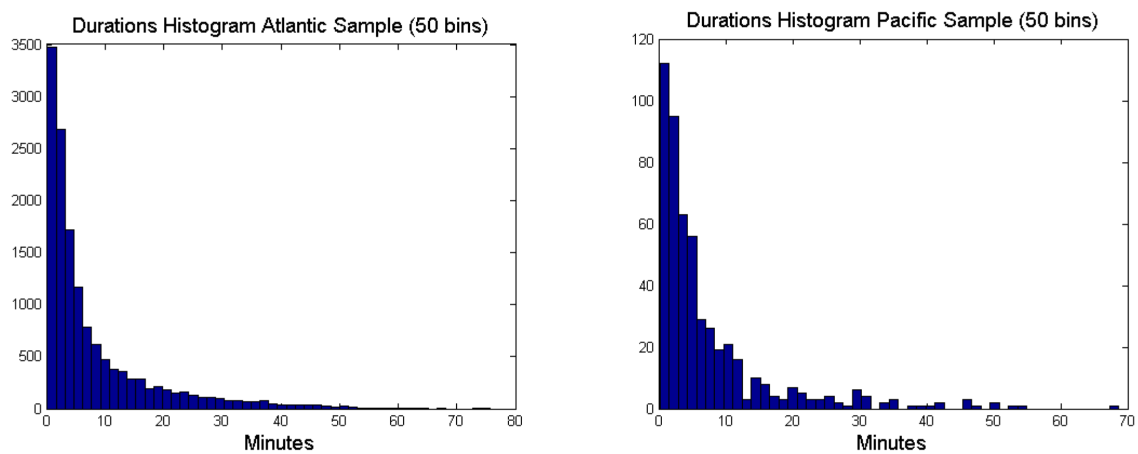

Figure 6: Both Atlantic and Pacific histograms are accurately described by an exponential distribution.

Trial	Scale Parameter (μ)	Max Duration (minutes) (minutes)
1 (Atlantic)	8.25	69.17
2 (Atlantic)	8.60	71.00
3 (Atlantic)	9.64	79.67
4 (Pacific)	7.54	68.67
5 (Pacific)	6.92	60.17
6 (Pacific)	8.71	54.50

Table 3: These durations are inclusive of all the intersections of all azimuths, up to a range of 300km from the source. The slightly lower durations in the Pacific Ocean are probably due to the lower dive depth of the sperm whales. Since 3MB defines the whale dives using descent/ascent speeds and reversals, which are almost all the same between both Atlantic and Pacific whales, the Atlantic whales naturally dive longer.

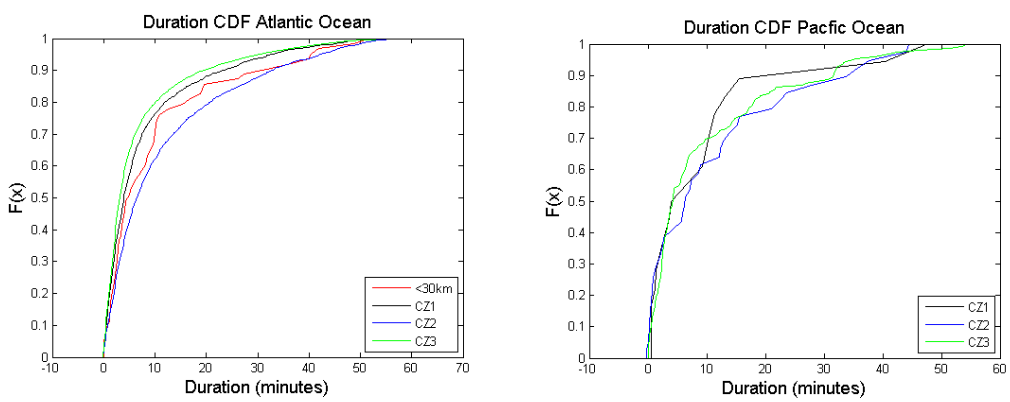

Figure 7: These are the CDFs for one 10 hour simulation in the Pacific and Atlantic Oceans. The CDF for the Pacific Ocean is less smooth due to fewer data points. Notice that a majority of the durations are less than 10 minutes.

3.4 Whale Densities at Each CZ

Finding how many whales are clicking in each CZ at any given moment is also a useful metric to obtain. Because farther CZ's cover a larger area, we expect more whales to be in farther CZ's then closer ones. This was validated by our simulation, and visuals can be seen in Figure 8.

Once the intersections had been separated by location, I found the whale density by finding out how many whales were intersecting a ray trace at every time during the simulation. I assumed the densities followed a Gaussian distribution, so these times were then averaged and a standard deviation was taken as an error. Results can be seen in Table 4. For specific ranges that correspond to each CZ refer to Table 4.

Table 4: Whale Density at each CZ (whales/sec)

	Near Source	**CZ1**	**CZ2**	**CZ3**
Atlantic CZ Range	$<$ 12km	49-76km	111-140km	173-204km
Pacific CZ Range	$<$ 12km	42-69km	95-128km	149-186km
Trial 1 (Atlantic)	$0.74 \pm .57$	27.95 ± 4.18	77.86 ± 6.59	104.98 ± 7.39
Trial 2 (Atlantic)	$1.52 \pm .71$	24.04 ± 3.50	71.92 ± 5.01	120.99 ± 8.33
Trial 3 (Atlantic)	$0.71 \pm .59$	23.53 ± 3.96	56.43 ± 5.12	119.91 ± 6.93
Trial 4 (Pacific)	0.00	$0.26 \pm .44$	$1.61 \pm .90$	2.48 ± 1.08
Trial 5 (Pacific)	0.00	$0.81 \pm .67$	$0.76 \pm .61$	3.50 ± 1.28
Trial 6 (Pacific)	0.00	$0.52 \pm .50$	0.66 ± 52.0	2.75 ± 1.18

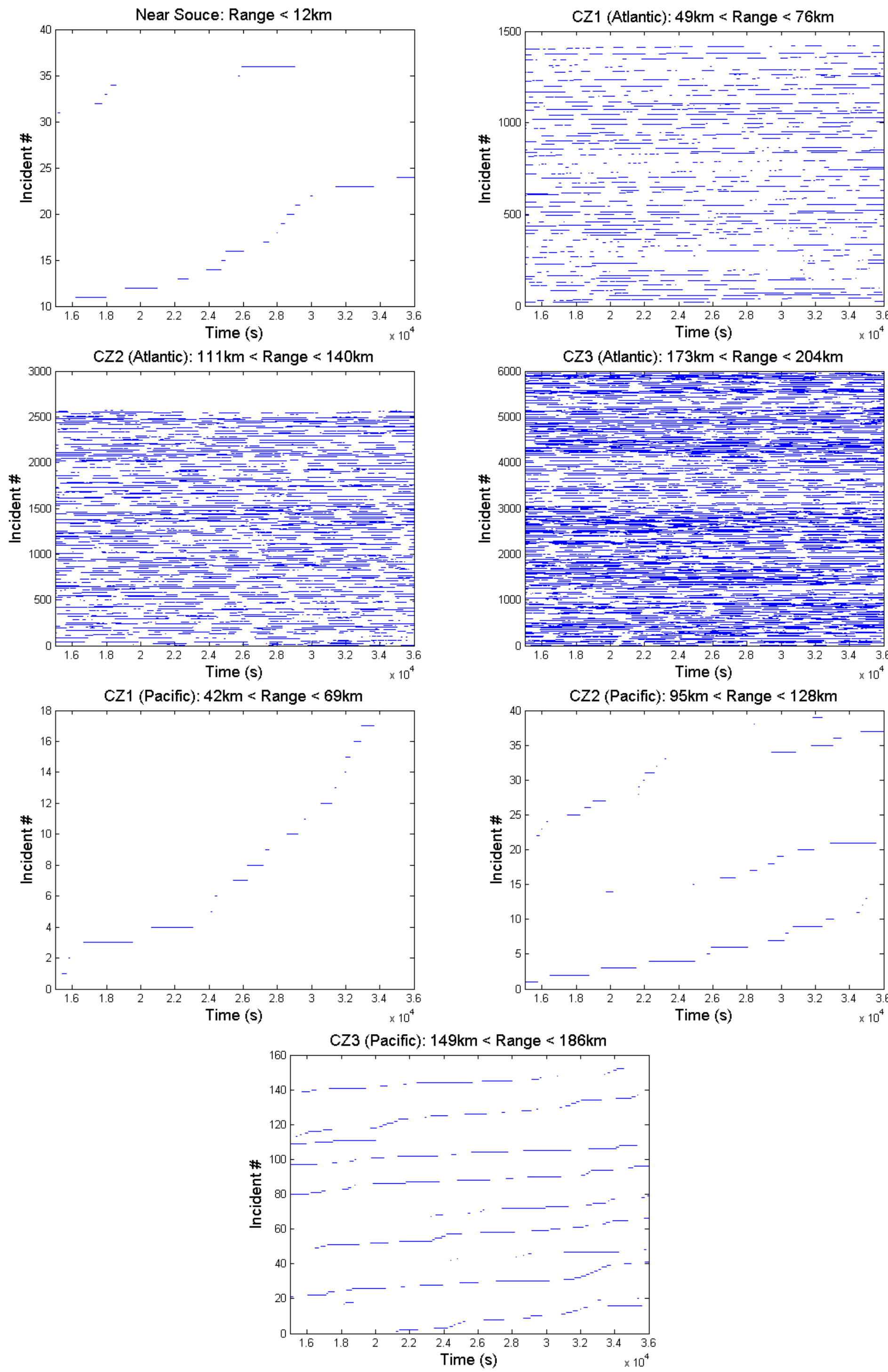

Figure 8: The x-axis is the absolute time and runs the length of the simulation. Each increment on the y-axis is a single incident in which the whale intersects the ray trace, and the length of each line is the duration for which the intersection occurred. The CZ range is roughly defined by when the ray traces intersect 2000m of depth, which is the limit of a majority of the whale dives.

3.5 Horizontal Isotropy

All previous analysis assumed the hydrophones were receiving data from all azimuths. In order to see if my simulations support data collection from horizontally directive arrays, I analyzed how whale densities decreased as the surveyed area decreased. To achieve this, I arbitrarily set a direction–due north in my case. I then set a cutoff angle where everything outside the cutoff angle was not included in calculations. The cutoff angle was defined east and west of due north, so a cutoff angle of 40° would exclude anything greater than 40° east of north and 40° west of north for a total inclusion angle of 80° centered around due North. My finding was whale density decreases linearly with respect to cutoff angle. This is expected since cutoff angle is linearly correlated with area, so if the whale density is horizontally isotropic, the angle should linearly decrease with density. The results from one of our trials can be seen in Figure 9.

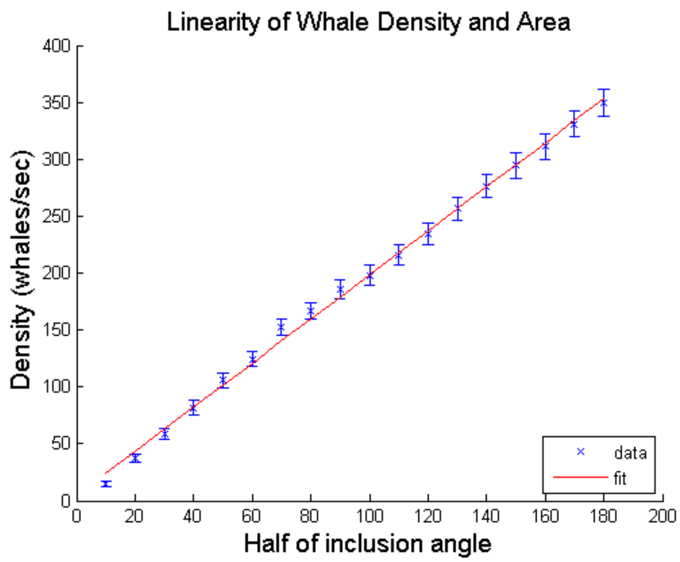

Figure 9: The whale density includes all intersections with CZs up to 300km. The error bars are the standard deviation at each specific cutoff angle. The data was then fit with a line using the least squares method. The error bars were not factored in the fit because I did not want the fit to be biased towards the points at lower cutoff angles, which have more restrictive error bars. The line has a correlation coefficient of 0.999 confirming that our data is linear.

3.6 Accounting for Attenuation

The next part of my analysis was factoring in the attenuation of the clicks from the whales to the receiver. Absorption is mainly due to ionic relaxation of magnesium sulfate and boron-borate. To determine the affects of attenuation on the clicks, I gathered intensity data from CASS's eigenray program at different points along a whale's intersection with the ray traces. After summing up all the paths for each target location, the intensities were then converted into decibels. This analysis showed that within one intersection, the variation in decibels was roughly 5dB. A point to note is that we only used a single attenuation coefficient for each frequency, which was the average over all depths. This simplification loses accuracy regarding different attenuation at different depths.

Using the fact that the variation during one intersection was roughly 5dB, I simplified calculations by only using one point per intersection. This point was chosen by averaging the times when the whale entered and exited the ray trace, effectively choosing a point in the middle of the intersection. This method also avoids the error of choosing a point outside the ray trace, but was flagged as a point of intersection because of the intersection threshold that was set before. Lastly, all intersections of less than one minute were excluded to avoid false intersections, again a result of the intersection threshold.

This process was executed for each whale intersection at frequencies from 1 kHz to 10 kHz with increments of 1 kHz. The data was then sorted by which CZ the whale had intersected. The results are in Figure 10. Since absorption from clicks at low frequencies is relatively low, clicks from far whales can still be heard. Using a low pass frequency filter, the click density may be high enough that individual clicks cannot be distinguished.

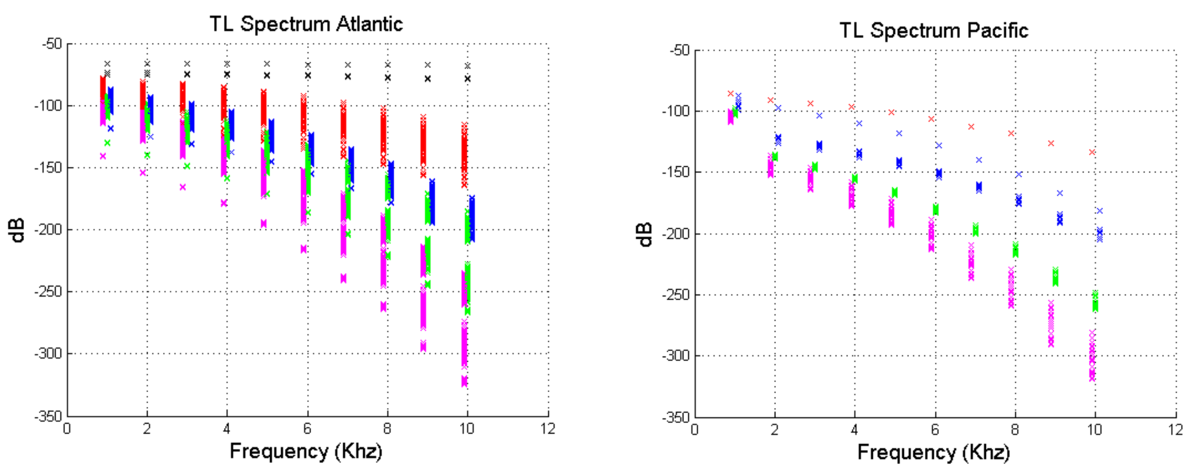

Figure 10: Black points represent whales near the receiver, red points for whales in CZ1, blue points for whales in CZ2, green points for whales in CZ3, and magenta for all points greater than CZ3. The data points are artificially staggered around each frequency for visual clarity.

4 Next Steps

In order to simulate noise on a hydrophone, we will need to obtain a source level spectrum of the clicks. With the source level spectrum, the click rate at each CZ, and the transmission loss spectrum at each CZ, we can obtain a statistical measure regarding the amount of clicks we expect to hear and at what frequency we expect to detect them at.

As a rough estimate, I also used the eigenray graphs to estimate the receiving angles at which a hydrophone array will detect these clicks. In the most extreme case, for a whale traveling directly at or away from the array at a speed of 1 m/s, we expect the DE angle to change around the order of 2° per 10 minutes. This value was calculated by assuming the change in DE is linear. At the leading edge of the CZ, the rate of DE change is higher (See Fig: 11). The difference in between readings at different depths and CZs was negligible at the precision I was using.

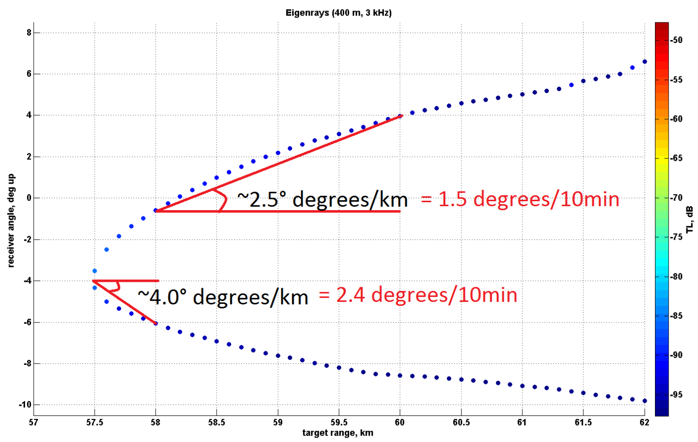

Figure 11: The transmission loss at the first CZ for a whale at 400m of depth. The y-axis represents the angles at which a receiver will detect a whale at each location. The CZ leading area is the area from 57.5km to 58km in range. This area may deserve special attention when calculating changes in receiver angle. An example of the linear approximation used is represented by the red angles.

References

[1] Biondo, A.C., 1998, “A Primer on Underwater Acoustic Propagation and Modeling.”

[2] Urick, R.J., “Principles of Underwater Sound (3rd Ed)”, McGraw-Hill Book Company, New York, NY, 1983.

[3] Watwood, Stephanie L. et al. 2006. “Deep-diving foraging behavior of sperm whales.”

[4] Goold, John C., Jones, Sarah E. 1995, “Time and frequency domain characteristics of sperm whale clicks.”

[5] Hanser, Sean et al. 2012, *Pacific Navy Marine Species Density Database* “Technical Report 4 May 2012”

[6] *Commander Task Force 20, 4th, and 6th Fleet Navy Marine Species Density Database*, “Technical Report,” Norfold,VA. March 20, 2012.

[7] Amano, M. and Yoshioka, M. (2003). “Sperm whale diving behavior monitored using a suction-cup attached TDR tag.” Marine Ecology Progress Series 258: 291–295/

[8] Aoki, K., Amano, M., Yoshioka, M. Mori, K., Tokuda, D. and Miyazaki, N. (2007). “Diel diving behavior of sperm whales off Japan.” Marine Ecology Progress Series 349: 277-287.

[9] Miller, P. J. O., Johnson, M. P., Tyack, P. L., and Terray, E. A. (2004). “Swimming gaits, passive drag and buoyancy of diving sperm whales Physeter macrocephalus.” Journal of Experimental Biology 207:1953-1967.

[10] JASA 72(3) Sept 1982 pg. 896.