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Detection of Acoustic Sources Using Time-Reversal Methods

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DETECTION OF ACOUSTIC SOURCES USING TIME-REVERSAL METHODS

by

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Abstract

The goal of this research is to characterize the impact of using an equivalent-fluid method for a solid seabed on the use of time reversal procedures for detecting the origin location of an emitted sound. There are two different ways of modeling how sound propagates through water: modeling sound as a ray and modeling sound as a wave. It is easier to model the propagation of sound through water with a ray model; using a ray model allows for the collection of grazing angles with respect to the bottom. These will be important when determining bottom intensity loss of the sound when taking the equivalent fluids into account. When a sound wave interacts with the bottom of the ocean it is hard to estimate how much energy is lost to the bottom; the equivalent-fluid method is a way to simulate the ocean floor's density as a complex density so that it can be easily manipulated and affect how much intensity is lost to the bottom. The equivalent-fluid method will introduce errors when calculating the bottom loss from the ray grazing angles; this research will hinge on finding how much these errors will affect time reversal simulations. The results were rendered inconclusive, but can be confirmed with future research. This research could be applicable in the field of wildlife detection as well as long range vessel detection.

Key Terms: Ocean acoustics, equivalent-fluid approximation, sound source detection

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Chapter 1: Introduction

The purpose of this project is to find a method of detecting the location where a sound was emitted in shallow water. The formulated method will be dependent on two key pieces of ocean acoustics study: an expanded equivalent fluid model, and time reversal analysis. These methods will be used to simulate an ocean acoustic field and, reversing the time, trace the acoustic arrivals at a receiver back to their common origin.

The expanded equivalent fluid method is a simulation technique that describes the effect of the ocean floor on reflected sound. It will be possible to find the intensity of the reflected sound after it interacts with the bottom using this method. The expanded equivalent fluid method treats the ocean floor as having a complex density.

The time reversal method consists of gathering data from a receiver and reversing all of the time dependent parameters such that it will be possible to run a simulation that describes a time reversed field. Performing the reversal of the field is called phase conjugation. Phase conjugation will allow for the location of the unknown source.

Chapter 2: Literature Review

Detecting the location of an emitted sound underwater in a shallow water environment can be based on the received sound at a final range. This research will be largely dependent on computer simulations that are performed with several distributions of MATLAB as well as FORTRAN 77 based code. Using computer simulations will allow for a controlled environment that minimizes unknown values that affect the parameters collected. In order to understand the research at hand, one must understand how sound is represented as a ray, how the time reversal mirror works, and how the use of an equivalent fluid approximation could impact the time reversal procedure.

Representing Sound as a Ray

A ray is similar to a vector in that it shows the direction of a particular item. Rays have a direction, but they do not have a magnitude so one cannot know how intense a ray is at any point during its propagation. Sound in the ocean can be modeled with ray equations. Due to sound waves being similar in nature to electromagnetic waves, or light, most of the equations dealing with sound rays can be related to optics. All methods of representing sound as a ray are based on Snell's Law, which governs how a ray acts when it travels through a medium that changes the ray's speed.

One method of representing sound as a ray can be derived from the equations governing ray transport:

$$\delta_{xx}z = -C^{-1}\delta_z C[C_0 sec^4\theta/C]$$

In this equation, θ is the angle that the ray makes with the horizontal, C_0 is a reference sound speed, and C is the sound speed of the current medium. A ray can travel at a maximum angle of about 15 degrees with respect to the horizontal or it could be expected to hit the ocean floor, lose energy, and be lost after traversing a long range. This 15 degree maximum allows for the above equation to be abbreviated with a small-angle approximation where $tan\theta = \theta$. This gives the following equation:

$$\delta_{xx} z = -C^{-1}\delta_z C$$

This equation will represent sound that is traveling through the ocean sound channel[1].

Another way to represent sound as a ray is based on the Helmholtz wave equation. The Helmholtz wave equation is as follows[3]:

$$[\nabla^2 + k^2(r,\omega)]\psi(r,\omega) = f(r,\omega)$$

This is a three-dimensional, elliptic partial differential equation that can be solved either analytically or numerically. The system of ray equations derived from this equation is as follows[2]:

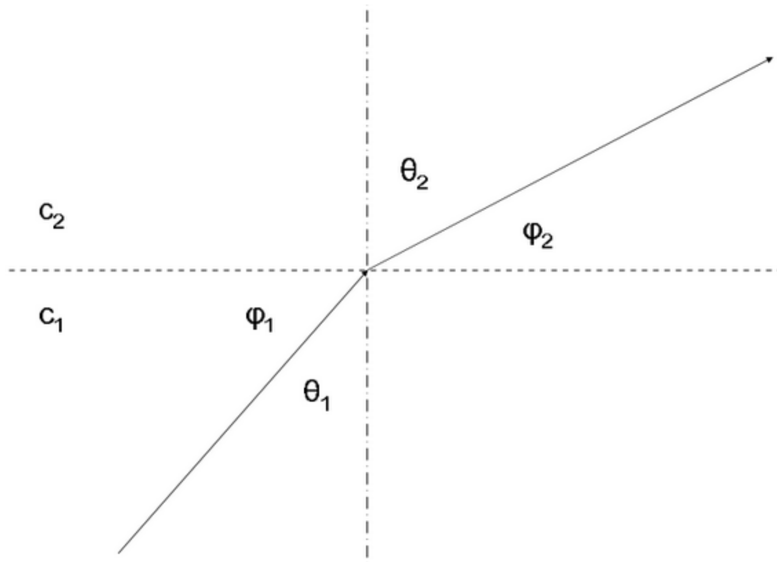
$$\frac{dz}{dr} = \frac{\partial H}{\partial p}$$
$$\frac{dp}{dr} = -\frac{\partial H}{\partial z}$$
$$H = -(c^{-2} - p^2)^{1/2}$$
$$\frac{dt}{dr} = c^{-1}(1-(pc)^2)^{-1/2}$$

where $p = sin\theta/z$, z is depth, and θ is the angle to the horizontal. This system of equations will model rays at a specific point in time. The simulation program will use a modified fourth-order Runge-Kutta technique with an adaptive step size to propagate the rays forward in time[2][8].

Although multiple methods to represent sound as a ray have been presented, the one constant with all methods is that they follow Snell's law. As previously stated, Snell's law governs how a ray acts when it travels through a medium that changes the ray's speed. This law states that when a ray propagates through an increase of ray speed within the medium it is traveling, the ray bends toward the slower of the two sound speeds. The formula that is associated with this law is as follows:

$$n_1 sin(\theta_1) = n_2 sin(\theta_2)$$

where $n_1$is the index of refraction of the medium that the ray is transferring from, n_2 is the index of refraction of the medium that the ray is transferring to, $\theta_1$is the angle the ray makes with the axis normal to the transfer point while it enters, and θ_2 is the angle the ray makes with the transfer point while it exits. A diagram that explains this effect is as follows:



Where the sound speeds are represented by $C_1$and C_2, and the transfer angles are represented by θ_1 and θ_2. This diagram shows a ray traveling from a slower sound speed, C_1, to a faster sound speed, C_2[10].

Using rays for the emulation of sound will allow for the development of a geometric representation that shows how sound the sound in question propagates through the ocean. Using rays also allows for the gathering of grazing angles of the sound with respect to the ocean floor, this will be important for finding the acoustic energy lost to the ocean floor.

Time Reversal Mirror

The time reversal mirror takes a detected sound field and reverses its propagation properties so that it can be traced to the direction from which it originated. The time reversal mirror is fairly simple to think about; Kuperman says that it can be compared to rewinding the output of an analog tape recorder[5]. Kuperman also says that the time reversal mirror will receive a signal from a source, then back propagate it to the origin using a different set of sources placed at the location of the received signal[7].

Characterizing Bottom Loss

As sound propagates through shallow water it interacts with the ocean floor; the ocean floor affects the acoustic energy by both absorbing and reflecting it[6]. Due to the muddy characteristics of the ocean floor at some locations, the ocean floor can sometimes be thought of as a dense fluid. In general, however, when the sound energy interacts with the ocean floor, the presence of solids can have an effect. For harder seafloors, the solid properties are significant. Sound can interact with a solid in three different ways; it can be absorbed into shear waves, transmitted into the floor, and reflected off the ocean floor. Bottom loss happens when the sound energy is absorbed into the ocean floor, either as transmitted sound waves or elastic shear waves in the solid.

One of the main parameters that govern the sound's interaction with the ocean floor is the speed of transverse elastic shear waves. Elastic shear waves are responsible for some of the lost sound energy. These waves can be thought of as vibrations within the medium itself. This shear interaction is what makes computer simulations involving the ocean floor computationally expensive. Dr. Vera has formulated a method to simulate the ocean floor that is both fairly accurate and computationally inexpensive; this method is a type of equivalent fluid approximation[4]. Instead of using a normal density, the equivalent fluid method approximates the ocean floor with a complex density, which is made up of a real part and an imaginary part. The complex density is based on a curve fit to the bottom loss that occurs when the sound interacts with the sea floor; using a complex density uses parameters that do not require the simulation of shear models.

Acoustic energy lost to the ocean floor is calculated with the collected grazing angles in conjunction with the equivalent fluid approximation, where bottom loss is a function of grazing angle[4]. Grazing angles are the angles that the sound make with the seafloor when reflecting off of it. The bottom-loss calculations will accurately work for a short interval of grazing angles that are not sufficiently large [9], or less than forty-five degrees[4].

Chapter 3: Methodology

The methods used to find the origin of a sound involve a time-reversal mirror approach and equivalent fluid approximation for acoustic interaction with the bottom. In order to perform the research and use these approximations, an ocean acoustic simulation environment must be developed for shallow water. The simulations will be performed with distributions of MATLAB and FORTRAN based code. Simulations with given parameters will be performed in this simulated environment and will output desired information. The first set of simulations will be executed with ray equations that describe how the sound will propagate through water. The simulation program will be written to produce and store the grazing angle of each interaction that a ray has with the ocean floor. The simulation will be performed in normal time, then will be modified to reverse time. The modified simulations should return the source location that was defined for the original simulations.

Once the simulations are performed, all of the grazing angles will be collected and then displayed in a grazing angle histogram, which will be used to find and filter out all of the grazing angles that do not commonly occur. Once filtered, the grazing angles will then be used to characterize the phase errors that may come about as consequences for using an equivalent-fluid approximation in more sophisticated wave-based acoustic simulations. An equivalent fluid model uses a set of effective parameters to represent an actual solid that is capable of absorbing acoustic energy as both sound and transverse shear waves in the solid. Once the phase errors are characterized, it will be determined whether or not the current method is valid for performing time reversal in shallow water based on the value of the phase errors. The phase errors will be relevant to wave simulations in that they will determine if the equivalent-fluid approximation can be used in time reversal.

Chapter 4: Results

Environment

The ray simulations were performed with two fairly simple simulated environments. For the purposes of the following simulations, the environments consist of sound speed as a function of depth and the depth of the seafloor. The sound speed used in all of the following simulations is based on measurements in the Gulf of Mexico. Figure 1 gives a visual representation of the first simulated environment where the depth of the water between the source and receiver varied between 480 meters and 650 meters. The source is located at 0 kilometers and the receiver is located at 12 kilometers. The second environment is similar to the first in that the source is located at 0 kilometers and the receiver is located at 12 kilometers, but the depth does not vary between the two. The ocean floor remains flat between the source and receiver at a depth of 650 meters.

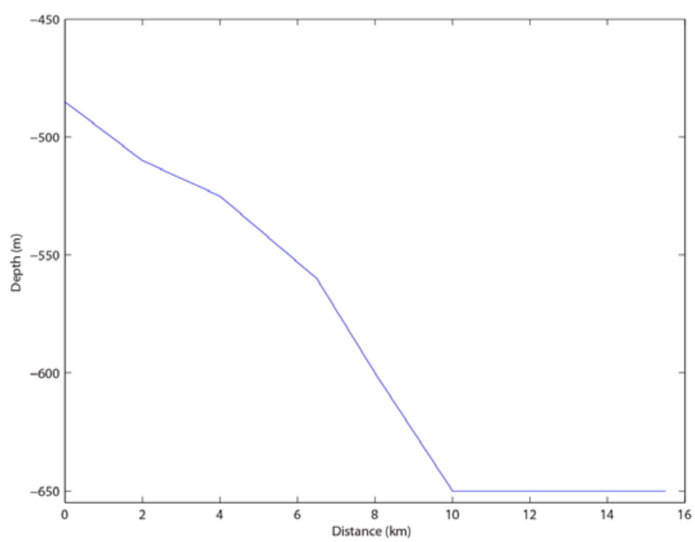


Figure 1: This figure shows seafloor depth as a function of range for the range-dependent environment.

Ray Simulations

The ray simulations were performed using MATLAB. The code initially loads the data to describe the environment, and then loads the preferences set by the user. The main preferences set by the user include the set of ray launch angles to be traced, the source depth, the receiver range, and the sound speed in the water. Using the preferences previously stated and a set of differential equations the code propagated the rays incrementally through the defined environment.

The code returns sixteen different values for each ray that is simulated. These values describe events that the ray went through on its journey to the receiver location. Such events include interactions with the ocean floor and interactions with the surface. The data received is used to create the graphs in the following sections.

The ray simulations record how many times the ray bounced off of the surface and the ocean floor during its journey to the receiver. This information is useful because it can be graphed to show how a group of rays launched at a particular interval of angles acts as shown in Figure 2 for the depth varying environment.

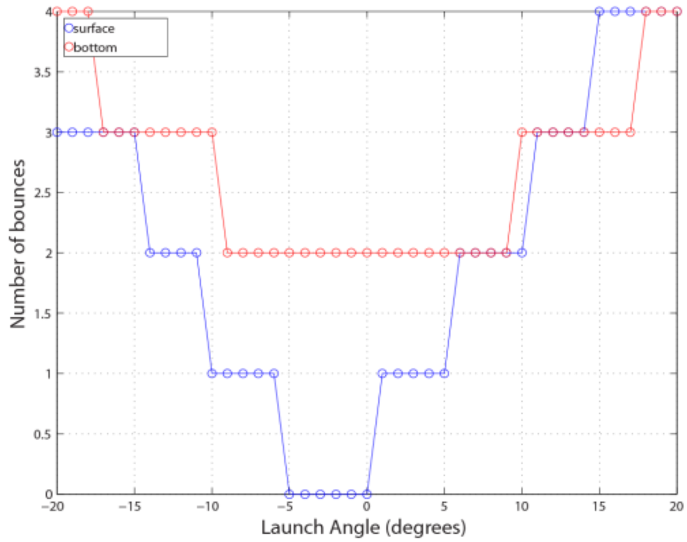


Figure 2: This figure shows the number of bounces as a function of launch angle for the range dependent environment.

Other information that is collected is the arrival depth and travel time of the ray. This information allows for the visual representation of the location of the sound at the final range.

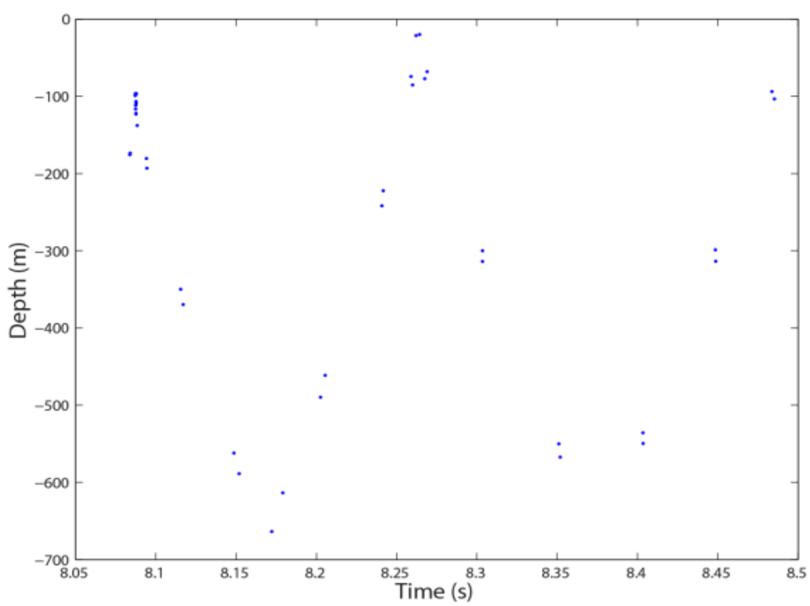


Figure 3: This figure shows the depth of the received ray with respect to the travel time of that ray for the depth varying environment.

Figures 4 and 5 contain the similar information as Figures 2 and 3 but for the constant depth environment.

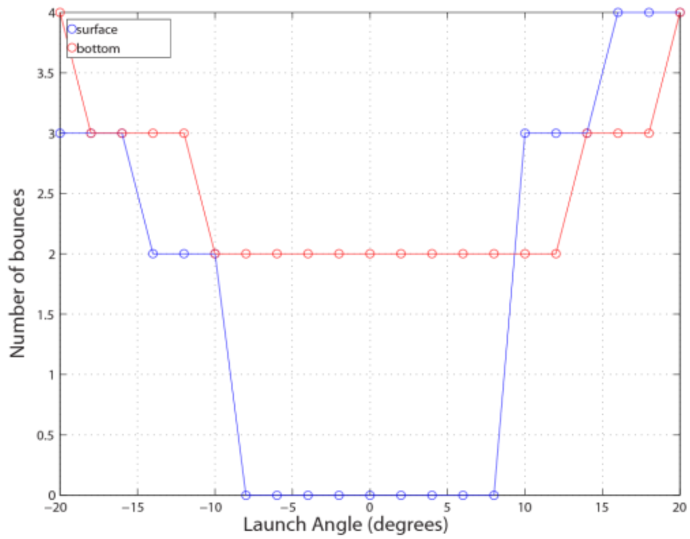


Figure 4: This figure shows the number of bounces as a function of launch angle for the constant depth environment.

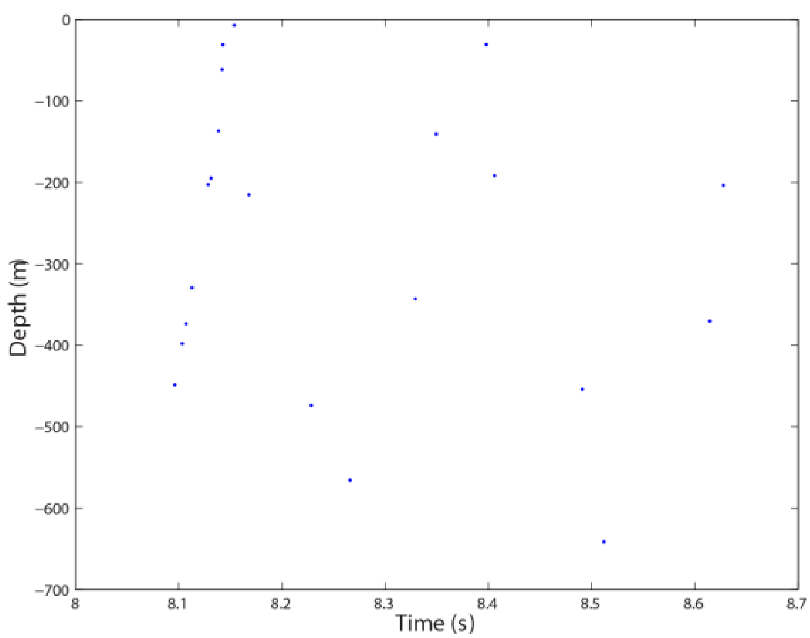


Figure 5: This figure shows the depth of received ray with respect to the travel time of that ray for the constant depth environment.

These graphs show similar characteristics, but are not entirely the same. When comparing the two sets of data it can be seen that simple environment had more rays that did not interact with the surface of the water at all, even after interacting with the floor.

<u>Time Reversal - Ray Simulations</u>

Reversing the ray simulations required editing of the original code. The environment was reversed, the launch angles were changed to the received angles that are reflected about the vertical axis, and the source depth was changed to the received ray depth locations. The time reversal simulations were performed with the simpler of the two environments. These simulations returned the same type of values that the forward simulations returned which makes the two simulations easily compared.

Figure 6 compares the two simulations by showing the difference in travel time of the forward simulation and the backward simulation of the rays on the x-axis and the difference between final depth of the reverse simulation and the source location on the y-axis. A graph that depicted a perfect run would have all of the data points at the origin of the graph. Figure 6 shows that the time reversal simulation returned values within 3 meters of the original source depth while also showing that the rays arrived within 0.6 milliseconds of their expected travel time.

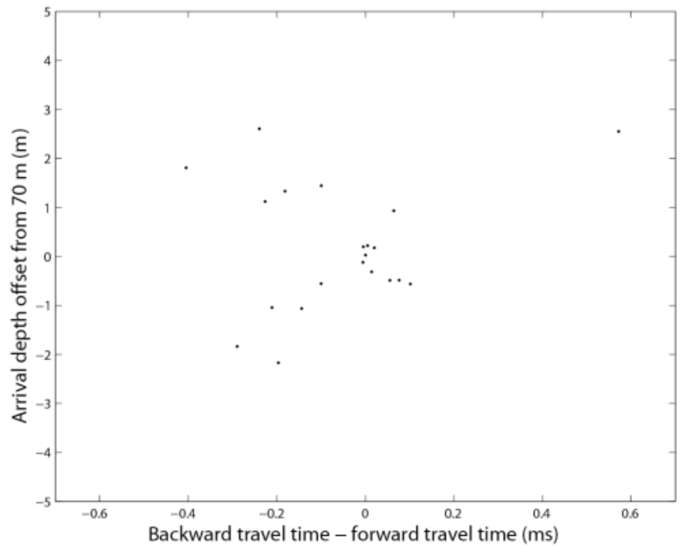


Figure 6: This figure shows the difference of arrival depths compared to the difference in travel times for each ray.

When the rays bounce off of the ocean floor they produce a grazing angle. A grazing angle is the angle that a ray forms with the ocean floor when it interacts with it. The grazing angles for each ocean floor interaction for every ray were collected and put into a histogram which shows the frequency of each grazing angle compared to all of the others. Figure 7 shows the grazing angle histogram for the constant depth environment. The range of grazing angles regarded as significant in an attempt to mimic acoustic bottom loss to a solid with an equivalent fluid will be based on this result.

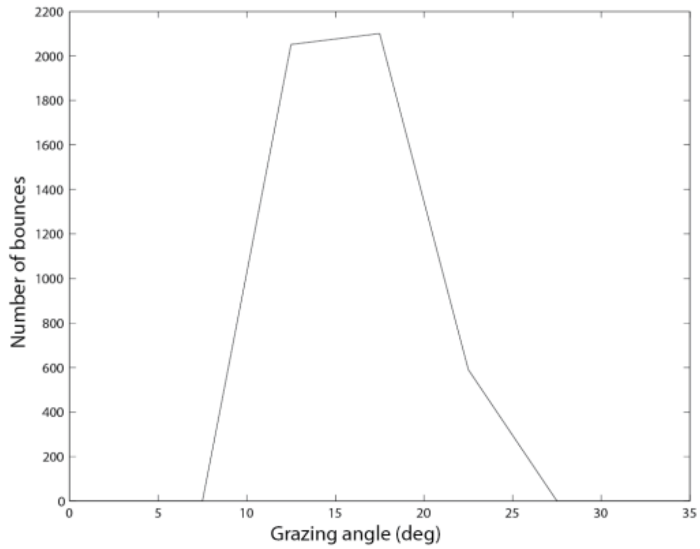


Figure 7: This is the grazing angle histogram.

Equivalent Fluids

Once the grazing angle histogram was formed it was decided which interval of angles would be most important when producing an equivalent fluid. This interval was then entered into a program along with the density of the ocean floor, the sound speed through the ocean floor, and the shear speed through the ocean floor. The interval of angles that was decided to be most important for the simple ray simulation is 8-28 degrees.

The equivalent fluid was found for two different types of ocean floor, one that closely mimics dense volcanic basalt and one that mimics muddier ocean floor similar to the one of the Gulf of Mexico. The process used to find the equivalent fluid approximation for the two floor substances involved performing a curve fit of bottom loss to grazing angle for the interval of grazing angles deemed most important as seen in Figures 8 and 9 then generating a complex density based on the curve fit.

	Actual Values			Equivalent fluid		
	Density $\frac{kg}{m^3}$	Sound Speed $\frac{m}{s}$	Shear Speed $\frac{m}{s}$	Real Part of Density $\frac{kg}{m^3}$	Imaginary Part of Density $\frac{kg}{m^3}$	Effective Sound Speed $\frac{m}{s}$
Volcanic Basalt	2100	2200	1100	2250	500	5000
Gulf of Mexico	1700	1700	600	1750	250	1200

Volcanic Basalt Equivalent:

Equivalent fluids are determined on the basis of bottom loss. Bottom loss is the amount of energy lost to the seafloor when acoustic energy interacts with it. It can be seen in Figure 8 that the equivalent fluid closely mimics the energy lost to the bottom of the actual solid for the grazing angle interval of 8-28 degrees.

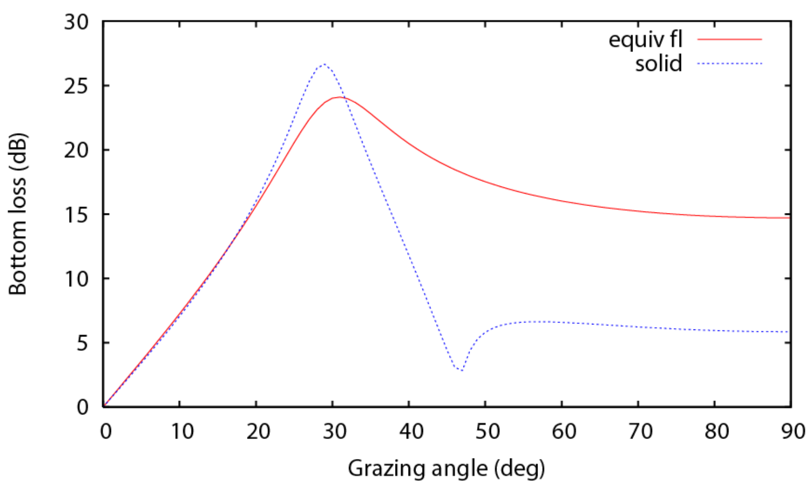


Figure 8: This figure shows energy lost to the bottom as a function of grazing angle.

Since the reflection coefficient is a complex number, it has both a magnitude and a phase. The fit is determined on the basis of the magnitude of bottom loss[4]. The phase of the equivalent fluid reflection coefficient may differ from that of the elastic solid. The absolute value of the phase errors associated with the volcanic basalt was considerable above 15 degrees which can be seen in the following Figure 9.

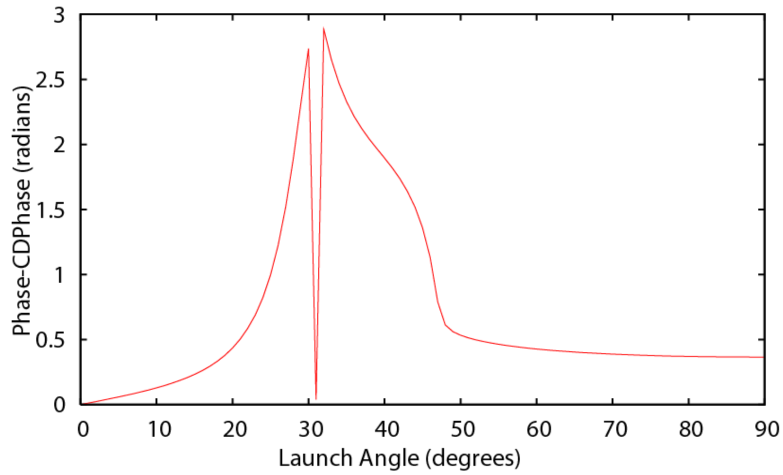


Figure 9: This figure shows the phase error as a function of grazing angle.

Gulf of Mexico Equivalent:

Similar to Figure 8, Figure 10 shows a comparison of the equivalent fluid approximation for the Gulf of Mexico equivalent compared to the actual solid seabed when measuring energy lost to the bottom.

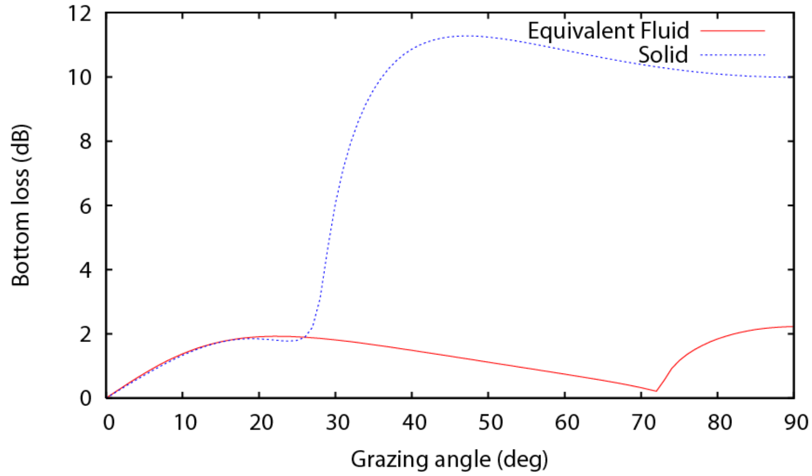


Figure 10: This figure shows energy lost to the bottom as a function of grazing angle.

The absolute value of the phase errors associated with the Gulf of Mexico was considerable above 20 degrees which can be seen in Figure 11.

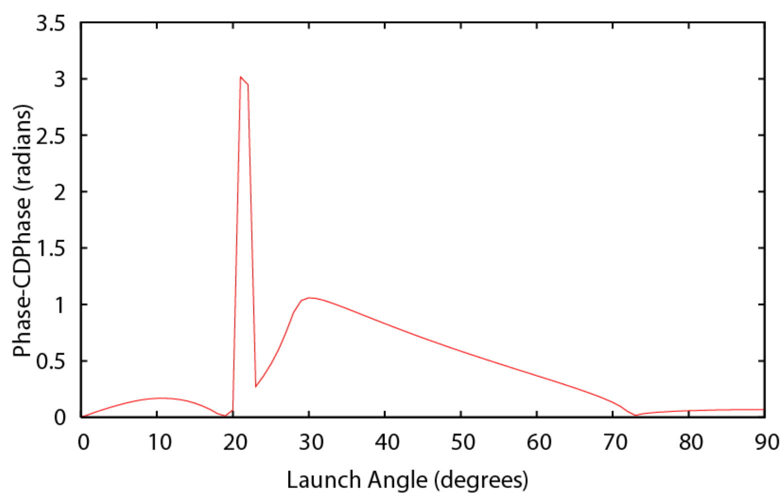


Figure 11: This figure shows phase error as a function of grazing angle.

Time Reversal - Wave Simulations

Reversing wave simulations was similar to reversing ray simulations in that the original code had to be edited to perform as desired. Wave simulations work by advancing a wave front through a specified environment using a wave equation; the strategy involves taking the wavefront received and using it as the source of sound in an environment that is reversed.

Using parameters based on an ocean floor comprised of volcanic basalt, the following graph was obtained where the vertical axis is depth, the horizontal axis is arrival time, and the color represents intensity which is on a 30dB dynamic range scale:

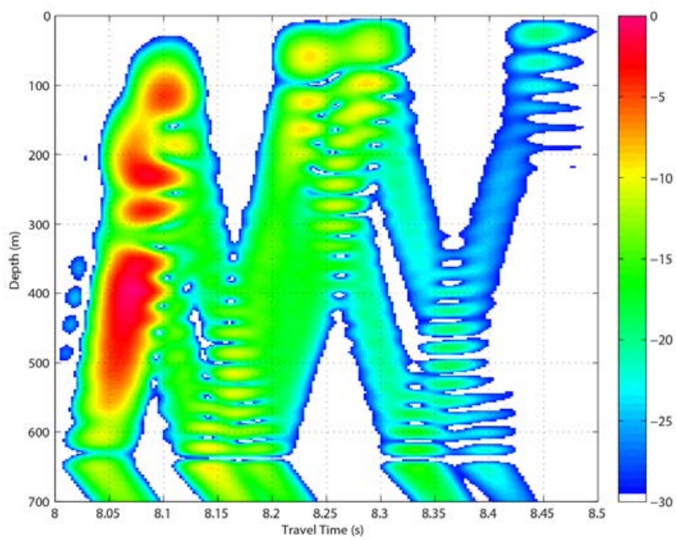


Figure 12: This figure shows the arrival wave front for a forward simulation. This wave front was formed from a source that was 150m deep; the final wavefront was then used with the edited wave time reversal code to obtain a similar plot:

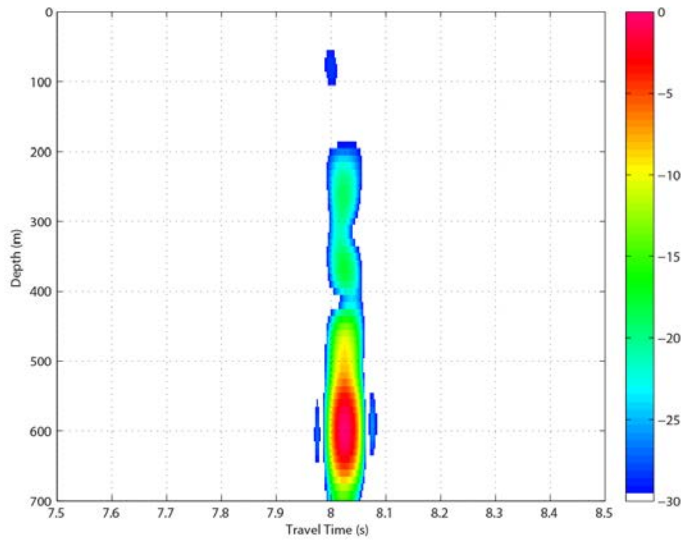


Figure 13: This figure shows the arrival wavefront for a reverse simulation.

This plot shows localization of the sound at around 600m when using time-reversal.

Chapter 5: Discussion

The findings suggest that it is possible to use equivalent fluids with time reversal, but there is error that is introduced. It can be seen in the phase error comparison graphs that the error is non-negligible between the real density and the complex density phase comparisons, thus showing that the phases of a wave would be changed by a maximum of about 3 radians from what it should be when interacting with the seafloor; since 3.14 radians of phase constitutes half of a cycle, the maximum possible error would be 3.14 radians. Also, when inspecting Figure 13, it can be seen that the sound energy localized at a location that was around 450m deeper than that of the source. Based on Figures 12 and 13, this study shows the ability to trace received signals back to their range accurately, but not the ability to locate the source depth. The fact that the range was correctly identified is seen by the localization of the reversed signal in travel time.

Although a definite conclusion cannot be drawn from the data, the data does allow for the inference of which seabed material will return the most accurate results. When comparing the phase errors of the volcanic basalt material to the Gulf of Mexico material it can be inferred that the softer Gulf of Mexico material will return more accurate results, as a whole, for grazing angles less than 20 degrees. One way that could increase the accuracy of the equivalent fluid is to more accurately estimate the interval of grazing angles that the fluid is calculated for; this will give the calculations less room for error when the new bottom is being calculated.

The accuracy of time reversal in ray simulations is easily evaluated as can be seen in Figure 6. Figure 6 shows an error of around 3 meters for the arrival depth and around .6 milliseconds for the arrival time. This error can be attributed to the way the rays are propagated forward with differential equations. The computer program solves the differential equation with a numerical method which could be why error is present.

A different way that could be useful for time reversal of waves in shallow water could be to calculate the equivalent fluid based on the phase of the reflected wave. Since the equivalent fluid is currently designed to be calculated such that the amount of sound energy lost to the ocean floor is accurately predicted, the calculation method could be edited so that the phase is accurately predicted instead.

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