EVALUATION OF AN AUTONOMOUS UNDERWATER VEHICLE FOR ACOUSTIC SURVEYS, INVESTIGATION OF 3D PROPAGATION EFFECTS AT THE NEW JERSEY SHELF BREAK FRONT AND ACOUSTIC BACKSCATTER IN CONTROLLED WATER WAVE FIELDS

BY

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This study is comprised of three sections. The first section examines the feasibility of acoustic surveys using an autonomous underwater vehicle to tow acoustic arrays. Particularly the study will focus on the Webb Research Slocum underwater glider. The acoustic data will be analyzed for background noise and compared in time to the actions of the glider during the experiment. The comparison shows while actions of the glider do cause significant noise, the resultant noise happens are predictable times in the mission. The second section of this study will investigate the underwater 3D propagation effect known as the 'horizontal Lloyd’s mirror' at the New Jersey shelf break front. This effect is characterized by a doubling of sound intensity level resulting from sound totally internally reflecting off the shelf front at low grazing angles. Modeling shows there is potential for the Lloyd’s mirror effect to occur at the New Jersey shelf break front and this research sought to explore this effect using experimental data collected off the coast of New Jersey during the Shallow Water 2006 Experiment (SW06). Analysis of the data showed an increase in sound intensity level as the distance between the source and receiver increased from approximately 28.2 km to 34.7 km, which the modeling also supported. The third section will focus on characterizing the acoustic backscattering from the water surface in relation to the surface conditions. A scaled experiment was conducted in a wave tank using a 18kHz omnidirectional source to examine acoustic surface backscatter resultant from different surface wave conditions created by a wave maker. The acoustic returns were analyzed for time of arrival differences between the direct surface reflected signals. Modeling was developed based upon work by Godin, Fuks and Charnotskii, with probability distribution functions (PDFs) of acoustic propagation travel time and acoustic intensity dependent on rough surface slope and elevation. The experimental results matched
trends of the PDFs and with further experimentation the surface conditions can be inferred from the acoustic backscattering.
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Lastly I would like to thank my parents and friends for their love and support through the past two years, along with my boyfriend who without his help and encouragement I would have lost my sanity.
I wish to dedicate this thesis to my parents who have provided so much love and support over the years.
PREFACE

This thesis is written in manuscript format, with three separate sections. The first section is an acoustic survey with autonomous underwater vehicles, the second is 3D propagation effects at the New Jersey shelf break front and the third is acoustic backscatter in controlled water wave fields. All three sections incorporate theoretical and experimental work in the field of underwater acoustics.

The first section is a feasibility study of a Slocum underwater glider for acoustical surveys. A simple experiment was designed where the glider towed a passive hydrophone off the coast of New Jersey with a stationary acoustic source deployed off the side of a ship. The increases in background noise were compared to the mechanical actions of the glider. Overall the glider was found to have good potential as a tool for acoustic surveys because the noise sources of the glider were predictable and not constant.

The second section is an investigation of the 3D propagation effect, the horizontal analogue to the Lloyd’s mirror effect, during the Shallow Water 2006 (SW06) Experiment at the New Jersey shelf break front. Data was collected with ship-towed acoustic source, a J15 transmitting at 93 Hz, and a stationary receiver, the Woods Hole Oceanographic Institute Vertical Line/Horizontal Line array. The data was analyzed for increases in the noise level and compared to modeling using the normal modes modeling program, KRAKEN. Bathymetry from the experimental area was incorporated, along with the location of the shelf break front and an internal wave packet into a 3D KRAKEN model. The results of the data analysis and modeling show Lloyd’s mirror effect was most likely present during the SW06 Experiment.

The third section is a study characterizing the acoustic backscatter from controlled water wave fields in a scaled experiment. A scaled experiment was con-
constructed in the URI Ocean Engineering Department wave tank, using a bottom mounted acoustic source and receiver, wave gauges to measure the wave field concurrently with the acoustic recordings, and the wavemaker producing scaled regular and irregular wave fields. The wave fields were scaled from ocean surface gravity waves, with the regular wave fields using average values of the Pierson-Moskowitz sea states and the irregular wave field a JONSWAP sea spectra. Modeling was based upon work by Godin, Fuks and Charnotskii[? using a geometrical approximation to develop probability distribution functions (PDFs) of the acoustic travel time and acoustic intensity. Histograms of the measured acoustic travel times and acoustic intensity were compared with modeled results. It was concluded the geometrical approximation provided a means to estimate sea surface conditions via changes in the acoustic travel time and normalized acoustic intensity PDFs.
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Evaluation of an Autonomous Underwater Vehicle for Acoustic Surveys

1.1 Abstract

Acoustic data was collected on a single hydrophone towed by a Webb Research Slocum glider deployed by Rutgers University off the coast of New Jersey. A ITC-515 source was deployed off the side of a stationary ship, transmitting a 1.75 kHz signal with a source level of 147 dB re 1µPa at a depth of approximately 12 m in 14 m deep water. The glider flew perpendicular to and behind the ship by approximately 2 km and alongside the boat with about the same distance between the glider and boat. The intent of this study is to examine whether the Slocum glider is an adequate platform for acoustic remote sensing. Acoustic data from the glider-towed receiver was analyzed and compared in time to engineering data from the Slocum glider. Significant noise sources from glider were identified in the acoustic recordings. The increases in noise level by the glider occur at predictable times, and there are large sections where the glider contributes very little noise, leading one to conclude of the glider has potential as an acoustic survey platform.

1.2 Introduction

In recent years autonomous underwater vehicles (AUVs) are becoming popular as a useful tool in acoustic experiments. The AUVs have the capability to tow hydrophone arrays into locations and depths that ship-towed arrays have not been able to go. However, many of the AUVs have some drawbacks in terms of the noise level they generate and limited autonomy. The lack of true autonomy varies with the different models but the common restraint is the duration the AUV, with reasonable reliability, can follow a programmed mission.
This study examines an AUV with a lower noise level and a higher degree of autonomy for use in acoustic experiments. The Slocum underwater glider, developed by Webb Research Corporation [1] was chosen because it was believed to have a lower noise level and was capable of handling autonomous missions lasting for up to 30 days. With help from Rutgers University Coastal Ocean Observing Lab personnel and their fleet of Slocum gliders, deployments were planned using one of their gliders to tow a bioacoustic probe on short and longer missions to study the ability of the glider to tow equipment and to conduct a noise analysis.

Results from the glider-towed probe experiments showed the potential of the Slocum glider to tow acoustic receivers for prolonged periods. The potential noise sources on board the Slocum glider were identified and the acoustic recordings were analyzed for their acoustic signatures. The analysis showed the higher noise levels associated with the glider occur at predictable times and durations, leaving appreciable amounts of time with very little noise interference in the acoustic record. Therefore the Slocum underwater glider provides a useful platform for AUV-towed acoustic experiments.

1.3 Experiment Description

The aim of this study is to determine whether the Slocum underwater glider is capable of towing a hydrophone array for a prolonged period with minimal interference in the glider flight pattern and with acceptable noise levels. Experiments were proposed using one of the Webb Research Slocum underwater gliders to tow a bioacoustic probe made by Greeneridge Sciences, Inc. The bioacoustic probe is a small, compact, and water-tight unit that contains a passive hydrophone, pressure sensor, temperature sensor and a two dimensional accelerometer, commonly used to tag marine mammals to record their travel and sounds (see Figure 1). In addition to the acoustic signals, the probe also records the flight of the glider through
the pressure, temperature and accelerometer sensors. The slocum glider carries a sensor package which contains conductivity, temperature and depth sensors. There also is a compass and an altimeter onboard that record the direction and elevation of the glider. By analyzing the accelerometer of the bioacoustic probe along with the compass, altimeter, the activity of the fin, and movement of the battery pack in the Slocum glider, the effect of towing an array on the glider’s flight path can be determined.

Figure 1. Greeneridge Sciences bioacoustic probe with the different internal components indicated.[2]

The University of Rhode Island Department of Ocean Engineering owns a bioacoustic probe but did not have an available Slocum glider. A partnership with Rutgers University’s Coastal Ocean Observing Lab was formed, as they had a fleet of Slocum gliders which are used to frequently monitor the environmental conditions off the coast of New Jersey. Rutgers University gave URI the opportunity to test attachment methods for towing the bioacoustic probe and to conduct an acoustic survey with one of their Slocum gliders.

The first attachment method was to connect the bioacoustic probe directly to the back shaft near the fin of the glider. As the glider does not use a propeller for propulsion, but instead rides the underwater currents in a see-saw pattern from surface to bottom, there is only a small motor that runs the fin. The small fin
motor is quiet compared to the propellers in most other AUVs. A trial run with the bioacoustic probe directly mounted to the rear shaft showed that the fin motor is still too noisy acoustically for the probe to be so close and coupled through the shaft. The second attachment concept involved towing the probe behind the glider at a distance of 1-2 m. A few different attachment methods were proposed, and the best proved to be a rigid pole mount for the bioacoustic probe, with a cord attaching the pole to the back of the glider (see Section 1.4).

A trial run with the pole attachment was conducted during the Shallow Water 2006 (SW06) Experiment off the coast of New Jersey. The attachment method was secure but the bioacoustic probe failed to record any significant data. From the small amount of data recorded, it was determined that the pole was contributing to the acoustic noise. Another experiment was proposed with a Rutgers University Slocum glider in late April 2007. A new bioacoustic probe attachment pole was designed and built to reduce noise contributions. The experiment was designed to have a glider-towed hydrophone listening to a stationary source deployed from a vessel. The glider would move away from the boat by a few kilometers, flying perpendicular to the boat for the first leg of data collection and parallel for the second part, as depicted in Figure 2. The reason for the glider flying perpendicular and parallel to the acoustic source is in case of ship noise. The original concept for this experiment had the ship with the acoustic source moving, which would result in propeller noise behind the ship. When the plan switched to a stationary vessel the path of the glider was not altered.

The acoustic source used in the experiment was an International Transducer Corporation (ITC) 515, with an optimum frequency of 2 kHz and a transmit voltage response (TVR) of 143 dB re 1 µPa/Volt at one meter. For marine mammal safety the sound level (SL) was not allowed above 160 dB re 1 µPa at one meter. Using
Figure 2. The geometry of the glider’s path relative to the ship-deployed acoustic source on the April 25, 2007.

the relationship between TVR and SL:

\[ SL = TVR + 20 \log(V_{in}) \]  

where \( V_{in} \) is the voltage applied to the source. The frequency of 1.75 kHz was selected for the lower sampling frequency required of the processor onboard the bioacoustic probe. The TVR at 1.75 kHz is approximately 138 dB. The source was given 1 volt of power, along with a gain of 3.5, resulting in an input voltage of \( V_{in} = 3.5V \). That yields at SL of 148 dB re 1\( \mu \)Pa. The acoustic source was deployed at a depth of 12 m in a water depth of 14m. The glider with bioacoustic probe in tow was deployed first and allowed to get approximately 2 km behind the ship. The acoustic source was then lowered over the side of vessel and given a 1 V CW signal at 1.75 kHz with a gain of 3.5. The sound intensity level of the signal can be calculated using the passive SONAR equation:

\[ SIL = SL - TL \]  

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At distances between 1-2 km the SIL is between 115-120 dB re 1 µPa.

where SIL is sound intensity level, SL is sound level and TL is transmission loss. For transmission loss the cylindrical geometrical spreading assumption is used, and transmission loss due to absorption and scattering are neglected. The geometrical spreading transmission relationship is:

\[ TL = 10 \log(r) \]  

where \( r \) is the radial distance from the source. Figure 3 shows the theoretical sound intensity level over distance, illustrating an intensity level of approximately 115-120 dB re 1 µPa at 1-2 km from the source.

After the deployment the data from the bioacoustic probe and Slocum glider was downloaded and compared. Since the purpose of this study is to identify the noise sources on board the glider and determine if the noises arrive at predictable intervals, the acoustic and engineering data were aligned in time.
1.3.1 Hydrophone: Bioacoustic Probe

The passive hydrophone used in this experiment is onboard the bioacoustic probe developed by Greeneridge Sciences, Inc. The bioacoustic probe consists of multiple sensor systems in a relatively small, water-tight package (see Figure 1). The probe runs off battery power and has its own internal processor and memory storage. These features make the probe ideal for autonomous remote sensing. The probe has a passive broadband hydrophone, pressure sensor, temperature sensor, and a two-axis accelerometer. The probe’s original intended function is as a marine mammal tag, where it is attached to a marine mammal in order to record their vocalizations, environmental noise, and movements. These functions of the bioacoustic probe are well suited for the purposes of this study as the interest is in the glider noise and ability to tow an acoustic instrument. The accelerometers provide a measurement for how smoothly the probe is towed by the glider, and the pressure and temperature measurements help verify the path of the glider.

The hydrophone is limited in frequencies it can record by the sampling frequency capability of the processor onboard the probe. Currently the bioacoustic probe can record a signal up to 7.4 kHz as its highest sampling frequency is 20 kHz[2]. The water temperature affects the sampling frequency the probe can sustain, where in colder temperatures the battery may not be able to maintain an output voltage to keep the probe active. At temperatures under 10°C the probe can go to sleep prematurely reducing the amount of data stores from full capacity at 1.0 GB to 100 MB[2]. The reduction in memory results in a reduction in the sampling frequency the system can sustain for longer periods of time. With a memory of 1.0 GB the probe can record 500 million data samples. At a sampling frequency of 4096 Hz the recording duration is 33.9 hrs. However at cold temperatures the recording duration for the same frequency could be as low as 3.39
Figure 4. Temperature recorded on the bioacoustic probe during deployment.

In this experiment the temperature was below 10°C, as depicted in Figure 4. Accordingly the bioacoustic probe shut down earlier in the mission than expected due to the cold water temperatures. At approximately 2.2 hrs the probe turned off due to receiving insufficient power to sustain data recording. However, the problem is not the battery itself, as the battery tested immediately after the probe was recovered still had full charge. The other electronic components which relay the battery power to the different applications within the probe are sensitive to temperature and cause the probe to shut off prematurely in cold temperatures.

The original plan was to use 2 kHz as the acoustic frequency with a sampling frequency of 8192 Hz. However, during the tank tests the probe would fail shortly after initializing. The sampling frequency had to be scaled back to facilitate greater recording durations. A new sampling frequency of 4096 Hz was chosen and the source signal frequency was reduced to 1.75 kHz in order to be less than half of the sampling frequency. The pressure, temperature and accelerometer channels sample at a rate of 1 Hz.
1.3.2 Slocum Underwater Glider

The Slocum underwater glider is an AUV designed and manufactured by Webb Research Corporation. The Slocum gliders are unique compared to other AUVs because they do not use a propulsion system. Instead the glider uses internal buoyancy control mechanisms and wings to glide through the water in a saw-tooth pattern in the vertical plane. A small fin is used in tangent with a internal compass to maintain a heading. The glider dives in a saw-tooth pattern by sliding its battery package forward, pitching the nose of the glider down, and ascending by sliding the batteries backward, raising the nose. The glider will also take one water ballast in the front noise cone in a small open chamber for a descent and push the water ballast out with a volume piston for an ascent.

The glider’s propulsion system demands much less power which allows for deployments that can cover distances greater than 1500 km, with durations longer
than thirty days and diving depths of 200 m. These features make the glider an ideal autonomous remote sensing platform, along with its ability to communicate via an iridium phone every time it surfaces. The glider can transfer data and receive new missions, through this iridium communication link. The glider allows for customized science payloads, which contain sensors to measure different environmental parameters in the water. For our experiment the glider had a science bay with an onboard CTD (conductivity, temperature and depth) package.

1.3.3 Glider-Towed Hydrophone System

Previously the Slocum glider has not been commonly used to tow acoustic devices, however there is one notable study with a glider-towed hydrophone array that took place off Hawaii[3]. After studying the glider’s propulsion and flight pattern, the best attachment method that interfered least with the glider’s dive patterns and lateral movements was a neutrally buoyant rigid pole. The tow rod was 3/4” Polyvinyl Chloride (PVC) pipe one meter in length with the bioacoustic probe mounted at one end and counterweighted at the other end to ensure balance and neutral buoyancy. The rod was attached to the glider by 300 lb test nylon rope to minimize vibrations from the glider being coupled to the probe.

A test during the SW06 Experiment with a Rutgers University glider towing the probe-tow rod system for two weeks in duration proved that the attachment method was successful. The extra drag of the tow rod and bioacoustic probe do cause the glider to have to compensate in water currents and dives, but the glider was still able to successfully complete a mission.

The glider acoustic survey experiment was conducted off the coast of New Jersey on April 25, 2007. Figure 6 shows the tow rod attached to a Rutgers University Slocum glider with the bioacoustic probe mounted on the end.
1.4 Noise Sources On Board the Glider

The Slocum glider has a few internal sources of noise that could contribute to the background noise received by the probe. The main sources of noise are the (1) fin steering, (2) movement of the battery, (3) volume piston and (4) air pump. There is also mechanical and flow noise associated with the movements of the fin. The fin is on for a majority of the time during a mission. The battery which slides forwards and backwards when the glider descends and ascends respectively has the potential to add noise. The volume piston moves a small amount of water in and out of a port in the nose cone in order to provide the dynamic moment for changing pitch to dive or ascend. The air bladder is located in the rear of the glider and serves to raise the back end of the glider out of the water while at the surface and communicate via iridium. The iridium sensor is located in the back tail section as shown in Figure 5.
In order to determine whether these noise sources are present in the acoustic record, the recorded data of the activity of the different possible noise sources was compared to the acoustic record in time. First a small segment of a glider mission is examined, comparing the motion of the glider with the actions of the potential noise sources. Figure 7 demonstrates the actions of the air pump, steering fin, battery movement and volume piston in conjunction with the glider’s saw-tooth dive pattern with the bioacoustic probe in tow. The black line represents the glider’s dive path, the red marks represent the commanded actions sent to the various components of the glider and the blue marks are the measured values of the actions taken by the various components.

1.4.1 Air Pump

The air pump consists of a rubber air bladder in the tail cone which serves to provide additional buoyancy at the surface to raise the tail section with the antenna out of the water for communications. The tail section is flooded during deployment, so the air is pumped from the mid-hull interior, providing up to 1400 ml of buoyancy. The air pump mechanically switches off when the differential pressure between the bladder and internal hull become 6.25 PSI[4]. Since the pump only operates at the surface, as shown in Figure 7, it is unlikely to affect the acoustic data.

1.4.2 Fin Steering

The fin is located the most aft on the Slocum glider and acts as a rudder. During a mission the onboard computer has a pre-programmed course to follow, which it monitors with compass headings and uses the fin to correct the glider’s course. The fin can move up to 45 degrees laterally[1]. As seen in Figure 7 the fin is predominantly at 0.6 radians (approximately 34.4 degrees), indicating the glider
Figure 7. Comparison of actions taken by potential internal noise sources (air pump, fin steering, battery movement, and the volume piston) in a Slocum glider during an earlier deployment. The red lines represent the commanded actions, blue the measured actions and black is the glider’s dive path.
was correcting for a strong stable current. If the fin steering affected the acoustic recording, the noise effects would most likely appear at the change from neutral position. The computer commands the fin to move to a set position, which the fin will maintain until given another command. So other than flow noise, the fin and its motor should not have affected the acoustic record significantly during this mission.

1.4.3 Battery Movement

The Slocum glider uses an 8.4 kg battery pack which can move along a rod inside the mid-body of the glider to trim to the desired dive or ascension angles. The battery pack is driven forward or backward by a lead screw, acting as a vernier[1]. Figure 7 shows that although the battery pack is commanded to make a smooth motion from fore to aft and back, in reality it moves in steps. The step-like motion could cause a click to appear at the end of each step. The lead screw may also be able to create noise where the bioacoustic probe can pick up.
1.4.4 Volume Piston

The volume piston is located in the front nose cone of the glider. The piston serves to take water in and out of the glider as ballast for diving and ascending by operating a small pump. The pump is operated by a 90 watt motor and rolling diaphragm seal, and can pump up to 504 cc of sea water in or out of a 12 mm diameter port in the nose cone. The pump was commanded to change the volume of the port abruptly as seen in Figure 7, and the measured values reflect that as well. The movement of the piston and seal, along with the venting or drawing of water quickly have the potential to show up in the acoustical record.

1.5 Acoustic Analysis

Taking an initial look at the acoustic signal the bioacoustic probe recorded, Figure 9, there is apparent background noise most likely due to the environment and flow noise, but there are also spikes in the noise level at regular intervals. During the first hour of recording the glider was being tested for mission soundness, so the ITC-515 source was not activated and there was a lot of background noise due to the glider testing. The boat provided a lot of noise initially, and the glider spent a lot of time near the surface where the waves slapping against its body would have added to the noise level.

The 1.75 kHz source comes on about 1.5 hrs into the glider deployment. The glider then begins its mission of a sawtooth pattern behind and alongside the ship staying 1-2 km away. The record ends at approximately 2.2 hrs because the low temperatures caused the probe to turn off. As a result almost 2 hrs of the glider mission was not recorded. However the 45 min of data that was collected provided valuable insight into the noise sources on board the glider.

In Figure 10 the 45 min of the mission are focused on, along with the potential noise sources. The spectrogram in the upper portion of the figure shows four
Figure 9. Spectrogram of the acoustic recordings from the bioacoustic probe on April 27, 2007. The colorbar indicates sound pressure level in dB re 1\(\mu\)Pascal. The time axis is the duration the probe collected data.

distinct spikes in noise level corresponding to the saw-tooth motion of the glider, portrayed by the black line. The noise is fairly consistent as the glider descends except for a large, brief gain at the bottom of the glider’s descent, followed by a relatively noise-free ascent towards the surface.

1.6 Discussion

Previously the activities of the air pump, fin steering, battery movement, and volume piston have been analyzed for potential to affect the glider’s ability to conduct an acoustic survey. The air pump would seem to be an unlikely candidate because it should only activate at the surface and the noise of interest occurs on the descent. The fin would also seem to be an unlikely source of noise, as it was locked in one position for most of the mission. That leaves the battery and volume piston as probable sources of noise.
Figure 10. The upper plot is the spectrogram taken from bioacoustic probe recordings during the April 27, 2007 glider deployment compared with the glider’s path and internal potential noise sources. The time axis is different from Figure 9 as this is the glider’s mission time and there was a time offset between the two. The 1.75 kHz signal can be seen from 2.62-2.9 hrs between 100-120 dB re $1\mu$Pascal, along with various background noise from 80-140 dB re $1\mu$Pascal. The lower plot has the actions of the air bladder, fin, volume piston and battery correlated in time with the acoustic recordings.
Looking more closely at the bottom part of Figure 10 where the actions of the noise sources are shown, the fin steering and volume piston correspond in time to the increases in noise level. However, the increases in noise do not appear to fit well with the pattern of movement by the fin. The increases in noise correspond with lateral fin movement only in one direction, in the opposite direction there is no reaction in the acoustic record. The Rutgers University gliders are very well maintained, so there should not be a mechanical reason for the fin steering to be noisy in one direction and quiet in another. That leaves the volume piston as the likely source of noise.

As the glider descends the volume piston takes in water to the front nose cone in order to ballast the glider for diving. The diaphragm would have slid aft in the nose cone to allow the water in, which supposedly leaves the 12mm diameter port open. This could create flow noise as the glider dives with this open port. When the glider reaches the furthest extent of its dives the volume piston is commanded to move from the furthest extent back to the forward position quickly. That would cause the diaphragm to shove forward quickly, expelling the water from the port and sealing it shut in order to ascend. At the turning point in the bottom of the dive there is a sharp spike in noise level. The quick motion of the piston and diaphragm pressing forward and expelling water could create a loud noise, and the events correspond in time with the sudden increase in noise level.

1.7 Conclusion

In conclusion out of the air bladder, fin steering, battery movement and volume piston, it appears that the volume piston is the likeliest source of noise during dives of the glider. When the glider is at the surface there is significant noise possibly from waves striking the glider body, but during the underwater dives the ascending portions are relatively quiet. The descending dives have a fair amount of noise with
a sharp spike in intensity at the bottom of the dive.

After comparing the actions of the volume piston in time with the noise level in the acoustic data, the volume piston had the best correspondence. The open port in the nose cone during the dive corresponds to the consistent level of noise and the quick forward movement of the diaphragm to eject the water stored in the port for ascension would coincides with the sharp spike in sound.

Although the volume piston appears to cause significant noise, the lack of noise during the ascension would mean half of the glider mission would be quiet enough for an acoustic survey. Even the descending portion of the dive is useable as long as the frequency is above 500 Hz.

List of References


3D Propagation Effects at Shelf Break Front

2.1 Abstract

The shelf break front is a dynamic feature common to continental shelves. The front affects the acoustic propagation in many ways; 3D effects have been estimated to reduce transmission loss by more than 6 dB[1], and mode coupling at the front can complicate propagation across the front. The fronts themselves can vary in location by tens of kilometers, thus varying the 3D effect produced by the horizontal Lloyd’s mirror effect along the shelf break front. Previous research has reported an approximate 5.5 dB increase in noise level at a receiver close to the shelf break off New Jersey versus a receiver further inshore during the 1995 Shallow Water Acoustics in Random Media (SWARM) experiment[2]. In the present study signals recorded on the WHOI vertical line/horizontal line hydrophone array (VLA/HLA) from a ship-towed J15 source during the Shallow Water Experiment (SW06) on the New Jersey Shelf were analyzed for 3D propagation effects. The results of the analysis are compared with modeling of the 3D acoustic propagation using the Kraken normal mode model with the environmental parameters of the New Jersey Shelf and J15 source. Analysis of the acoustic recordings of the ship-towed J15 source is consistent with the modeling results, and the results show evidence for the horizontal Lloyd’s mirror effect.

2.2 Introduction

In order to investigate the 3D propagation effects an experiment was conducted during the Shallow Water Experiment (SW06) on the shelf break off the coast of New Jersey. Signals were recorded on the Woods Hole Oceanographic Institution’s vertical line array/horizontal line array (WHOI VLA/HLA) from a
ship-towed J15 source, using a simple CW tone at 93 Hz and a source depth of approximately 50 meters. The signals were analyzed for the presence of the horizontal analogue to Lloyd’s mirror effect, i.e. fronts can totally internally reflect sound incident upon them at low grazing angles. The direct and reflected modal rays can constructively interfere which has the potential to increase the intensity level by 6 dB. There is also the potential for greater reductions in transmission loss due to the presence of an internal wave packet that travelled to the west of the shelf break front and the J15 source during the experiment. The trapping of sound between the shelf break front and an internal wave packet may reduce transmission loss by 10 to 20 dB[3].

The object of this study is to verify the potential of Lloyd’s mirror effect at the New Jersey shelf break using modeling and determine if the effect is observable using data collected from the shelf break. The modeling will be completed with the KRAKEN normal mode model[4] using the environmental parameters of the New Jersey shelf. KRAKEN will calculate probable locations along the shelf break where the acoustic modal rays reflect off the shelf break boundary and create potential locations for constructive interference that can reduce the transmission loss appreciably. The collected acoustic data will be analyzed for reductions in transmission loss and compared to the modeling results.

2.3 Horizontal Analogue to the Lloyd’s Mirror Effect

The classical Lloyd’s mirror effect is an optical effect published in 1837 by Humphrey Lloyd. Lloyd designed an experiment to illustrate the interference pattern of light from a monochromatic source reflected on a glass surface at small angles of incidence that appear to also have a virtual source. The classical Lloyd’s mirror effect creates interference in the vertical (r-z) plane of the direct and surface reflected paths, producing a dipole radiation pattern. Figure 11 demonstrates the
basic setup of a Lloyd’s mirror effect experiment in the vertical plane. A laser emits light rays, some of which directly strike the screen and other rays at small angles reflect off the mirror (glass) surface to strike the screen.

![Diagram of a Lloyd's mirror effect experiment](image)

Figure 11. Geometrical comparison of the Lloyd’s mirror effect (upper panel) and its horizontal analogue (lower panel).

The classical Lloyd’s mirror effect can be applied to underwater acoustics with fronts and non-linear internal waves acting as a mirror. Fronts and non-linear internal waves can totally internally reflect sound incident at low grazing angles[1]. The Lloyd’s mirror geometry will be rotated onto the horizontal (x-y) plane for the underwater analogue. Figure 11 illustrates the rotation in the geometry. This is an overhead view of the horizontal analogue setup, while the classical Lloyd’s mirror effect is a side view. The horizontal analogue has a few differences with a finite critical angle and cylindrical spreading, whereas the classical Lloyd’s mirror effect has total surface reflection at all angles and spherical spreading for point
During World War II an underwater Lloyd’s mirror effect was first noted where a sinusoidal point source near the ocean surface produced an acoustic field with interferences between the direct path and reflected paths, that can be thought of as an above-surface image of the source. The basic geometry is illustrated in Figure 12 where the reflected ray, which can be thought of as coming from a virtual source above the water, will add with the direct ray to yield an acoustic pressure twice the amplitude of the direct ray[5].

Figure 12. Geometry for Lloyd’s mirror effect at surface interface, where $\theta_c$ is the critical angle calculated in Equation 4 and $\alpha_c$ is $90^\circ - \theta_c$ which is referred to as the critical grazing angle.

Similarly, as with the three dimensional effect noted at the ocean surface interface, the horizontal Lloyd’s mirror effect at the shelf is induced by the rapid change in sound speed at the boundary of fronts and internal wave packets. Figure 13 shows an example of the Lloyd’s mirror effect geometry in the horizontal plane, with the front having a sound speed different from the layer just beyond its boundary. The change in sound speed at fronts and internal waves results in a critical angle ($\theta_{\text{critical}}$) which is related to the change in sound speeds ($c_1$ and $c_2$).

$$\theta_{\text{critical}} = \sin^{-1}\left(\frac{c_1}{c_2}\right)$$

(4)
where $c_1$ cannot exceed $c_2$. Angles reflecting off the shelf break boundaries with a grazing angle greater than the critical grazing angle $\alpha_c$ (which equals $90^\circ - \theta_c$) most of the energy penetrates the front and is lost. Below the critical grazing angle the direct and reflected modal rays add with appreciable amplitude, where the sum of the direct and reflected modal rays is expressed as[1]:

$$p_{tot} = \sum_m a_m e^{ik_mR_0} + \sum_m a_m e^{ik_mR_1} R_m(\theta_{graz}) e^{ik_mR_2} \sqrt{k_mR_0 + k_mR_1 + k_mR_2}$$  \tag{5}

In equation 5 the $R_m(\theta_{graz})$ is the plane wave reflection coefficient for each mode $m$ and $R_0$, $R_1$ and $R_2$ are the distances along the path for the direct, frontal incident and frontal reflected modal rays respectively. The coefficient $a_m$ is the local modal coefficient and $k_m$ is the local eigenvalue of the $m^{th}$ mode. The relative x-y plane index of refraction ($n_m$) derived from the local modal eigenvalue is given as:

$$n_m(x, y) = \frac{k_m(x, y)}{k_m(0, 0)} = \frac{v_m(x, y)}{v_m(0, 0)}$$  \tag{6}

where the point (0,0) is an arbitrary origin in the x-y plane, x and y are the horizontal coordinates of interest, $k_m$ is the local eigenvalue of the $m^{th}$ mode and $v_m$ is the local phase velocity of the $m^{th}$ mode. This horizontal index of refraction acts on each individual vertical normal mode, giving each mode a slightly different trajectory in the x-y plane. The reflection is primarily a function of the sound speed difference, which leads to the reflection coefficient becoming small quickly past the critical angle. Figure 13 illustrates the basic geometry of sound reflecting of the change in sound speed at a shelf break front.

For reflection angles less than $\alpha_c$ the oscillations in the acoustic field yield up to a 6 dB increase in the field strength, twice the normal pressure. This is reasonable since the Lloyd’s mirror effect involves both a real source and an image source (from reflection) of the same strength. The Lloyd’s mirror effect is range
dependent, the acoustics experiences a falloff due to the dipole nature of the Lloyd’s mirror effect versus the monopole nature of the source[1]. Over the limited range examined in this study the effect is relatively small.

Previous studies have reported increases in field strength near shelf break fronts[1]. Badiey[2] reported a 5.5 dB increase in the noise level of a receiver close to the shelf break front off New Jersey, compared to a receiver further inshore during the 1995 SWARM experiment. This increase is indicative of the horizontal Lloyd’s mirror effect, considering the point sources of noise that would have been present during the 1995 SWARM experiment, i.e. waves, fishing activity, boat noise, etc. However, none of the evidence is conclusive because the front’s location was not recorded at the time of data collection and the noise sources were not tracked. To better study the horizontal Lloyd’s mirror effect an experiment was designed with a controlled acoustic source instead of noise. The shelf break front location and sound speed profile are recorded, along with the acoustic source which is towed from a ship.

2.3.1 Internal Waves

During the experiment a packet of non-linear internal waves was recorded passing to the west of the source and receiver, with the shelf break to the east of them. The combination of the internal waves and shelf break front has the ability to reduce transmission loss by 10-20 dB[3]. Nonlinear internal waves are generated in density stratified shallow water regions by tidal interaction with to-
pographical features. The shoals in the bathymetry at the continental shelf can cause a hydraulic jump condition from which internal wave packets can arise and propagate shoreward. Linear internal tides impinging upon the shelf at the critical angle can also steepen into nonlinear waves because of the shoaling bottom[6]. During the 1995 SWARM Experiment that also took place on the New Jersey continental shelf, acoustic fluctuations were recorded in the presence of internal waves. Badiey[6] conducted an analysis based on equations of vertical modes and horizontal rays and with a parabolic equation in the horizontal plane showing a frequency-dependent behavior of the intensity.

Several experiments have studied low frequency sound propagation in shallow water environments in the presence of internal soliton trains. A study in this field examined the frequency spectra variability in the Yellow Sea and recorded significant intensity decreases of up to 20 dB for specific frequencies[7]. This is anomalous attenuation and was reported as the result of resonant interactions because acoustic waves and the quasiperiodic spatial structure created by an internal wave train propagating nearly parallel to the acoustic propagation direction. Other studies have shown similar findings such as the SWARM 1995 study conducted on the New Jersey shelfbreak front, which reported strong variability, up to 7 dB, for broadband signal propagation through non-linear internal waves[2, 8, 9].

The horizontal Lloyd’s mirror effect has similar acoustic effects for a shelf break front and non-linear internal wave packet. Internal waves can also cause mode coupling[10, 11], resonant absorption can take place if the horizontal spectrum of the internal wave packet is sufficiently narrow[12, 13] and horizontal refraction can cause constructive and destructive interference in the acoustic rays[14]. There are a few differences however, which are summarized as following. The leading edge wave of a non-linear internal wave train created at a straight shelf break is
most likely straighter than the edge of a coastal front, due to the propagation properties of nonlinear waves. The plane wave reflection coefficient critical grazing angle for internal waves is half of that for a shelf break front because the internal waves do not span the entire water column, (unlike the front) which makes the front acoustically stronger. As a result of this, the front has a smaller critical range than the internal waves. A horizontal plane wave reflection coefficient can be generated not only for the individual leading edge wave of a soliton train, but also for the entire train similar to a standard layered medium reflection coefficient. The internal wave train moves at speeds of 0.5 to 1.0 m/s towards the shore, while the front is relatively stationary, creating a time-dependent Lloyd’s mirror effect in the case of internal waves. With only those few minor changes the horizontal Lloyd’s mirror effect induced by an internal wave can be described by the same equation and the same basic geometry as a shelf break front[1].

2.3.2 Shelf Break Front

There are a few different ideas about the formation of a shelf break front but most involve a flow convergence of some kind. Chapman described an along-shore flow spanning the whole shelf, causing the offshore Ekman flow to expel the gradient to the shelf break where it is trapped[15]. Chapman later argued differently, alongshore flow was not prescribed but was induced by a coastal buoyancy discharge[16]. Csanady hypothesized the frontal properties are forced by the surface wind and river runoff[17]. From many different opinions it is clear while the buoyancy of the shelf water has a coastal or upstream origin, the advection by the alongshore flow cannot by itself explain the frontal trapping at the shelf break[18]. It is a widely shared belief that the front is primarily a two-dimensional phenomenon resulting from cross-shore processes.

The continental shelf break has depths ranging from 50 to 150 m, with an
average slope range between 3° to 5°. The bathymetric profile of the continental shelf in the SW06 experimental area is shown in Figure 14. There is a fairly level portion in the first 30 km proceeding the steep drop off of the shelf break with depth ranging from 50 to 80 m. From 30 to 50 km in distance the slope increases to approximately 0.20°. The acoustic data recorded in this experiment was taken along the 110 m isobath, as the shelf break front forms near above lip of the shelf break. The shelf break itself is the steep drop off around 50 km in range from a depth of 150 to almost 300 m, resulting in a slope within the average range.

Figure 14. Bathymetric Profile of the New Jersey shelf break in the SW06 experiment area.

Previous studies have noted the maximum temperature variation in the frontal region occurs around 30 m depth, with a temperature change from 5-20°C[19]. In Figure 15 the water temperature across the shelf on Sept. 5 during the SW06 experiment are plotted. The quick change in temperature occurs at a depth between 20-40 m, with the temperature change of 10-20°C. This supports the variations reported in other studies. The change in temperature causes the sound speed to vary the most around 30-40 m depth, where the lower acoustic modes would also
be the most affected[19].

Figure 15. The water temperature across the shelf break from data collected on Sept. 5. The colorbar represent temperature in °C.

The shelf break front results from an abrupt transition from colder, fresher coastal waters to warmer, higher salinity offshore waters. The steep slope of the shelf break creates a boundary condition which limits the mixing between the two layers. The exact forces that contribute to the mixing (or lack there of) and to what extent they effect the system is not certain. What has been observed is on a large scale the shelf break is a rather stable feature present year round[20], but on a smaller time scale the front’s location along the shelf varies daily. During the SW06 experiment the front was observed to drift between the 80 m isobath to the 120 m.

The origin of the fresher, heavier water can be runoff from freshwater sources, more notably in winter[17]. The influx of fresher water results in the formation of a vertical front. However, the cause of the persistence of the front through summer is unknown. One potential cause is wind stress which may interfere with the momentum balance in a direction parallel to the front and cause geostrophic
adjustment motions normal to the front\cite{21}. A geostrophic adjustment model of thermocline movements developed by Csanady provided an reasonable description of the Lake Ontario spring thermocline, and was applied to the New England shelf break with some success, where wind-stress was a strong factor in front water entrainment\cite{21}.

While the wind-stress can effect the surface water layer, there are other important factors known to effect the surface and subsurface layers. The cross shore circulation is indicated as a shoreward subsurface flow in the upper slope water, an offshore surface drift and upwelling offshore from the front. An along isobath pressure gradient has an important role in reducing cross-shelf volume transport to a fraction of the Ekman transport. An increase in buoyancy flux increases the buoyancy contrast, producing a more distinct front closer to the shore, while wind stress results in the opposite effect. The balancing of the buoyancy flux and wind stress results in the observed drifting between the 80 and 120 m isobaths.

2.4 Shallow Water 2006 Experiment

In order to better understand the effects the continental front has on the acoustics, oceanography and autonomous underwater vehicle operations the Office of Naval Research (ONR) sponsored the Shallow Water 2006 (SW06) Experiment. The SW06 Experiment took place on the New Jersey shelf break front during July-August 2006 with multiple teams of scientists and engineers simultaneously conducted acoustic experiments. Figure 16 shows the approximate location of the experiment, outlined in the black box. The experiment focused on three main research areas: acoustics, LEAR (Littoral Environment Acoustics Research), physical oceanography, NLIWI (Non Linear Internal Waves Initiative), and vehicles AWACS (Acoustic Wide Area Coverage for Surveillance).

This study is based on an acoustic component of the experiment to deter-
mine the potential for the horizontal Lloyd’s mirror effect on the New Jersey shelf break front. This experiment consisted of a stationary acoustic receiver (WHOI VLA/HLA) and a ship-towed J15 acoustic source. The basic concept of the experiment is to transmit an acoustic signal parallel to the shelf break front, where the acoustic rays at low grazing angles will reflect off the front causing constructive and destructive interference, which will be recorded on the acoustic receiver. Figure 13 illustrates the basic geometry of the experiment, with acoustic rays reflecting off a change in sound speed at the front.

### 2.4.1 Ship-towed J15 Acoustic Source

The J-15 transducer used in this experiment operated at a frequency of 93 Hz with a source level of 165-168 dB. It was towed behind the R/V Knorr, an 85 m
vessel from WHOI that took part in the SW06 experiment on September 5, 2007. The J-15 was deployed at 50 m depth and towed for a distance of 60 km parallel to the shelf break front, which was located at the 110 m isobath that day, based on scanfish measurements. Figure 17 shows the J15 source used in this experiment being prepared to be lowered over the side of the R/V Knorr.

Figure 17. The J15 source deployed during the experiment on Sept. 5, 2007 off the R/V Knorr.

2.4.2 WHOI VLA/HLA

The WHOI VLA/HLA receiver, also known as the Shark array, was deployed at the beginning of the SW06 experiment at 39° 01.3’N latitude and 73° 03.0’ longitude. There are 16 hydrophone elements in the vertical line array and 32 elements in the horizontal line array. The vertical array is suspended with the shallowest element at approximately 11 m depth and has an 79 m overall aperture. The horizontal array is mounted on the seafloor with moorings and has a 472 m overall aperture.
2.4.3 Background Environmental Data: Scanfish

The Scanfish (depicted in Figure 18) is a towed undulating system designed by Marine Survey Solutions to collect profile data of the water column in oceanographic, bathymetric and environmental monitoring applications[22]. The Scanfish actively generates an up or down force to position the tow-fish in the water column, creating a sawtooth profile of oceanographic data. The Scanfish used during the experiment was set up as a moving CTD, recording position, depth, temperature and conductivity. Conductivity can be related to salinity, and depth to pressure, in order to calculate the sound speed profile which is dependent on temperature, salinity and pressure. The speed of sound in water is related to the temperature, pressure and salinity:

\[ C = f(T, P, S) \]  

(7)

The Scanfish was towed behind the R/V Endeavor during the SW06 experiment along and across the continental shelf. The sound speed profiles calculated based on the scanfish measurements allow the front’s location to be tracked. With the sound speed profiles from September 4 the deployment of the J-15 source was planned to progress parallel, within a few kilometers of the front’s location on the 4th.

2.5 Data Analysis

Once the acoustic and environmental data were collected, the environmental data were analyzed first to determine if the conditions were favorable for 3D propagation effects. First the Scanfish track was plotted along with the RV Knorr’s path and WHOI VLA/HLA location, as seen in Figure 19. The red line of the R/V Endeavor/Scanfish tract on September 5 is going across the continental shelf, while the R/V Knorr towing the J-15 source moves along the shelf. The sound speed
profile was extracted from the Scanfish data on September 5, using a MATLAB program given in Appendix B[23, 24]. The sound speed is displayed in figure 20 where the sharp change in sound speed indicates the front is at approximately the 110 m isobath. The J-15 source’s position is roughly marked in Figure 20 at 50 m depth and a few kilometers inshore from the 110 m isobath. The change in sound speed is approximately 1495 m/s to 1505 m/s. The difference of 10 m/s would result in a critical grazing angle of approximately 7 degrees(Equation 4).

After the environmental data showed potential for the 3D propagation effects, the acoustic data were analyzed for fluctuations in the sound level. Fluctuations in the received sound level were observed but it was suspected that some were due to noise from other ships in the area. The locations of the other research vessels were correlated in time to compare with the increases in sound intensity. Some of the intensity increases seen in the acoustic reception were found to be due to another ship. The KRAKEN normal modes model was used to validate whether the bathymetry and environmental conditions could support the remaining intensity
Figure 19. The tracts of the R/V Knorr towing the J-15 source and the R/V Endeavor towing the Scanfish on Sept. 5. The blue dotted line represents the tract of the R/V Knorr, the blue and red solid line the R/V Endeavor, with the red representing where the sound speed data plotted in Figure 20 was collected, and the grey circles are the mooring for different acoustic devices using in the SW06 Experiment.

Figure 20. Sound speed profile across shelf recorded on Sept. 5, where the color bar represents the sound speed and the range is increasing away from shore.
increases in the data.

### 2.5.1 Changes in the Sound Intensity Level

The first step in studying the sound intensity level variations is to examine the whole acoustic record from the WHOI VLA/HLA on Sept. 521. We can observe a few sudden changes in sound level with the potential for 3D effects, however there is one that significantly stands out with an increase in amplitude of approximately 20 dB around 4.75 hours into the recording. This is more than twice the sound intensity increase expected for the Lloyd’s mirror effect. While there are reports of an internal wave packet travelling to the west on that day which can increase the sound intensity level by 10-20 dB\[2\], the sudden increase of approximately 20 dB likely had another source. Ship noise was suspected, as up to 5 research vessels at any time were conducting experiments in the SW06 experimental area and could come fairly close to each other. There are other oscillations in intensity in the acoustic record that have more moderate fluctuations around the 6 dB expected for horizontal Lloyd’s mirror effect.

![Figure 21. The sound pressure level recorded on the J15 source correlated with the distance between the source and receiver.](image-url)
2.5.2 Ship Noise

In order to determine if ship noise affected the WHOI VLA/HLA recordings, the locations of the other research vessels in the area were tracked. The only vessel that was near the R/V Knorr on Sept. 5 was the R/V Endeavor running Scanfish tracts. Figure 22 shows the two ship tracts were relatively close. The positions of R/V Knorr and Endeavor are compared in time, with the numbers 1-17 in the figure correlating between the two ship’s tracts. Spectrograms were created at the same times as the positions 1-17 from the WHOI VLA/HLA recordings.

Figure 22. The tracts of the R/V Knorr and R/V Endeavor on Sept. 5 with position correlated.

In particular interest is the relative positions of the two ships at the sudden 20 dB increase. As can be seen from Figure 23, which corresponds to positions 11 and 12 along the ship paths, the noise level is relatively low. Figure 24 which corresponds to positions 13 and 14, shows the noise level increasing, significantly at position 14. Coincidently at point 14 R/V Endeavor changes direction. The R/V Endeavor previous to point 14 was travelling towards the WHOI VLA/HLA receiver, and at point 14 makes a sharp turn such that the rear of the ship is pointed
towards the receiver. That would direct the propeller noise towards the receiver, significantly increasing the noise level. The increased noise level is sustained past point 14 (see Appendix B for other spectrograms) adding support to the notion that the propeller noise is responsible for the noise level increase. Based upon the specgram/ship position analysis any sound intensity increases past the 4.75 hrs cannot be analyzed for 3D effects.

Figure 23. Spectrogram of received acoustic signal on the WHOI VLA/HLA at points 11 and 12 from Figure 22.

Figure 24. Spectrogram of received acoustic signal on the WHOI VLA/HLA at points 13 and 14 from Figure 22.
2.5.3 Potential for 3D Effects

Unfortunately the latter portion of the recorded acoustics is obscured by ship noise, but there are earlier sections of the data that show potential for the horizontal Lloyd’s mirror effect. At points 3-8 (approximately 28 to 35 km along the R/V Knorr tract) some variations in sound intensity were noted. Illustrated in Figure 25 are the variations in intensity and sound pressure level at positions 3, 5 and 8 (28.2, 30.3 and 34.7 m respectively away from the receiver). The 93 Hz source in present in the spectrogram at 28.2 km and disappears from the spectrogram at 30.3 km. However, the 93 Hz band reappears in the 34.7 km spectrogram. Similarly, in the sound pressure level plot there are greater amplitudes at 34.7 m than 30.3 m, where without another noise source or effect the sound should fall off with distance. Since the sound intensity level increases with distance provides the possibility that 3D effects may be present. In order to determine if 3D effects are responsible for the increase in sound intensity level over distance KRAKEN normal mode modeling will be used.

2.6 KRAKEN Normal Modes Model

As discussed in Section 2.5 some portions of the acoustic data show potential for 3D propagation effects and the environmental data show the conditions were favorable. In order to further explore the 3D propagation effect modeling was done using a standard normal mode program. This program, KRAKEN, is based on a vertical mode-horizontal ray approach to take into account the 3D environmental effects. KRAKEN is a standard normal mode model capable of two dimensional and three dimensional acoustic propagation modeling [4]. The program was set up to calculate probable locations along the shelf break front where acoustic modal rays reflect off the shelf break boundary to create constructive and destructive interference, and plot the transmission loss in the same area.
Figure 25. Comparison of acoustic sound levels at distances 28.2, 30.3 and 34.7 km from source to receiver. The sound pressure level plot has been demodulated and low-pass filtered in relation to the 93 Hz source signal. Notice the 93 Hz band present in the spectrogram at 28.2 km, which disappears at 30.3 km and reappears at 34.7 km.

The KRAKEN modeling results of transmission loss and interactions of the acoustic modal rays illustrate whether 3D propagation effects are possible given the basic environmental and bathymetric conditions of an area. Initially KRAKEN was given a wedge-shaped bathymetry to create a simple model of the shelf. After having convinced ourselves that the model showed promise for the horizontal Lloyd’s mirror effect, the model was refined to accept 3D bathymetry from the SW06 experimental area. With a more accurate depiction of the environmental conditions during the experiment the modeling results should more accurately predict the 3D propagation effects.
2.6.1 Normal Model Method

In studying long-range propagation, the method of normal modes was first used by Pekeris for shallow water sound propagation[25]. The principal assumption of the method of normal modes is no coupling between normal modes because of the horizontal variations of the medium[26]. In our case the sloping sea floor creates the horizontal variations, as seen in Figure 20. Pierce[26] pointed out the normal mode method in a stratified medium is mathematically equivalent to the adiabatic approximation for the separation of electron and nuclear motions in the solution of the Schrödinger’s equation. The normal mode method is limited by the wavenumber difference between the stratified medium layers, causing the approximation to fail if the difference becomes too small. This is understandable since multiple sources of the same wavelength could generate a resonance which would alter the wave amplitude.

Pierce used this method to examine the case of acoustic propagation in shallow water with a variable bottom depth. The 3D version of KRAKEN, given information such as bathymetry, acoustic frequency, source and receiver locations, calculates the relative sound intensity and acoustic modal ray propagation. The program uses the adiabatic approximation as an assumption that when going from one range to the next the modes will couple adiabatically, or not transfer energy to another mode[4]. Following steps by Pierce[26] and Weinberg and Burridge[27] to derive the adiabatic approximation we begin with the two dimensional Helmholtz equation,

\[ \frac{\rho}{r} \frac{\partial}{\partial r} \left( \frac{r \partial p}{\rho \partial r} \right) + \rho \frac{\partial}{\partial z} \left( \frac{1}{p} \frac{\partial \rho}{\partial z} \right) + \frac{\omega^2}{c^2(r, z)p} = \frac{-\delta(z - z_s)\delta r}{2\pi \times r} \]  

(8)

where \( \rho \) is the fluid density, \( r \) is the radial distance, \( z \) is the depth, \( \omega \) is the angular acoustic frequency, \( p \) is the pressure and \( c \) is the sound speed.
Because the modes can be summed, the solution to the Helmholtz equation can be represented as,

\[
p(r, z) = \sum_{m} R_m(r)Z_m(z, r)
\]  

(9)

where the local modes \( Z_m(z, r) \) are defined by

\[
\rho(r, z) \left[ \frac{1}{\rho(r, z)} Z'_m(z, r) \right]' + \left( \frac{\omega^2}{c^2(r, z)} - k^2_m(r) \right) Z_m(z, r) = 0
\]  

(10)

The prime denotes differentiation with respect to \( z \) and \( k \) is the horizontal wavenumber. The local modes, \( Z_m(z, r) \), at any range \( r \) are found by solving the depth-separated modal Equation 10 with the environmental properties at that range. Substituting that into the Helmholtz equation yields

\[
\sum_{m} \rho \frac{\partial}{\partial r} \left( r \frac{\partial (R_m Z_m)}{\partial r} \right) - \sum_{m} k^2_m(r) R_m Z_m = \frac{-\delta(z - z_s)\delta r}{2\pi r}
\]  

(11)

which can be re-written,

\[
\sum_{m} \left[ \frac{\rho}{r} \frac{\partial}{\partial r} \left( r \frac{\partial R_m}{\partial r} Z_m \right) + 2\frac{\partial R_m}{\partial r} \frac{\partial Z_m}{\partial r} + \frac{\rho}{r} \frac{\partial}{\partial r} \left( \frac{r}{\rho} \frac{\partial Z_m}{\partial r} R_m \right) \right]
\]

\[
- \sum_{m} k^2_m(r) R_m Z_m = \frac{-\delta(z - z_s)\delta r}{2\pi r}
\]  

(12)

Porter assumes the density \( \rho \) is independent of range, which allows us to apply the operator[4],

\[
\int \frac{Z_l(z, r)}{\rho} dz
\]  

(13)

and with the use of the orthogonality property some of the terms in Equation 12 will fall out.
$$\frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial R_m}{\partial r} \right) + \sum_m 2B_{lm} \frac{\partial R_m}{\partial r} + \sum_m A_{lm} R_m + k_l^2(r)R_l = -\frac{Z_l(z_s) \delta r}{2\pi r} \quad (14)$$

where

$$A_{lm} = \int \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial Z_m}{\partial r} \right) \frac{Z_l}{\rho} dz$$

$$B_{lm} = \int \frac{\partial(Z_m)}{\partial(r)} \frac{Z_l}{\rho} dz \quad (15)$$

The adiabatic approximation can be stated as an assumption that the coupling of $A_{lm}$ and $B_{lm}$ are negligible[4] yielding,

$$\frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial R_m}{\partial r} \right) k_l^2(r)R_l = -\frac{Z_l(z_s) \delta r}{2\pi r} \quad (16)$$

A WKB approximation of equation 16 yields the solution[4]

$$R_l(r) \approx A e^{i \int_0^r k_l(s) ds} \frac{\sqrt{k_l(r)}}{\sqrt{k_l(r)}} \quad (17)$$

Substituting equation 17 back into equation 9 obtains the final acoustic pressure used by KRAKEN.

$$p(r, z) \approx \frac{i}{\sqrt{8\pi r}} e^{-\frac{iz}{4}} \sum_{m=1}^{\infty} Z_m(z_s) Z_m(z, r) e^{i \int_0^r k_m(s) ds} \frac{\sqrt{\delta m(r)}}{\sqrt{k_m(r)}} \quad (18)$$

Given the acoustic pressure, KRAKEN can calculate the transmission loss, which is of primary interest in this study as it will illustrate fluctuations in the sound intensity level. Transmission loss is defined as:

$$TL(r, z) = -20 \log \left| \frac{p(r, z)}{p_0(r = 1m)} \right| \quad (19)$$

where $p_0(r) = e^{i k_0 r / 4\pi r}$ is the source acoustic pressure at one meter. Thus transmission loss can be written substituting Equation 18 and $p_0(r)$ into Equation 30.
\[ TL(r, z) = -20 \log \left| r \sum_{m=1}^{\infty} \frac{Z_m(z_s)Z_m(z, r)}{\sqrt{k_m(r)}} \right| \]

In the case of shallow water acoustics it is often appropriate to use incoherent transmission loss since the modes usually interact with the bottom and the bottom is a complex structure. The incoherent transmission loss can be written as[4]:

\[ TL(r, z) = -20 \log \left( \frac{2\pi}{r} \sum_{m=1}^{\infty} \frac{Z_m(z_s)Z_m(z, r)}{\sqrt{k_m(r)}} \right) e^{i \int_0^r k_m(s) ds} \] \tag{21}

2.6.2 Horizontal Refraction

In this study the reflection/refraction of the acoustic rays is of great interest. KRAKEN has the ability to plot the acoustic ray paths over a given area, along with the individual rays interactions with each other as influenced by the environment and bathymetry. Each mode obeys Helmholtz equation with the mode’s phase speed acting as the ocean sound speed[4]. From the Helmholtz equation a horizontal refraction equation is derived, which can be solved by looping over an initial azimuthal angle, repeating the process for each mode. The azimuthal angle is determined by the parameters the user puts into the KRAKEN program, determining the width of the fan of beams propagating from the source and the number of beams. Each angle results in a beam, which is traced out through the field with its contribution summed up with the other beam contributions. This procedure is repeated for each mode, with the number of modes determined by the user. Generally in this study only the first three modes are used to reduce the program’s calculation time.

As done earlier, we begin with the Helmholtz equation, applying the adiabatic approximation for normal modes. This yields the horizontal refraction equation used by KRAKEN[4].
\[
\frac{\partial^2 \phi_l}{\partial x^2} + \frac{\partial^2 \phi_l}{\partial y^2} + k_l^2(x, y)\phi_l = -Z_l(z_s)\delta x\delta y
\] (22)

KRAKEN solves the horizontal refraction equations using Gaussian beams, where the refractive medium for the beams is set by the phase velocity field \((\phi_l)\) corresponding to particular modes represented by the subscript \(l\). The beam is defined by a central ray, with all other outlying rays falling off in intensity in a Gaussian form as a function of distance from the central ray. The contributions from all the Gaussian beams are added, with the beam being represented as:

\[
g_l(s, n) = A \sqrt{c(s)} q(s) e^{-i\omega[\tau(s) + \frac{p(s)}{c(s)} n^2]}
\] (23)

where \(c(s)\) is the medium’s sound speed, \(\tau(s)\) is the travel time, and \(p(s)\) and \(q(s)\) are complex quantities. A full description of this is given in the KRAKEN normal modes mathematical background in the Ocean Acoustics Library[4].

2.6.3 Wedge Shaped Bathymetry

KRAKEN was originally set up for 2D modeling, which involved very basic bathymetry such as a wedge-shaped sea floor. The wedge served as a crude rendering of the shelf break, descending from 50 to 110 m over the range of 15 km with the shelf break front at 12 km (see Figure 26). The program moves progressively through the range across the shelf, calculating the Gaussian rays and transmission loss in the field. In the 2D model the program takes a set of ranges along the shelf and a set of matching depths. KRAKEN uses a loop which passes the depth element at specific ranges to subprograms which calculate the affects of the depth change on the horizontal refraction equation, Gaussian modal rays and transmission loss. The user inputs the frequency of the source, depth of source and receiver, the angular spread and number of angular steps. In the case of our experiment the source was at 50 m, the receiver at 40 m, with an angular spread
of $70 - 110^\circ$ degrees and 41 steps between the angles.

Figure 26, shows the KRAKEN modeling results for the 2D wedge bathymetry with the shelf break at 12 km range across the shelf and two acoustic modes. The color shading in the background represents transmission loss. The black and red rays are the acoustic modal rays propagating outwards from the source, reflecting off the imposed boundary at 12 km. The black rays represent mode one and the red mode two. Some rays bend and cross over the straight rays, potentially creating constructive or destructive interference depending on the phase of the two rays as they cross. The 2D modeling was conducted before the SW06 experiment to determine good locations for towing acoustics sources. As seen in Figure 26 at approximately 30 km along the slope the modal rays approach the critical angle and begin reflecting. Because of this effect the transmission loss exhibits some focusing between 30 to 60 km along the slope and 8 to 12 km across the slope. Therefore during the experiment is it best to be within a few kilometers of the shelf break front and with a distance of at least 30 km between source and receiver in order to observe the horizontal Lloyd’s mirror effect.

Figure 27 is a plot of just the transmission loss along the shelf slope 25 to 55 km. The fluctuations in transmission loss become significant around 40 km, supporting Figure 26 which also predicts 3D propagation effects between 30 to 60 km along the shelf slope. The next step is to use 3D modeling to gain greater detail into potential locations for 3D propagation effects on the New Jersey shelf break.

2.6.4 Experimental Area Bathymetry

The KRAKEN normal mode model was modified to accept 3D bathymetry from the New Jersey experimental area. Bathymetry with good resolution was available in the experimental area, reflecting the irregular surface and varying
Figure 26. KRAKEN normal mode model plot of the acoustic modal rays and sound intensity level for a 2D wedge shaped bathymetry. The shelf break is at 12 km across the slope, and at approximately 30 km along the slope the modal rays begin to bend at the shelf break front. The white-dotted line marks the location of the transmission loss plot in Figure 27, taken along the shelf break boundary.

Figure 27. KRAKEN normal mode model plot of the transmission loss for a 2D wedge shaped bathymetry along the white-dotted line in Figure 26.

slopes of the continental shelf. Figure 28 is a 3D plot of collected bathymetric measurements in the SW06 experimental area, which were used to generate KRAKEN
plots of the modal rays and transmission loss. The plot shows how poorly a simple wedge modelled the bottom shape. With the more accurate depiction of the environmental conditions the modeling results will have a stronger correlation to the collected data and give more support to the possibility of horizontal Lloyd’s mirror effect being present at the shelf break front.

Figure 28. 3D plot of the bathymetry of the SW06 experimental area off the coast of New Jersey.

In figure 29 the transmission loss is in the background, represented by the color scale and the propagation of the first two modal rays are overlayed on top. On Sept.5, during the SW06 experiment, an internal wave packet was reported as passing on the western side of the shelf break. Two boundary conditions were put into KRAKEN for the shelf break front at 12 km and an internal wave packet at 2 km. The modal rays begin reflecting off the shelf break front around 30 km along slope like in the 2D model. However, the modal rays begin reflecting off the internal wave packet near 15 km along slope. The focusing of the transmission loss is apparent in regions with the reflected modal rays, especially strong 30-50 km along slope and 2-5 km across the slope near the internal wave packet. There
is also significant transmission loss focusing near the shelf break front 30-50 km along slope and 8-12 km across slope.

![3D KRAKEN results of acoustic modal rays reflecting off a shelf break front and non-linear internal wave packet](image)

Figure 29. 3D KRAKEN results of acoustic modal rays reflecting off a shelf break front and non-linear internal wave packet. The source is at (5km, 0) and the white-dotted line is where the transmission loss in Figure 30 is plotted.

The transmission loss plot in Figure 30 illustrates at approximately 38 km along the shelf slope the acoustic rays have approached the critical grazing angle. The transmission loss begins to oscillate with the field attaining 6 dB reductions near 40 km. The oscillations in transmission loss are greater in amplitude and begin at less distance along the slope than the 2D modeling results. The oscillations are also less uniform reflecting the irregular shape of the shelf.

2.7 Discussion

Analysis of acoustic data recorded on the WHOI VLA/HLA receiver of the J15 ship-towed source showed the potential for 3D propagation effects at some ranges between source and receiver. Ranges of approximately 28-35 km (Figure 25) had variations in the transmission loss that were not uniformly increasing with distance. At approximately 30 km in range the transmission loss was less than at 28 km.
Figure 30. Transmission loss along range as shown by the white-dotted line in Figure 29. The blue line marks a 6 dB decrease in TL.

The acoustic signal should degrade with distance unless environmental factors are augmenting the signal whether it is through noise or 3D propagation effects. Ship noise did affect the sound level later in the acoustic record (Figure 24), but prior to 4.75 hrs there was no known source of significant noise other than the acoustic source. That would lead one to believe the increase in sound intensity level at 30 m was due to shelf break front and internal wave packet.

The KRAKEN normal modes modeling in both 2D and 3D environments showed the potential for the horizontal Lloyd’s mirror effect starting at similar distances between source and receiver. The modal ray plots Figures 26 and 29 both showed modal ray reflection beginning around 30 km along the slope. The J15 was towed parallel to the shelf break front, a few kilometers to the western side. In Figure 29 the three distances 28.2, 30.3, and 34.7 km where fluctuations in sound intensity levels were noticed are marked with white lines. The point at 30.3 km according to the modal ray results is a little premature, being on the cusp of the critical angle. The transmission loss plots figures 27 and 30 also indicate
30.3 m is a little too close in range as the rays reach the critical angle around 35 to 40 km along slope.

However the location is close and the model is not perfect, so 3D propagation effects could have been present. Beyond 40 m in range the reflections from the shelf break front and internal wave packet interact, which could have given some interesting acoustic analysis. Unfortunately the ship noise from the R/V Endeavor precludes meaningful analysis for fluctuations in transmission loss beyond 40 km between source and receiver. Potentially reductions in transmission loss by 10 to 20 dB could have been observed.

2.8 Conclusion

Data collected on the WHOI VLA/HLA receiver from a J15 ship-towed acoustic source during the SW06 Experiment showed potential horizontal Lloyd’s mirror effects at the New Jersey shelf break front. At a distance of 30.3 km from the source to receiver an increase in sound intensity level was observed from the sound intensity level at 28.2 km. The KRAKEN normal modes model was used in both in 2D and 3D to verify the potential for increases in sound intensity in the presence of a shelf break front. The modeling results showed reductions in transmission loss occurring after 35 km and modal ray reflections beginning after 30 km. This implies the Lloyd’s mirror effect is possible with a distance of 30 km between source and receiver. The model also showed potential in the 40-60 km range with both a shelf break front and internal wave packet contributing to the field effects, but unfortunately there is a lot of ship noise after 40 km from the R/V Endeavor precluding analysis. Overall the conclusion is 3D propagation effects were likely to have occurred on Sept. 5.
2.9 Future Work

This experiment demonstrated the potential for 3D propagation effects, but more definitive work is needed to make a stronger case. The acoustic recording from ranges beyond 40 km would have been very interesting to examine due to the presence of both the shelf break front and internal wave packet. However the ship noise from the R/V Endeavor interferes in the ranges of particular interest. Future work could include another experiment with both the shelf break front and an internal wave packet in the area, and keeping noise sources, such as a ship, to a minimum.

Besides a ship-towed source, a stationary source and receiver could be used for an interesting experiment combined with an FM sweep signal[1]. As the frequency changes the relative phase would change between the direct and reflected modal ray paths, which should result in correlated changes in the sound intensity level. The comparison between the times of the frequency changes and changes in sound intensity amplitudes would add weight to the horizontal Lloyd’s mirror effect theory. If the frequency changes are correlated well to the increases in sound intensity level that would strongly support the horizontal Lloyd’s mirror effect theory, as the changing ranges caused by the changes in frequency would reduce the influence of other factors.

List of References


3.1 Abstract

There is interest in deriving a relationship between water wave field conditions and their effect on acoustic backscatter. In this study regular and irregular wave fields are used to examine the effect that different wave heights, periods and surface roughness have on acoustic surface reflections. This is a scaled experiment conducted in a wave tank with scale factors of 1/10 for wave periods and 1/100 for wave heights to preserve similitude with ocean surface gravity waves. Modeling was conducted based upon work by Godin, Fuks and Charnotskii[1, 2, 3] focusing on differences in acoustic travel time and intensity given different wave field parameters. The modeling was compared with the acoustic travel time and intensity calculated from the collected data, indicating a broader spread of acoustic travel times in rougher wave fields.

3.2 Introduction

The purpose of this study is to characterize the acoustic backscatter in controlled wave fields with relation to the surface conditions. The ocean surface is a dynamic feature with many different factors shaping the surface conditions, wind being a primary force in determining the turbulence at the surface. The surface can vary from barely any oscillation other than long wavelength motion from the lunar tides, to a violently confused sea. Common methods for measuring sea surface conditions are ship board observations, wave poles on fixed structures where an observer sights the wave amplitude against the pole from shore, satellite measurements, laser altimeters, and waverider buoys. The buoys, altimeters, and wave poles are usually located close to the coast, so they cannot measure wave condi-
tions further out to sea. Ship and satellite observations can cover most any sea surface, but neither system has a static position. Mounting an acoustic system to the bottom of the seafloor would allow measurements to be taken at a static position and at depths over 6000 m.

Previously inverted echo sounders (IES) have been deployed on the ocean bottom up to 2000 m depth to use the acoustic backscattered signal to measure environmental properties of the ocean. Many studies have been conducted using a bottom mounted IES to analyze differences in the backscattered signals to investigate ocean winds [4], dynamic variations sea surface height[5, 6, 7], and depth of the thermocline [8]. However there have been relatively few studies that have analyzed the backscattered signals for the ocean surface wave spectra.

Medwin and Clay conducted a series of experiments in a large anechoic tank with scaled ratios of root-mean-square (rms) wave height/acoustic wavelength and wave correlation distance/acoustic wavelength taking similar values to ocean gravity waves. They used the Helmholtz-Kirchhoff integral theorem to generate a 3D surface-correlation function[9, 10, 11]. The Helmholtz-Kirchhoff integral has been a fairly popular approach in modeling acoustic backscatter from rough ocean surfaces, but there are limitations to the Kirchhoff approach. The integration requires approximations, such as the Kirchhoff assumption for scattering from a randomly rough surface, where the outgoing signal is the incident value multiplied by the plane-wave reflection coefficient at every point of the surface[12]. It is known the Kirchhoff assumption does not yield an exact solution but the magnitude of the error as a function of angle and frequency had not been evaluated until Jebsen and Medwin investigated it in 1982[12]. They found at 90° (normal to the surface) the Kirchhoff approximation was accurate but depending on the frequency, the error could increase quickly as the incident angle decreased relative to the error. For the
purposes of an IES the incident angles are very close to 90° relative to the incident plane, but in this scaled experiment the incident angles can be less than 80° off the incident plane. Originally this study used frequencies between 10-30kHz. At 10 kHz the work by Jebsen and Medwin showed the difference of 10° could create a significant difference between predicted and measured acoustic reflections[12]. Therefore another method was sought to model the acoustic backscatter.

There were studies of acoustic backscatter from rough surfaces that focused on analyzing the differences in the acoustic travel time and intensity by Godin, Fuks and Charnotskii[1, 2, 3]. They used the geometric optics approximation to investigate the statistical properties of travel time and intensity of the acoustic pulses backscattered by 2D and 3D rough surfaces. In their studies they derive probability density functions (PDFs) of the normalized travel time and intensity of the first and second backscattered acoustic pulses. They found that surface roughness typically decreases the mean travel time in the case of large-scale surface roughness[1], and in both 3D[3] and 2D[2] the travel time and acoustic intensity are strongly correlated, generally earlier arrivals have smaller amplitudes. This study will follow the work by Godin, Fuks and Charnotskii, using the geometric optics approximation to create PDFs of the acoustic travel time and intensity to compare with travel time and intensity distributions generated by the collected data.

The collected data is from a scaled experiment in a wave tank using an acoustic source and receiver mounted to the bottom of the tank to examine acoustic backscatter resultant from different surface parameters created by the wave maker. These wave fields are scaled models of Pierson-Moskowitz and JONSWAP sea conditions, preserving geometric, kinematic and Froude similitudes as best to the ability of the facilities. The primary objectives of this study are to (1) collect
acoustic and wave field data in various controlled wave fields, (2) better understand the surface scattering problem, (3) quantify acoustic surface scattering as a function of the wave field parameters, (4) develop modeling to predict the acoustic backscatter resultant from a given wave field parameters, and (5) recommend appropriate follow-up work.

3.3 Background: URI Graduate School of Oceanography PIES Unit

The concept of a bottom mounted acoustic device, directed towards the surface was developed in the 1970s at the University of Rhode Island (URI) Graduate School of Oceanography (GSO) by Watts and Rossby after Rossby introduced the idea of using the dependence of the acoustic travel time on the ratio of cold to warm water to monitor the depth of the main thermocline[8]. The device developed by URI GSO is called an inverted echo sounder (IES) and is a small self-contained glass sphere 17 inches in diameter with its own acoustic release, relocation and recovery system (see Figure 31)[13]. The IES unit has the battery and memory capacity to be deployed for up to 18 months and can be deployed at depths down to 6700 m. The primary function of the IES is to measure the travel time of the acoustic pressure signal from the sea floor to the ocean surface and back. Additional data channels are available to monitor pressure, temperature and ambient noise.

The IES the URI GSO uses emits a fairly wide conical beam (around 50 degrees at optimal performance, but up to 80 degrees is more typical) at 12 kHz, corresponding to a wavelength of approximately 12 cm[13]. The instrument emits pulses of 6 ms duration with constant amplitude and with some modification can transmit every few seconds. The backscattered signal received at the IES has precursor waves and a complex echo envelope 30-100 ms long. The signal is filtered to remove bias from the free ocean surface and processed to obtain a single travel time for each pulse, losing the surface backscatter information. Typically successive...
transmissions are made, an average is taken of the single travel times from the
transmissions, stored as a function of time onboard the IES and is retrieved after
the IES is recovered from deployment. The complex backscattering signal from
each transmission is not stored by the IES and hence, no wave information is
retrieveable from the data. The IES was originally designed to measure the location
of thermocline, which was found by Rossby to have a linear relationship with the
acoustic signal travel time[8]. The variable surface layer of the ocean with the
significantly warmer temperature is ignored so it cannot alias the signal travel
time estimate and the tidal frequencies are filtered out, in order to get a more
accurate location of the thermocline. It is planned in the future to modify the
IES system for a deployment to record the backscatter signal prior to filtering and
processing in order to analyze the effect of the surface conditions on the signal.

Figure 31. A diagram of the basic structure of the GSO PIES unit. There is the
17" diameter sphere which contains the sensors. The pinger is labeled near the
top of the PIES and various components used for retrieving the device are also
shown[13]
There are recorded samples of the complex backscattering signal measured by PIES, but there have not been many attempts to understand the backscatter signal and relate it to measurable ocean features, such as surface wave characteristics. Currently there are no methods available to process and invert such a complex backscattering signal to infer surface wave properties of interest. As the surface scattering problem is better understood, it will be possible to measure shorter period surface and internal waves through future hardware modification to the PIES system allowing digitization and recording of the raw signal. Those measurements in the ocean environment are of great scientific interest along with being important for a variety of federally supported programs and activities in ocean instrumentation and monitoring. In advance of the planned PIES deployment this study is using a scaled model experiment to develop a relationship between the water surface conditions and backscattered signal which will be used to analyze data in the future PIES deployment.

3.4 Experimental Setup

To study the acoustic backscattering problem a scaled model was developed in the University of Rhode Island (URI) Department of Ocean Engineering wave tank. The concept was an acoustic source and receiver mounted onto the bottom of the wave tank, with the source projecting towards the water surface (Figure 34). Above the water’s surface wave gauges are mounted onto I-beams to record the wave field conditions concurrent with the acoustic scattering. They are shown in Figure 32 and in Appendix C in Figure C.66, an illustration of the typical experimental configuration in the wave tank. There are four wave gauges and they are marked by the colors orange, blue, green and white. At one end of the wave tank is the wave maker, which consists of a flat panel that a hydraulic piston pushes forwards and backwards to generate waves, as seen in Figure 32. The wave
maker generates the wave field from user input in a LabVIEW interface within certain operational limits.

Figure 32. The URI Dept. of Ocean Engineering wavemaker generating a periodic wave field. At the far end of the tank is the flap-type wavemaker and halfway over the tank are the four wave gauges.

The wave tank was constructed in the Sheets Building at the University of Rhode Island’s Bay Campus by the department of Ocean Engineering in the 1960s for educational and research purposes. The tank is 30 meters long, 3.6 meters wide and 2 meters deep. The tank is equipped with a hydraulic piston driver flap-type wave maker and its operating depth is 0.75-1.5 meters. The wave maker can create regular and irregular wave fields, which are used to model sea surface conditions. A previous experiment[14] built a 20 meter long aluminum beach which for this experiment is being used to reduce the magnitude of reflected waves and allows for the generation of periodic waves. Figure 32 shows an example of periodic waves generated by the wave maker in the URI tank.

The relatively small dimensions of the wave tank provide some problems with acoustic and water wave reflections. Not only the surface and bottom reflect the
acoustic signals, but the wall reflections have to be taken into consideration because due to the proximity of the tank walls the wall reflections can interfere with the surface reflections. To help reduce the undesired reflections an acoustic baffle was constructed for the source and acoustic dampening blankets were laid in the tank along the walls and floor near the source and receiver (see Figure 33). Surface wave reflections can also affect the acoustic return signals by complicating the surface state and changing the wave spectra. The aluminum beach helps reduce a good portion of the water wave reflections by causing wave breaking.

Figure 33. The basic setup of the acoustic source and receiver with varying wave fields in URI wave tank with acoustic dampening blankets lining the bottom and sides of the tank. The blankets were placed in the tank to reduce the amplitude of the bottom and wall reflections. The different heights and periods of the waves at the surface are not drawn to scale.

While it is desired to create a reasonably accurate approximation of sea surface conditions within the limits of the wave tank capabilities, there are operational limitations of the wavemaker and restrictions due to the dimensions of the tank that reduce the water surface conditions that can be scale modeled. To develop a
correlation between sea surface conditions and acoustic backscattering, the surface parameters of the wave fields should reflect as many water surface conditions as possible. The waves produced by the wave maker were scaled to preserve geometric, kinematic and Froude similitudes to the best of the ability of the facilities and equipment. For the regular sinusoidal waves the average values of the Pierson-Moskowitz sea states were scaled for the experiment and the irregular waves are scaled from a JONSWAP wave spectrum. The wave heights were of particular concern because of operational limitations of the wave tank and wavemaker. The wave tank is not large enough to contain wave heights exceeding 15 cm and the wavemaker cannot generate wave heights much larger than that. Wave heights smaller than 5 cm were not used because the analysis will be based on acoustic travel time differences and for this preliminary work larger wave heights are needed for distinct travel time differences.

The acoustic signal used in this experiment is a 4-cycle sinusoid burst at 30 kHz with an amplitude of 3 volts peak-to-peak driven by a function generator. The frequency of 30 kHz was chosen bearing in mind the transmitting voltage response of the active hydrophone, acoustic wavelength and sampling frequency capability of the data acquisition system. Frequencies greater than 30 kHz could not be used because it is the upper end of the optimum frequency range of the acoustic source and the sampling frequency of the data acquisition system (DAQ) could not go much higher to satisfy the Nyquist frequency requirement. The DAQ receives the acoustic returns via an omni-directional, broadband passive hydrophone mounted at the same depth as the active hydrophone.

3.4.1 Acoustic Source and Receiver

The acoustic source used is an ITC-1001 hydrophone with an optimum frequency at 18 kHz and a TVR of 138 dB re 1V/µPa at 1 m at the 30 kHz frequency
used in this experiment. The receiver is a broadband Reson 4034 hydrophone with a usable frequency range of 1 Hz to 470 kHz and a receiving sensitivity of -217 dB re 1V/$\mu$Pa at 1 m at 30 kHz. Both the source and receiver are omnidirectional. The source and receiver are mounted adjacent to each other with a separation of 0.2 m on a flat plate. The flat plate is part of stand, seen in Figure 34, that sits on the bottom of the wave tank, placing the acoustic source and receiver 0.3 m above the bottom and 1.0 m from the water surface. The stand is placed underneath the row of wave gauges that will sample the wave field concurrently with the acoustic recordings.

![Acoustic source and receiver mounted on their stand beside the wave tank. The source is on the left and the receiver on the right side. The source has an acoustic baffle made of PVC and foam to help reduce the tank wall and bottom reflections.](image)

The acoustic source will send a 4-cycle sine wave pulse at 3 volts peak-to-peak, where the pulse duration was chosen due to the geometric constraints of the wave tank. The pulse is repeated at a 10 Hz rate, allowing enough time between received pulses for the tank reverberations to diminish. The data is acquired for a 10 second span in order to capture an accurate depiction of the acoustic backscatter in the
wave field since the wave periods are on the order of 1 second.

More than one frequency was used during testing but a frequency of 30 kHz was settled on for source transmission because the experiment needed the highest frequency the source can transmit with good performance. Higher frequencies are favored because of greater resolution in the time of arrival separations between the direct signal and direct surface reflection and the smaller acoustic wavelengths. Frequencies higher than 30 kHz were not used because while they may yield a better resolution for the time of arrival separations, higher frequencies require a Nyquist frequency that is greater than the data acquisition system can sample.

The 4-cycle sinusoid pulse is generated by a Stanford Research Systems DS345 30 MHz function generator and repeated every $1/10^{th}$ of a second with a burst rate function (see Figure C.66 in Appendix C for illustrations of how the equipment is setup and connected). Before the 4-cycle sinusoid burst is passed to the acoustic source, the signal passes through a Krohn-Hite 7500 amplifier with a gain of 10x. After the signal is amplified it is sent to the source, whereupon the direct and reflected pulses are received by the passive hydrophone. From the passive hydrophone the signal is passed through a Stanford Research Systems SR560 pre-amplifier, receiving a gain of approximately 1000x. The pre-amplifier also has a filter function, from which a band-pass filter was used with bounds at 300 Hz and 100 kHz.

The DAQ records the 3 Volt peak-peak 4-cycle sinusoidal pulse before amplification and the received signal after passing through the pre-amplifier on channels 5 and 6 respectively. The data is acquired simultaneously, allowing for accurate arrival time differences to identify reflections, i.e. direct surface, bottom, bottom-surface. Figure 35 illustrates the geometry of the principal tank reflections. For the purpose of this study the greatest interest is in the direct surface reflection, how-
ever, the direct transmission, bottom reflection, wall reflection and surface-bottom reflection all appear fairly close in the acoustic record as evidenced in Table 1.

![Figure 35](image_url)

Figure 35. The geometry of the main acoustic reflections in the wave tank. The distances the acoustic pulses travel are shown.

Since the distances the acoustic signal travels are known, the travel time can be calculated as shown in Table 1. This information is key for data analysis, as the travel time variations will be compared to determine a relationship between surface conditions and acoustic backscatter. The fluctuating surface height in the different wave fields provides a varying travel time that this study sought to ascertain its predictability. The challenge is to determine if that is a reliable method to determine surface conditions from acoustic backscatter.

Figure 36 is an example of the time of arrival differences from experimental data, illustrating the main reflections shown in Figure 35. The figure depicts one backscattered pulse reflected from a flat surface. The experimental data supports the travel times calculated in Table 1, with the difference between the direct acoustic signal and surface reflected signal being approximately 1.26 ms. The reliable time separations and differences in amplitude were taken advantage of for identify-
Table 1. The distances and travel times of the main reflections of the acoustic signal by the geometry of the wave tank, assuming a sound speed of 1450 m/s given the wave tank’s typical water temperature was approximately 10°C.

<table>
<thead>
<tr>
<th>Reflection</th>
<th>Distance (m)</th>
<th>Travel Time (ms)</th>
<th>Relative Travel Time (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct</td>
<td>0.2</td>
<td>0.1379</td>
<td>0</td>
</tr>
<tr>
<td>Bottom</td>
<td>0.6325</td>
<td>0.4362</td>
<td>0.2983</td>
</tr>
<tr>
<td>Direct Surface</td>
<td>2.611</td>
<td>1.800</td>
<td>1.662</td>
</tr>
<tr>
<td>Surface-Bottom</td>
<td>2.01</td>
<td>1.400</td>
<td>1.262</td>
</tr>
<tr>
<td>Wall</td>
<td>3.758</td>
<td>2.600</td>
<td>2.462</td>
</tr>
</tbody>
</table>

Figure 36. An example set of acoustic returns from one pulse incident on a calm surface. The separations in the time of arrivals between the different reflections is similar to the values predicted in Table 1.

3.4.2 Wave Gauges

The wave gauges used in this experiment are the WG-50 model manufactured by RBR consisting of a weatherproof control unit and a wave probe shown in Figure 37. The probe wire is made of a conductive material and accordingly the capacitance varies as the relative water level on the wire changes. There is a linear
relationship between depth of immersion and the capacitance output of the gauge. In order to calibrate the gauges for reading wave heights the gauges are moved incrementally from the bottom to top, pausing to take readings at the increments. Voltages are recorded corresponding to the changes in capacitance into the DAQ. These voltages are equated to the distance along the wave gauges, and are used as calibrations to determine wave height.

![Wave gauges used in the URI wave tank.](image)

Figure 37. The wave gauges used in the URI wave tank. The outside gauges (1 and 4) are 20 cm in length, while the inner gauges (2 and 3) are 15 cm. The major components of the gauges are labeled - stepper motor, control unit and wave probe. (The third wave probe is missing because it is broken)

The wave gauges are moved by stepper motors, which are controlled by a ST400NT Multi-axis stepper motor controller board made by RMV Electronics Inc. The motor controller controls the four wave gauges stepper motors through a RS-232 serial port on the computer. The gauges require a 12 volt power supply and 2.2 A individually.

The calibration readings are used to generate calibration coefficients that re-
late the relative water height to the voltage outputs. After recording the calibration data the gauges are moved to the halfway position to take measurements of the wave field corresponding simultaneously with the acoustic readings. The voltages are read into the DAQ and sampled at the same frequency as the acoustic channels.

There are two different sizes of wave gauges, the outer wave gauges are 20 cm in length and the inner wave gauges are 15 cm. When taking wave field data the lengths of the wave gauges need to be considered in relation to the wave height. The smaller wave gauges should not be used with wave heights much over 10 cm, as the wave gauge will not function properly if water splashes over the top of the wave probe.

3.4.3 Wavemaker

The URI tank is equipped with a flap-type wave maker driven by a hydraulic piston. The piston is controlled by a servo motor and potentiometer, which behaves as a voltage follower. In order to minimize the reflection of waves back towards or behind the wavemaker, barrels were placed in the back of the wavemaker as a means of energy dissipation. Figure 38 illustrates the physical set up of the wave maker paddle and piston.

For the wave maker to create reliable wave fields the stroke length of the paddle needs to be related to the wave height it would generate. The basic premise of a long, narrow wave tank and piston driven wavemaker has been well developed over the past century. Drawing from pervious work by Bengston[14] with the URI wave maker, a boundary value problem was developed using a linear solution to a 2D small amplitude water wave theory relating stroke length to wave height. The solution to the boundary value problem for this piston drive flap-type wave maker is:
where $H$ is the wave height, $S$ is the piston stroke length, $k$ is the wave number, and $h$ is the water depth. This relationship between wave height and stroke length utilizes the linear dispersive relationship for water waves[15]:

$$
\frac{\sigma^2}{g} = k \tanh(kh) \quad (25)
$$

As the wavemaker’s piston servo mechanical system behaves as a simple voltage follower, Bengston developed a transfer function which relates the driving voltage amplitude ($V_a$) to the wave period ($T$) and piston stroke length ($S$). Bengston[14] created a regression analysis Fortran program which, given measurements of the voltage, stroke length and period, returns an equation describing the relationship between the three variables:

$$
V_a = A_0 + A_1 S + A_2 T + A_3 ST + A_4 S^2 + A_5 T^2 \quad (26)
$$
The relationships between voltage, stroke length and period were used to create two LabVIEW programs that take wave height and period parameters from the user to create wave fields with the wave maker. The first LabVIEW program was made for regular sinusoidal waves and the second for irregular waves. The first LabVIEW program, named wave2.0 requires the user to input a wave height, wave period and number of cycles, outputing a corresponding voltage series to the wavemaker. The second program, Random Wave Generator 4.0 requires the user to upload a text file of voltages which correlate to wave height. The voltage file is generated by a MATLAB program random.m (see Appendix C) that outputs irregular waves within a JONSWAP or Pierson-Moskowitz wave spectrum. For the irregular wave experiments a JONSWAP spectrum was used, as the JONSWAP spectrum is a more accurate depiction of the ocean surface waves.

3.4.4 Data Acquisition System

The data acquisition (DAQ) system to be used throughout this project is an IO TECH 3000 DAQ presented in Figure C.66. The manual for the IO TECH DAQ is available online at the company’s website[16]. The DAQ is capable of synchronous analog input, analog output, digital I/O and counter I/O. There are 8 differential analog channels, with channels 1-4 acquiring voltage level readings from the wave gauges, channels 5-6 acquire voltage readings from the passive and active hydrophone, and channels 7-8 are power and ground. Data acquisition triggers off the active hydrophone channel when the voltage is above a certain voltage level the user sets. For both the regular and irregular waves the DAQ triggers when the voltage goes above 1 V. Through experimentation 1 V was found to trigger the DAQ on the an acoustic pulse and not mistakenly because of environmental noise.
3.5 Scaling

For most coastal engineering problems the forces associated with surface tension and elastic compression are relatively small and can be neglected[17]. Therefore the selection of the appropriate hydrodynamic scaling law is based on an evaluation of whether gravity or viscous forces are dominant. If gravity forces are dominant the Froude number is important and if viscous forces are dominant, the Reynolds number. In this case the Froude number is dominant, as will be discussed in the following Section 3.5.3. The dominant number coupled with geometric similarity provide the necessary conditions for hydrodynamic similitude in the majority of coastal models.

The object is to develop a geometrically scaled model that is feasible in the dimensions of the URI wave tank without overly bothersome scale effects. The LabVIEW software which runs the wave maker generates a wave field based upon user-defined wave height and period. Since those two values and water depth are the only values that can be altered, the scaling will focus on them. For the purposes of scaling the prototype depth will be assumed to be 100 m, as the future deployment of the PIES unit will be in coastal waters off the Northeastern US coast.

The similitudes relate the scale of a prototype, which in this case is the open ocean at 100 m depth, to the scale of a model, the URI wave tank at 1 m depth. Discrepancies between the prototype and model in the different similitudes can cause scale effects. Many times all the similitudes cannot be met because of limitations of the laboratory facilities. In this study laboratory effects will be a factor because of competing restrictions due to the wave tank dimensions and the need for significant acoustic travel time variations. The wave tank dimensions require that no wave heights greater than 20 cm are used because at 15 cm degradation
of the wave form starts to occur due to reflection from the walls of the tank and becomes progressively worse as the wave height increases. There also is a lower limit on usable wave heights as the acoustic returns are analyzed for travel time differences. Wave heights less than 5 cm are avoided because their travel time difference from a flat surface are less than 0.05 ms. Since this is a preliminary study wave heights with larger travel time differences are chosen to develop a relationship between surface conditions and acoustic travel time.

The combination of the limitations in tank dimensions and acoustics require the wave heights used in this study be between 5 cm and 15 cm, otherwise the laboratory effects would contribute inaccuracies to the backscattered data. Those limitations will limit the Pierson-Moskowitz sea states that can be scale modeled in the wave tank.

3.5.1 Geometric Similarity

The first similitude that must be preserved in a scaled model is geometric similarity. Geometric similarity is satisfied if the ratios of all corresponding linear dimensions are equal between a model and prototype.[18] Given the prototype operating water depth is assumed to be approximately 100 m, and the water depth in the wave tank from surface to acoustic devices is approximately 1 m, the geometric ratio is $1/100^{th}$. This means all model waves must be $1/100^{th}$ of the prototype wave height.

3.5.2 Dynamic Similarity: Froude Criterion

Despite observing geometric similarity the forces exerted by wave motion on an object or boundary may not be in similitude in the model unless the ratios of the vectorial forces in the two systems is the same[17]. That means there must be a constant prototype to model ratios of all masses and forces acting on the
systems. From Newton’s second law the vector sum of the external forces acting on an element in the system must be equal to the element’s mass reaction to the forces.

\[ m \frac{dV}{dt} = \sum F_n \]  

(27)

For a hydrodynamic problem Newton’s second law can be written in terms of:

\[ \vec{F}_i = \vec{F}_g + \vec{F}_\mu + \vec{F}_\sigma + \vec{F}_e + \vec{F}_p \]  

(28)

where \( \vec{F}_i \) is the inertial force, \( \vec{F}_g \) gravitational force, \( \vec{F}_\mu \) viscous force, \( \vec{F}_\sigma \) surface tension force, \( \vec{F}_e \) elastic compression force, and \( \vec{F}_p \) pressure force. Overall dynamic similarity requires that ratio of inertial forces between the model and prototype be equal to the ratio of the sum of all the active forces. Perfect dynamic similarity requires the same, plus that all individual force ratios be equal. There is no known fluid that will satisfy perfect dynamics similarity if the model is smaller in dimensions than the prototype[18]. For practicality some of the forces must be neglected if they are believed to be relatively unimportant to the primary physical mechanisms being studied.

In the case of this study the most vital forces are inertia and gravity. The free water surface is a balance of inertial force of the water and gravitational force of the atmosphere, and that ratio of inertial to gravitational forces is called the Froude number. The Froude number is:

\[ F_r = \sqrt{\frac{\vec{F}_i}{\vec{F}_g}} = \sqrt{\frac{\lambda \rho^2 v^2}{\lambda \rho^3 g}} = \frac{v}{\sqrt{g \lambda}} \]  

(29)

where \( g \) is gravity, \( \rho \) is fluid density and \( v \) is velocity. The Froude model criterion requires the ratio of fluid velocity to square root of gravity multiplied by wavelength must remain the same between the model and prototype. Since both the model
and prototype are subject to the same gravitational forces, the ratio of velocity to wavelength must remain the same in both systems. To preserve geometric similarity the model wavelength is $1/100^{th}$ of the prototype and therefore the ratio of velocities must be $1/10^{th}$.

$$\frac{v_p}{\sqrt{g \lambda_p}} = \frac{v_m}{\sqrt{g \lambda_m}}$$

(30)

where gravity is the same for both prototype and model. This results in the velocity scale factor being the square root of the wavelength scale factor.

$$\frac{v_p}{v_m} = \sqrt{\frac{\lambda_p}{\lambda_m}}$$

(31)

As this experiment does not measure wave velocity, rather wave height and period are the two controlled variables, the Froude number is used to determine the scale factor for wave period. Wavelength is related to period by:

$$\lambda = 1.56 \times T^2$$

(32)

Thereby the wave period scale factor will be related to the square root of the length scale factor. In summary the wave height scale factor between prototype and model is $1/100^{th}$ and $1/10^{th}$ for the period.

Another important scaling factor is the Reynold’s number, which comes into effect when viscous forces dominate in a hydraulic flow. The Reynold’s number and Froude number cannot both be satisfied. As previously mentioned, the similarity of one of these numbers combined with geometric similarity provide the proper conditions for hydrodynamic similitude in the majority of coastal models. Since the majority of coastal hydrodynamic models are scaled according to the Froude model law[18], the froude and geometrical similitudes combine to give satisfactory dynamic similitude between our model and prototype.
3.5.3 Wave Field Generation

The objective of this study is to generate a scaled model of sea surface conditions similar to conditions the GSO IES will experience. The GSO IES has experienced many different sea states and deployment depths but this experiment focuses on a proposed future deployment in shallow water such as on the US east coast continental shelf. The wavemaker will be used to generate wave field conditions scaled to the average conditions of the Pierson-Moskowitz sea states for the periodic waves and a JONSWAP wave spectrum for irregular waves, preserving geometric and Froude similitudes. In the first stage wave fields will be generated as a sinusoid with regular wave height and period. In the second stage of the experiment irregular wave fields will be generated with varying wave height and period, giving a closer model to sea surface conditions of the ocean.

In order to have a reproducible experiment a reliable method for wave generation had to be devised. Documented use of the wave tank in recent years[14] provides confidence that the wave tank can generate quasi-linear, periodic waves. In order to avoid nonlinear effects the wave maker needs to be limited to producing small amplitude waves with small paddle motions. Larger paddle motions result in a nonlinear, chaotic environment in the wave tank.

The wavemaker given a wave height and period by the user creates the wave field environment. It was shown in previous testing that the generated wave periods tended to have better accuracy than the generated wave heights in the URI wave tank[14], which was also observed in this experiment. In this project the capacitance wave gauges will serve to measure and verify the wave heights and wave periods. The data acquired from the wave gauges will be compared to the user specified inputs given to the wave maker to verify its accuracy. Wave field data was first collected from the wave gauges given wave periods and wave heights.
within the peak operating range to determine the reliability of the wavemaker. After the wavemaker was verified to generate wave heights and periods with reasonable accuracy, the next stage was to begin testing using the values of the main experiment.

3.6 Experimental Methods

This project focuses on generating 2D wave fields. The ocean environment is obviously not a 2D environment but this simplification of the problem will lay the foundation for future 3D wave field work. The first section of testing will consist of regular sinusoidal waves based on average periods and wave heights of Pierson-Moskowitz sea states. The periods and wave heights were scaled down by $1/10^{th}$ and $1/100^{th}$ respectively and possess a gaussian wave spectra. Table 2 shows the average parameters of sea states whose scaled values are within the limits of the wavemaker and acoustic requirements. Those Pierson-Moskowitz sea states are 6, 7, and 8.

<table>
<thead>
<tr>
<th>Sea State</th>
<th>Average T (s)</th>
<th>Average $\eta$ (m)</th>
<th>Scaled T (s)</th>
<th>Scaled $\eta$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>8.0</td>
<td>4.88</td>
<td>0.8</td>
<td>0.049</td>
</tr>
<tr>
<td>7</td>
<td>10.0</td>
<td>7.62</td>
<td>1.0</td>
<td>0.076</td>
</tr>
<tr>
<td>8</td>
<td>13.0</td>
<td>13.72</td>
<td>1.3</td>
<td>0.137</td>
</tr>
</tbody>
</table>

Table 2. The average values of Pierson-Moskowitz sea states 6, 7 and 8, along with the scaled values used in the experiment, where $T$ represents the period of the wave and $\eta$ the wave height.

For the first portion of the experiment regular sinusoidal wave fields will be used to examine the relationship between acoustic backscatter and wave field conditions. The regular sinusoids provide a controlled wave field where the effects of the variation in period and wave height can be more easily studied. The scaled sea states 6, 7 and 8 were selected because of the acoustic travel time difference requirements for wave height and the wave tank’s limitations on wave heights. As sea state 6 has a scaled wave height of 4.9 cm, it is the lowest that can be used...
for meaningful results in this study. Given the limitations of the size of the tank and capability of the wavemaker the highest wave height used was the scaled wave height from sea state 8 of 13.7 cm.

The wavemaker is operated through a LabVIEW interface program, called wave2.0 for the regular sinusoidal waves, which given water depth, wave height and wave period will generate a series of voltages. Those voltages are sent to the wavemaker piston, driving the piston to push the heavy flat panel with varying speed and distance (as seen in Figure 32). The user sets the number of cycles the wave maker produces, which determines the duration of time the wavemaker will run the wave pattern.

The second section of 2D wave field testing is irregular waves with a JONSWAP spectrum. The JONSWAP spectra was used in place of a Pierson-Moskowitz wave spectra because JONSWAP more accurately depicts the wind-driven gravity waves on the surface. In the open ocean the wave spectra was found to never fully develop[19]. Instead the wave spectra continues to develop non-linear, wave-to-wave interactions over long distances, which a Pierson-Moskowitz wave spectra does not account for. The Pierson-Moskowitz wave spectra is represented by:

\[ S(\omega) = \frac{\alpha g^2}{\omega^5} e^{-\beta \omega^4} \]  

(33)

Where \( \omega = 2\pi f \) is the wave angular frequency, \( \alpha = 0.0081 \), \( \omega_0 = 0.797 g/U_{10} \) and \( U_{10} \) is the wind speed at 10.0 m above the sea surface. The peak frequency of a Pierson-Moskowitz spectrum is:

\[ \omega_p = \frac{0.797 g}{U_{10}} \]  

(34)

The significant wave height calculated from the Pierson-Moskowitz sea spectrum
is:

\[ H_s = 0.21 \frac{(U_{10})^2}{g} \]

Hasselmann[19] after analyzing data from the Joint North Sea Wave Observation Project (JONSWAP) proposed another wave spectra which accounted for the non-linear, wave-to-wave interactions over long distances. As the JONSWAP is a more accurate depiction of ocean surface gravity waves, it was desired to create a scaled JONSWAP wave spectrum in the wave tank. A program was developed which could generate a series of voltages to send to the wavemaker corresponding to an irregular wave field with a specified wave spectra.

To create an irregular wave field a MATLAB program `random.m` was created by Stefan Grilli which could generate a voltage series for the wavemaker with either a Pierson-Moskowitz or JONSWAP sea spectra. The program `random.m` works by taking a user defined data file `tank.dat` which contained information such as, the target period, target significant wave height, fetch, wind speed at 10 m above the ocean surface and water depth, and calls another program `spectre.m` to generate the wave spectra based on the given information. The given target period was 1.5 s and the target significant wave height was approximately 10 cm. (see Appendix C for all the `tank.dat` inputs in Table C.6)

If the fetch given in `tank.dat` is -1, `spectre.m` will generate a Pierson-Moskowitz wave spectra, otherwise a JONSWAP will be generated. In this case a fetch of 12000 m is given, whereupon the program uses the JONSWAP case to calculate the wind speed 10 m off the water surface \(U_{10}\) and the constant \(\alpha\) used to generate the wave spectra. \(U_{10}\) and \(\alpha\) are calculated by the following equations:

\[ U_{10} = \frac{10648 \times g^2}{Fetch \times (\omega_p)^3} \]
\[
\alpha = \frac{0.57}{\sqrt{g \times \text{Fetch} / U_{10}^2}}
\] 

(37)

The JONSWAP wave spectra is calculated over a pre-fixed frequency interval, \(\omega\), with a fixed number of frequencies within the interval. The low frequency cutoff is \(\omega_1 = 0.35\), the high frequency cutoff is \(\omega_2 = 32\), number of frequencies for initial spectral analysis is 1000. The spectrum is defined as:

\[
S(\omega) = \frac{\alpha(g)^2}{\omega^5} e^{-\frac{5}{4} \left( \frac{\omega}{\omega_p} \right)} e^{-\frac{(\omega - \omega_p)^2}{2\sigma^2\omega_p^2}}
\]

(38)

where \(\sigma = 0.07\). The spectre.m program then finds a narrower frequency interval for the wave spectrum, focusing on the frequency spectrum closer to the target frequency.

In order to meet the eventual goal of generating a series of wave heights to create a voltage series for the wavemaker, the wave spectra needs to be related to surface variations. Related to the spectrum is a series of characteristic numbers known as the spectral moments:

\[
m_k = \int_0^\infty \omega_k S(\omega) d\omega
\]

(39)

where \(k = 0, 1, \ldots\). The spectral moment, \(m_0\), is the variance of the surface:

\[
m_0 = \int_0^\infty \omega S(\omega) d\omega
\]

(40)

The square root of the surface variance is the standard deviation of the surface, which according to commonly held standards, four times the standard deviation is the significant wave height, \(HS_0\):

\[
HS_0 = 4\sqrt{m_0}
\]

(41)
The *spectre.m* program goes on to fine tune fetch, U10 and \( HS_0 \) to match the target significant wave height \( HS_t \) by using a correction constant, \( \beta = HS_0/HS_t \). The corrected U10, \( U_{10c} \), is found by multiplying U10 by \( \beta \). The \( U_{10c} \) value is then used to calculate a new fetch:

\[
Fetch_c = \frac{10648g^2}{U_{10c}\omega_p^3}
\]  

(42)

In turn corrected values for \( \alpha \), the wave spectra and \( HS_0 \) are calculated using the corrected fetch and \( U_{10c} \). The corrected wave spectra was used to generate amplitudes and phases of the free surface where:

\[
A_n = \sqrt{2\Delta \omega S_c(w)}
\]

(43)

\[
\varphi_n = 2\pi R
\]

(44)

where \( R \) represents a random number between zero and one. The surface amplitude, phase, corrected wave spectra, frequencies and significant wave height are relayed to the *random.m* to generate a wave elevation time series defined as:

\[
\eta = \sum_{n=1}^{N} A_n \cos(\omega_nt + \varphi_n)
\]

(45)

This wave elevation time series is given to a MATLAB function *zeroup.m* that computes the zero up-crossing height from the given time series data. The function outputs a time series of wave heights and periods, which are passed to another function *flap.m* that uses the wavemaker transfer function, \( S_0/\eta \), relating the stroke length of the flap-type wavemaker to the water wave height.

\[
\frac{S_0}{\eta} = \frac{2k_d d + \sinh(2k_d d)}{(4\sinh(k_d d)) \times (\sinh(k_d d) + (1 - \frac{\cosh(k_d d)}{k_d d}))}
\]

(46)
There is also a correction applied to for the difference in water depth and the hydraulic jack location, \( S_0/\eta = S_0/\eta \times \frac{dt}{d} \), to the wavemaker transfer function, where \( dt=1.925 \text{ m} \). The transfer function is used to transform individual waves into wavemaker stroke length, \( \text{Stroke} = \eta \times S_0/\eta \). Another transfer function, Equation 26, is used to relate the stroke length to a voltage series which is given to the wavemaker for generating waves.

In application, the resultant wave field produced from the irregular JON-SWAP wave spectra voltage series by the wavemaker had a maximum wave height and peak period different from the intended wave field. Differences were to be expected as mechanical imperfections and friction within the wavemaker system would alter the observed wavemaker output from the given wave field parameters. Another MATLAB code \textit{analysis.m} (found in Appendix C) was used to take the observed wave spectra, compare it to the target wave spectra generated by \textit{random.m} and use the differences to create a new target wave spectra accounting for the mechanical imperfections.

However, there were problems with implementing the improvements made by \textit{analysis.m}. The programs \textit{random.m} and \textit{analysis.m} had not been used with the URI wave tank and wavemaker before and there were no significant improvements after many attempts using \textit{analysis.m} to bring the measured spectra closer to the target spectra. Figure 39a. shows the water surface elevation corresponding to the voltage series \textit{random.m} generates for the wavemaker. The signal is approximately 327 seconds long with surface elevations varying from +/- 7.0 cm. After the corresponding voltage series are implemented by the wavemaker, the resultant wave field bears little resemblance to the target wave field in Figure 39. In Figure 39b. the surface elevation varies from +/- 2.5 cm, yield a maximum wave height around 5 cm, and the peaks do not match between target and measured wave fields.
After investigating possible causes for the failure to produce the target wave field such as environmental, mechanical, computer and human error, the primary cause was determined to be human error. The wave periods and surface elevations were within the optimum operating range of the wavemaker, and although the irregular wave field requires frequent changes wave field parameters the wavemaker has previously been able to produce a desired irregular wave field[14]. Instead, user error in using the LABVIEW program, *Random Wave 4.0*, caused the discrepancy in the wave field. The *Random Wave 4.0* program requires the voltage series and size of file as inputs for operation. The voltage series file size is 32,700 data points, while the default setting is 1000 data points with a given sampling frequency of 100 Hz. This means if the user fails to change the file size input the LABVIEW program attempts to implement a 10 s voltage series, despite being given a 327 s voltage series. There appeared to be a repetition of a 10 s segment of time within the observed surface elevations that were collected for a 300 s duration. Therefore the conclusion is the user’s failure to input the correct length of the file resulted in the wave field not matching the target.

Figure 39. The surface elevations of the target wave field (a) and the measured wave field (b) produced in the URI wave tank. The surface elevations and peaks do not correlate well.
The repetition of the first 10 s of the irregular wave field resulting in a different wave spectrum than intended, but the wave field was irregular and therefore useful for analysis. The hydrophones and wave gauges record to the DAQ for a duration of 10 s during data collection, so the repetition of the wave field does not affect the individual data sets too adversely. The recording time length for data collection was chosen to get acoustic backscattering from different waves in the wave field, and also as not to make data files that were too large. As the wave periods are on the order of 1 s, 10 s will give approximately 10 individual waves that the sound can reflect off. This gives multiple reflections that can be analyzed for trends in acoustic travel time differences.

3.7 Experimental Results

Both regular and irregular wave fields were collected, although there were problems producing the irregular wave fields. Over the whole duration of the irregular wave program (327 s) the wave field bore little resemblance to the voltage series given to the wavemaker, appearing to be much more uniform in wave height. However, when the wave data is taken concurrently with the acoustics data only 10 s of data was collected and the wave fields although lacking in wave height appeared fairly good over the short period. The regular wave field series also had a similar problem with wave heights that were shorter than the initial inputs to the wavemaker LabVIEW program.

3.7.1 Regular Wave Fields

In Figure 40 the 10 s data samples of regular sinusoidal wave heights generated in this experiment are shown. The regular wave field data sets for the average values of sea state 6, 7 and 8 had average wave periods of 0.803, 1.00, and 1.30 s, and average wave heights of 4.12, 5.45 and 11.0 cm respectively. Just as Bengston[14]
found the wavemaker produces wave fields with periods that are very close to those given to the operating program, but the wave heights are off by a significant amount. In the future this might be reduced by recalibrating the wavemaker paddle.

![Wave Height - Regular Field Sea State 6](image1)

![Wave Height - Regular Field Sea State 7](image2)

![Wave Height - Regular Field Sea State 8](image3)

(a) (b) (c)

Figure 40. Three 10 s samples of the regular wave field modeled after average values for Pierson-Moskowitz sea states 6 (a) 7 (b) and 8 (c). The wavemaker was given a wave height of 4.9 cm and a period of 0.8 s for (a), a height of 7.6 cm and a period of 1.0 s for (b) and a height of 13 cm and a period of 1.3 s for (c).

### 3.7.2 Irregular Wave Fields

The irregular data sets 2, 6, 7, and 9 have average period of 1.057, 1.083, 1.128 and 1.1812 s, and average wave heights of 3.42, 4.20, 4.57 and 4.15 cm respectively.
While each data set is irregular the periods and wave heights are not what they were intended to be. The irregular wave voltage series generated by `random.m` (see Appendix C) had a peak period of 1.5 s and a peak height of 9.71 cm. However, as you can see from the plots in Figure 41 and the wave field is not reaching wave heights above 6 cm.

![Irregular Wave Field #2](image1)

![Irregular Wave Field #6](image2)

![Irregular Wave Field #7](image3)

![Irregular Wave Field #9](image4)

Figure 41. Four (a,b,c,d) 10 s samples of the irregular wave field modeled after a JONSWAP wave spectrum with wave heights ranging from approximately 2.0-6.0 cm and periods of 0.6 seconds to 1.7 seconds, within the limits of sea state 6.

Through the wave spectra of the target JONSWAP spectrum generated by `random.m` and the measured spectrum of the wavemaker’s output the difference in the peak frequency are illustrated. The target JONSWAP wave spectra has its
peak frequency of 0.67 Hz, corresponding to a peak period of 1.5 s. The measured wave spectra of the wavemaker’s output has multiple peaks with the largest at approximately 1.15 Hz, corresponding to a peak period of 0.870 s. There are also peaks at between 0.5-1.5 Hz, corresponding to peak periods of 0.67-2.0 s. If the periods and wave heights from the collected data are scaled up, they would have a significant wave height around 5.0 m and a period of 8.7 s, which, are within the parameters of sea state 6. However the full scale values of the target spectrum would be within the parameters of sea state 7. The measured wave field is considerably different from the target wave field, but still usable for modeling and comparison.

Figure 42. (a) The target JONSWAP wave spectrum generated by random.m for the irregular 2D waves with a peak frequency of 0.67 Hz (or a period of 1.5 s). (b) The measured wave spectrum generated by the wavemaker using the voltage series corresponding to the target wave field depicted in Figure 39. The measured frequency spectrum is shifted higher than the target spectrum to approximately 1.15 Hz, at almost twice the target frequency.

3.7.3 Acoustic Backscattering in a Regular and Irregular Wave Fields

The acoustic signal sent in this experiment, shown in Figure 43a, is a 3 Vpp sinusoidal burst repeated every $1/10^{th}$ of a second for 10 s. The signal is given a gain of 10x prior to being sent to the acoustic source. The received acoustic signals in
Figure 43b-d are given an amplification of 1000x before those readings were taken with the DAQ. From this general overview of the acoustics it can be seen that the presence of a variable wave field creates variances in the acoustic amplitude. This will be used later to explore the relationship between dimensionless acoustic intensity and the wave field parameters.

Figure 43. (a) The sent acoustic signal, 3 Vpp with a burst every 1/10th of a second for 10 seconds. (b) The received acoustic signal from a calm, flat surface. The oscillations in signal amplitude are more pronounced than in (a). (c) The received acoustic signal backscattered from a regular sinusoidal surface with a period of 1.0 s and wave height of 7.6 cm. The signal amplitude oscillates more than (a) and (b). (d) The received acoustic backscattered signal for irregular wave field 7 (figure 41(c) shows the wave field conditions). The acoustic amplitude oscillates and varies on a similar order to (c).
In Figure 44 there is a closer look at an individual set of a sent pulse and the resultant acoustic backscatter in the case of a variable wave field (a) and a flat surface (b). Both pulse sets were selected at the same point in their acoustic record (the 35th ping out of 100). The difference in backscattered signal’s amplitude is easy to see and later in the Numerical Analysis Section on Dimensionless Acoustic Intensity the relationship between the wave field parameters and the acoustic amplitude/intensity will be explored.

Figure 44. (a) This is from the irregular wave field data set 7. The sent acoustic pulse is in red and the resultant backscattered signal in blue. (b) This is from the flat surface data set and similarly the sent pulse is in red and the resultant backscattering in in blue. Both pulses were selected at the same point in time in their acoustic record (they both are the 35th pulse out of 100).

However the time of arrival differences that will be analyzed in the next section for variances with wave field parameters are not so easily discernable. The differences in the time of arrivals will be rather small, so in order to best observe an noticeable change all the time of arrival differences between the direct and surface-reflected pulses for a data set (each set contains 100 pulses) will be calculated and histograms will be plotted to observe the distribution. The spread and amplitude of the distributions will be examined in relation to the surface conditions and compared to travel time PDFs derived from work by Godin, Fuks and
3.8 Numerical Analysis

Previously, Godin and Fuks[1, 2], and Fuks, Charnotskii and Godin[3] investigated the statistical properties of travel time variations and pulse intensity backscattered by 2D and 3D rough surfaces. They concluded the probability distribution functions (PDFs) of the normalized deviation of the travel time ($\tau$) of the first and second backscattered pulses in the absence of roughness are functions of a dimensionless parameter, $T_D$, which is given by:

$$T_D = \frac{\gamma^2 H}{\sqrt{2\pi}\sigma}$$  \hspace{1cm} (47)

where $\gamma^2$ and $\sigma^2$ are the variances of the rough surface slope and elevation, and $H$ is the source altitude. The expression is derived for an omni-directional source assuming the rough surface has Gaussian statistics and the pulse duration is sufficiently short such that signals backscattered near individual specular points on the rough surface do not overlap in time. The pulse durations and time separations between the repeated signal were designed to satisfy that requirement in this experiment.

However, this study focuses on the first backscattered pulse because due to the scale of the tank, bottom and side reflections interfere with the later surface reflections. Thereby, the PDF of the normalized travel-time difference ($\tau$) for the first arrival can be described in terms of $T_D$ as:

$$w_1(\tau) = \tau \varphi_s(\tau)e^{-\varphi_s(\tau)}$$

$$\varphi_s(\tau) = T_D e^{-\frac{\tau^2}{2}}$$  \hspace{1cm} (48)

Where the mean travel time of the first arrivals has the form,
\[
\langle \tau_1 \rangle = \left[ \frac{1}{\pi 2T^2} + \frac{1}{\sqrt{4ln^2T + 1 + 2\gamma}} \right]^{-\frac{1}{2}}
\] (49)

Following the work of Godin and Fuks\cite{2, 1}, Figure 45 shows the PDF and mean travel time of first arrivals for various values of \(T_D\) from Equation 47.

![Figure 45. The travel time difference of the arrival of the first backscattered pulse at different values of the dimensionless parameter \(T_D\), assuming a spherical wave and omni-directional source.](image)

Fuks et al.\cite{3} also derived the expression for the intensity PDF \(w_1(J)\) in terms of the joint PDF \(w_1(\tau, J)\) of the propagation time \(\tau\) and the intensity \(J\).

\[
w_1(J) = \int_0^\infty w_1(\tau, J)d\tau
\] (50)

where the joint PDF \(w_1(\tau, J)\) of the propagation time \(\tau\) and the intensity \(J\) is given by:

\[
w(\tau, J) = \frac{1}{2J^3} \sqrt{\frac{3}{\pi}} e^{-\frac{3J^2}{4}} erfc\left[\sqrt{\frac{2}{J}} - \frac{\tau}{2}\right]
\] (51)

Fuks et al.\cite{3} defined \(J\) as the normalized acoustic intensity:

91
\[ J = \frac{I}{I_0} \]  

(52)

In their study they defined the normalizing intensity \( I_0 \) as the intensity of a signal scattered from a specific gaussian curvature based on an average of the second derivative of the surface elevation in the x and y direction. That study however was dealing with 3D wave fields and this study focuses on 2D fields. Instead the dimensionless intensity, \( J \), is found by normalizing the wave fields acoustic intensity with the flat surface acoustic intensity. Intensity is defined as:

\[ I = \frac{P^2}{\pi 4r^2} \]  

(53)

where \( P \) is acoustic pressure and \( r \) is the radius of the area affected by the pressure. As both the flat surface and rough surface voltage series would be converted in the same manner to an acoustic pressure and would be subject to the same area, we can simply use the voltage series to derive the dimensionless acoustic intensity. The maximum voltage of each surface-reflected pulse in a rough wave field is calculated and divided by the corresponding maximum voltage of the flat surface field to get the dimensionless acoustic intensity \( J \). Similar to the travel time differences, the dimensionless intensity \( J \) values for a wave field will be plotted in a histogram to compare the spread and amplitude with the \( J \)'s from the other wave field conditions.

Smaller intensity levels reflect a higher surface maxima which, correlates to a larger surface curvature and conversely intensity levels greater in magnitude indicate a smaller surface height and curvature as the dimensionless parameter \( T_D \) (Equation 47) is directly related to surface height. Assuming a Gaussian correlation function for the surface roughness Fuks et al.[3] have derived expressions for the intensity PDF Equation 50 for both plane and spherical waves. This experiment uses spherical wave case, given our omni-directional source. Figure 46
Figure 46. Intensity PDF $w_1(J)$ of the first backscattered arrival for a spherical incident wave.

using set values for $T_D$ and assuming a spherical wave front shows the intensity PDFs calculated using the approach outlined by Fuks et al.[3] and illustrates the relationship between surface height and intensity.

Godin and Fuks[1] also investigated travel time bias resulting from surface roughness. They showed in the case of large-scale roughness, when one specularly reflected point moving randomly around its unperturbed position it results in negative travel time bias. That effect would decrease the mean travel time. In the opposite case of small-scale roughness there are many specular points, destroying the single path propagation and resulting in a positive travel time bias.

The determining factor between large-scale and small-scale surface roughness is the relationship between correlation length ($\rho$), surface slope ($\gamma$) and the angle of incidence ($\theta$). Where,

Small-Scale Roughness

$$|\gamma_x| > \rho_x \cos(\theta)$$  \hfill (54)
Large-Scale Roughness

\[ |\gamma_x| < \rho_x \cos(\theta) \]  (55)

In the case of surface gravity waves the conditions of Equation 55 are met, and experiments in the open ocean have observed a negative travel time bias.[5] The travel time bias for a surface reflected acoustic wave is:

\[ \langle \Delta(t) \rangle = \frac{2\sigma^2}{c(z_s + z_p)} \left[ \sin^2(\theta) \cos(\theta) - a^2 \frac{1 + \cos^2(\theta)}{\cos(\theta)} a^2 \right] = \frac{z_s z_p}{\rho_x^2} \]  (56)

Where \( \langle \Delta(t) \rangle \) is the travel time bias, \( \sigma \) is the rms surface elevation, \( z_s \) is the source depth, \( z_p \) is the receiver depth, and \( \theta \) is the angle of incidence. Equation 56 is not valid for small grazing angles equal to or smaller than the characteristic slope of the rough surface. In the case of an inverted echo sounder with \( \theta = 0 \) and \( z_s = z_p \) Equation 56 simplifies to:[1]

\[ \langle \Delta(t) \rangle = -\pi^2 \sigma^2 t_0 \lambda^{-2} \]  (57)

Where \( t_0 \) is the two-way travel time and \( \lambda \) is the surface wave wavelength. With known travel time bias, wave height, and two-way travel time one can obtain the surface wave’s wavelength. Following an example in work by Godin and Fuks[1] of travel time bias plotted as a function of the receiver depth, a similar plot was generated. Figure 47 illustrates the increasingly negative travel time bias as the receiver depth increases in a wave field with characteristics of open ocean surface gravity waves (a roughness correlation length of \( \rho_x = 200 \text{ m} \) and an rms surface elevation of \( \sigma = 2 \text{ m} \)). The acoustic source is assumed to be at 1000 m, reflecting a fairly deep deployment.

In past IES deployments, travel time variations due to surface roughness were considered noise, and to suppress the noise observed travel times are averaged over
Figure 47. Travel time bias of a surface-reflected acoustic wave as a function of receiver depth, assuming a roughness correlation of $\rho_x = 200$ m, sound speed of 1500 m/s, an RMS surface elevation of $\sigma = 2$ m, and three different incident angles were used of $0^\circ$, $45^\circ$, and $60^\circ$. The source depth is assumed at 1000m, and the receiver depth is varied.

many pulses.[5] However, in this study the travel time variations are of primary interest as they indicate the surface condition, such that the travel times will not be averaged out in the eventual full scale IES experiment. Therefore it is important to know how the travel time bias is related to the characteristics of the surface and how the acoustic devices are deployed.

3.9 Comparison of Experimental Data and Model

3.9.1 Acoustic Travel Time PDF

Once the data was collected concurrently for the acoustics and wave field conditions with regular and irregular waves, the acoustic data was analyzed for travel time for the direct surface reflection. As previously mentioned, each data set is 10 seconds long with an acoustic pulse sent every $1/10^{th}$ of a second, yielding 100 acoustic returns. The MATLAB code *ArrivalTimeDiff.m* (Appendix C) isolates
the individual acoustic pulses for analysis. The beginning of the direct return and surface-reflected return are isolated (see Figure 35 for reference of the different acoustic returns) and the time difference between them is calculated. As shown earlier in Table 1 the travel time for the direct pulse from source to receiver in the case of a still surface is approximately .138 ms and the direct surface reflection 1.40 ms. The relative travel time between the two is approximately 1.26 ms.

The sections below show histograms of the arrival time differences calculated by *ArrivalTimeDiff.m* for regular and irregular sinusoidal wave fields. Figure 48 shows travel time differences with about 50 instances of approximately 0.96 ms and 25 instances of 1.08 ms. The reason there are a total of 75 returns instead of 100 is some of the surface-reflected acoustic returns have an amplitude very close to the direct signal, which makes it very difficult to differentiate with the MATLAB program resulting in erroneous arrival time differences. Therefore the *ArrivalTimeDiff.m* program removes any results that are obviously wrong, usually giving less than 100 arrival times for an individual data set.

![Flatwater](image)

Figure 48. Histogram of the travel time between the direct acoustic pulse between source and receiver, and the surface-reflected acoustic return at a calm water surface.
The expected relative travel time difference for flatwater conditions is about 1.26 ms yet the results from the analysis are 0.96 ms and 1.08 ms, giving a discrepancy of approximately 0.3 ms. However there is the issue of travel time bias mentioned earlier in the previous section. That is a fairly small discrepancy, but in our efforts to find a relationship between surface conditions and the acoustic backscattering it could be significant. In the previous section Godin[1] and Watts and Rossby[5] reported there is a travel time bias associated with the water surface roughness. Surfaces with large roughness have a negative travel time bias, predisposing them for early arrivals while surfaces with small roughness typically have a positive travel time bias. However, flatwater has no roughness and therefore would allow for many specular points, predisposing the acoustic returns for a positive travel time bias. That however, would mean for late arrival from the surface-reflections, which is the opposite of the results.

From figure 47 travel time biases were shown on the order of -0.1 s in deep water deployments with a rough surface. In this experiment’s case our water depth is much more shallow, approximately 1.0 m. In Figure 49 the travel time bias is plotted for a source depth of 1.0 m, incident angles of 0°, 15°, and 30° and a sound speed of 1450 m/s. The roughness correlation length and RMS surface are based upon the average values for a scaled Pierson-Moskowitz sea state 6 at 2.40 m and 0.035 m respectively. The travel time bias for a source and receiver at 1.0 m and an angle of 0° is -0.3 ms, which is the same magnitude as the discrepancy noticed between the predicted and measured times of arrival for the calm surface conditions. While a negative travel time bias does not apply to a flat surface, it will apply to the cases below of the irregular and regular wave fields as they have been modeled after surface gravity wave values typical of sea states 6-8.
Figure 49. Acoustic travel time bias for a source depth of 1.0m, with incident angles of 0°, 15°, and 30°. The roughness correlation length is $\rho_x=2.40$ m, with a RMS surface of $\sigma=0.035$ m and a sound speed of 1450 m/s.

**Regular Wave Fields**

In Figure 50 there are three travel time distributions for regular sinusoidal waves representing the average wave height and period for Pierson-Moskowitz sea states 6, 7 and 8. As the data sets increase progressively in wave height and period the travel time distribution spreads out. However it is unknown whether it is the wave height or period which is the stronger factor in the width of the distribution.

In order to verify our experimental results the travel time distributions are compared with travel time PDFs based on work by Godin, Fuks and Charnotskii[1, 2, 3] using the experimental wave parameters. The travel time PDF defined in Equation 48 is dependent on the $T_D$ and $\tau$, where $T_D$ is defined by equation 47 and $\tau$ is the dimensionless travel time difference defined by:

$$\tau = \frac{\delta(t)}{2\sigma} = \frac{h}{\sigma} \quad (58)$$

where $\delta(t)$ is the difference between the actual travel time from a varying
surface and the travel time of a pulse reflected from the mean surface, $\sigma$ is the square root of the variance of the rough surface elevation and $h$ is the height of the varying surface. The MATLAB program GodinPrep.m in Appendix C calculates the $T_D$ and $\tau$ values given the height and period of the wave field. The program zeroup.m is used to generate the wave heights and periods of the individual waves in a given data set. Using the shallow water assumption depth $< \lambda/11$ the phase velocity is calculated and is multiplied by the periods to find the wavelengths of
the individual waves. The wavelengths are then used to calculate the mean rough surface slopes ($\gamma^2$), by dividing the wave height by half the wavelength. This yields not the most precise surface slope but is close enough for this study. The mean of the surface slopes and the mean of the wave heights are applied to Equation 47, yielding the dimensionless parameter $T_D$ for the given wave conditions. The calculated $T_D$ value are applied to Equation 48 generating a PDF for the given wave field. The dimensionless travel time $\tau$ was converted into the travel time from the rough water surface and back using the relationship in Equation 58.

Figure 51 shows the propagation time PDFs for the regular sinusoidal wave fields. As the collected data demonstrates, the wave field modeled after sea state 7 has less of a spread over of the travel time than the wave field modeled after sea state 8 with the greater period and wave height. However, the regular wave field with the smallest wave height and period modeled after sea state 6 has a PDF very close to sea state 8, which was not expected. However, with the wave heights and periods so relatively close to each other the dimensionless parameters $T_D$ are all very close to one resulting in very similar propagation time PDFs.

**Irregular Wave Fields**

Figure 52 below contains histograms of the time of arrival differences between the direct and surface-reflected acoustic signals in an irregular wave field that was attempted as a scaled version of JONSWAP wave spectra, but as discussed previously while still irregular over the 10 s data collection intervals it is not the wave spectre originally intended.

As was hoped the irregular wave data have very similar travel time distributions. They all are spread from about 0.92 to 1.1 ms, with a large concentration towards the 0.95 to 1.0 ms range, a dip between 1.0 and 1.05 ms and a second, smaller concentration of arrivals between 1.05 to 1.1 ms. Given the irregular wave
The two concentrations of arrival times in Figure 52 is an interesting feature. There is a difference of approximately 0.1 ms between the first group centered around 0.95 ms and the second group about 1.05-1.1 ms. With a sound speed of 1450 m/s a travel time difference of 0.1 ms equates to a distance of 14.5 cm, which would be the round trip distance of a wave height of 7.25 cm. The wave heights of the irregular wave fields could vary up to approximately 7 cm, so the two groups of travel time could reflect the crests and troughs of the wave field.

Examining the propagation time PDFs of the irregular wave data sets in figure 53 the wave field conditions for the data sets 2 and 9 have a narrower
Figure 52. Histograms of the time taken by an acoustic pulse to travel to the water surface and return in an irregular wave field recorded in the URI wave tank on June 30. These plots are generated from data sets (a) 2, (b) 6, (c) 7, and (d) 9, which are 10 second samples of a scaled JONSWAP sea spectra within sea state 6 wave field conditions.

distribution over dimensionless travel time difference than data sets 6 and 7. These data sets were all found to be very similar in the analysis of the collected data’s travel time distribution, but there are some slight differences, i.e. data set 9 has a slightly narrower travel time distribution and data sets 6 and 7 have slightly greater amplitudes in figure 52.
Additional Data - Varying One Parameter While Holding the Other Constant

To further understand the relationship between the wave surface conditions and the acoustic backscatter data was taken for two different cases: (1) where the wave period was held constant and the wave height changed between data sets and (2) when the wave height was constant and the wave period changed. The experimental data show the travel time difference distribution spreading as the regular sinusoidal wave period and height increased. However, it could not be discerned whether the wave period, height or a combination of both was the stronger factor in determining the distribution of travel time differences. The modeling based off of Godin, Fuks and Charontskii the PDF of propagation time is a function of surface roughness elevation and slope, as seen in Equation 47. The dimensionless parameter $T_D$ has a direct squared relationship with rough surface slope and an inverse relationship with rough surface elevation.

Below in Figure 54 the wave period is held constant while plots (a)-(d) rep-
resent the travel time difference between the direct and surface-reflected acoustic pulses at wave heights 4.0 cm to 10.0 cm. As the wave height increases the travel time difference distribution broadens and shifts towards earlier arrivals. As it was mentioned earlier, large-scale roughness is prone to early acoustic arrivals so it is logical that increasing wave heights which cause increased roughness would shift the travel time distribution toward earlier times.

Figure 54. Histograms of the travel time difference between the direct and surface-reflected acoustic pulses where the wave period is held constant and the surface height is varied. (a) has a wave height of 4.0 cm, (b) 6.0 cm, (c) 8.0 cm, and (d) 10.0 cm.

The other case under investigation, a static wave height with different periods, is shown in Figure 55. Regular sinusoidal waves with a wave height of 4.0 cm and
periods varying from 1.0 s to 2.0 s were used. The wave height of 4.0 cm is a bit shallower for a good acoustic travel time separation, but it was the best available. As the wave period increases there was practically no spreading or contraction of the distribution. In fact all the data sets had a distinct peak at a travel time of approximately 1.02 ms, with some increases in the number of return pulses at that time by the greater periods.

### 3.9.2 Acoustic Intensity PDF

Another method used in this study to characterize the relationship between surface conditions and the reflected acoustic intensity. Following the Equations 51, 50, and 52 a model was developed based upon work by Fuks, Charnotskii and Godin [3] for the acoustic intensity from reflections on rough water surface. As they reported in their study, and as the Figure 56 supports, the higher surface maxima result in a specularly reflected signal with smaller intensity. Typically the earlier an acoustic signal arrives the less energy it carries.

The $T_D$ parameters in this scaled study are generally on the order of one, and as Figure 56 shows, have a larger spread over the dimensionless intensity values with greater $T_D$ parameters. Accordingly in the experimental data we should observe decreases in acoustic intensity in wave fields with larger wave heights. In order to develop dimensionless intensity values for a wave field data set the received acoustic voltage series is divided by the flat water voltage series. Histograms were used to view the acoustic intensity distribution of the regular and irregular wave fields and the results are shown in Figures 57 and 58.

In Figure 57 the regular wave field intensity distribution does not appear to be spreading out increasingly as the wave height increases. One issue could be the wave conditions are so close to each other, with height differences of only a few centimeters. Similarly Figure 58 shows intensity distributions that are very
Figure 55. Histograms of the travel time difference between the direct and surface-reflected acoustic pulses where the wave height is held constant and the period is varied. The wave height is 4.0 cm and the periods are (a) 1.0 s (b) 1.25 s (c) 1.5 (d) 1.75 and (d) 2.0 s.
Figure 56. Acoustic intensity for various nondimensional parameters $T_D$ using the approach Fuks, Charnotskii and Godin\cite{3} outlined in their paper. The nondimensional acoustic intensity decreases as $T_D$ increases.

similar, which should be, as the wave field conditions affecting the irregular wave data sets are very similar.

3.10 Discussion

From Figure 56 it would not be expected to see significant changes in the acoustic intensity, as the difference in $T_D$ varies between 1.5 and 0.5 for the wave tank scaled wave fields. At $T_D=1.0$ the intensity PDF is spread broadly over the array of dimensionless intensities with a fairly low PDF amplitude. Small changes on the order of $1/10^{th}$ are not going to produce significantly different intensity PDFs. However, in a full-scale ocean experiment where the the dimensionless parameter $T_D$, which depends on rough surface slope and elevation, will experience more varied wave field conditions which could significantly change $T_D$ and thereby experience significant changes in normalized acoustic intensity.

The acoustic propagation time PDF did yield noticeable changes even with the small scale of the experiment. As the surface wave height increased the travel time
Figure 57. Histograms of dimensionless acoustic intensities for regular sinusoidal wave fields with (a) a period of 0.8 s and wave height of 0.049 m, (b) period of 1.0 s and wave height of 0.076 m and (c) period of 1.3 s and wave height of 0.137 m.

PDF broadened and shifted along the time axis towards earlier arrivals. The earlier arrivals would indicate a reduction in acoustic intensity, which was not observed as the intensity PDF is less sensitive to small changes in the surface roughness than the propagation time PDF as evidenced by the shape of the functions in Figures 56 and ???. However, when the wave height remained static and the wave period changed the propagation time PDF registered relatively no change, indicating wave height is a more dominant factor in determining acoustic travel time.

The propagation time PDFs were able to show the varying wave heights from
the crests and troughs of the wave field in Figures 50, 52 and 54. The acoustic travel time differences in the regular wave field in Figures 50 and ?? had a gaussian shape, as expected from the modeled propagation time PDFs. The travel time difference distributions spread out as the wave height increases, reflecting the increasing differences in wave height from crest to trough in the wave fields. The irregular wave field in Figure ?? has a different feature, where there is a gap between two groups of acoustic travel times of approximately 0.1 ms for all the histograms. The corresponds to a distance of 14.5 cm assuming a sound speed of
1450 m/s, which correlates to a wave height of approximately 7.25 cm. As the irregular wave fields could vary up to wave heights of 7 cm, the two groups of travel times would relate to the crests and troughs of the wave field. The reason for the 0.1 ms gap in the irregular propagation time histograms versus the regular propagation time histograms is most likely the irregular shapes and patterns of the wave field.

While the small scale of this experiment reduced some of the effectiveness of the geometrical optics approximation, it is believed the approximation would work well in a large-scale experiment. Reportedly the geometrical approximation has been used successfully by IES and many other acoustical applications.[3] As such the modeling developed in this study should provide a platform for the full scale experiment with an IES off the Northeastern United States coast for preliminary modeling and analysis of recovered acoustical data.

3.11 Conclusion

In conclusion the geometrical approximation outlined by Godin, Fukes and Charnotskii provides a means to estimate sea surface conditions via changes in the acoustic propagation travel time and in normalized acoustic intensity PDFs. The PDF relationships are based upon the dimensionless parameter $T_D$ which, depends upon the rough surface elevation and slope, and source depth. The scaled wave fields used in this experiment was based upon open ocean gravity waves, modeled after average values of a Pierson-Moskowitz and a JONSWAP wave spectra. In analyzing the acoustic propagation travel time early arrivals were noted, which are typical for the large-scale roughness of ocean surface gravity waves. Early acoustic arrivals are also linked to a reduction in acoustic intensity, however this effect was not able to be illustrated as the acoustic intensity PDFs have less variation at smaller $T_D$ values, and the $T_D$ values in this experiment were all around one.
The modeled acoustic travel time PDFs showed greater differences in the different wave fields than the acoustic intensity PDFs. As would be expected with greater height differences between the crests and troughs, the acoustic travel time PDFs depicted a broadening of the distribution of travel times as the wave heights increased in the wave field. To determine if wave height or period was the greater determining factor in the shape and size of the travel time PDF, data with the wave height held constant and a varying period, and data with a constant period and a varying wave height were analyzed for acoustic travel time differences. It was found wave height is the stronger factor.

With some more experimental testing and data from the full-scale experiment, this geometrical approximation approach can be used to further develop a relationship between acoustic backscatter and wave field parameters. The overall goal is to develop the relationship to the point where given an acoustic backscattered signal recorded in a wave field, the characteristics of the water surface conditions can be inferred. As such this study has provided a platform for future work in this field.

### 3.12 Future Work

In preparation for the GSO IES deployment off the northeastern United States coast, more work should be done with the scaled experiment in the OCE URI wave tank. Another attempt at producing irregular wave fields should be made, and data should be collected and analyzed in JONSWAP wave fields with different peak periods and significant heights. The different irregular wave fields would provide further testing of the accuracy of the geometrical approach for inferring surface conditions from acoustic backscatter.

### List of References


A.1 Additional Figures
A.1.1 Introduction

This sections contains additional plots that were not appropriate for the body of the first manuscript. Included is plotted data form the other bioacoustic probe channels. Below are plots of the additional data channels of pressure, accelerometers x and y recorded during the April 25, 2007 glider-towed experiment.

![Graph showing pressure measurements from the bioacoustic probe on April 25, 2007.](image)

Figure A.59. Pressure measurements from the bioacoustic probe on April 25, 2007.

A.2 Matlab Codes
A.2.1 Introduction

The following are Matlab programs used in this study to extract the data from the bioacoustic probe and analyze the acoustic recordings.

```matlab
APR07probeglidercompare.m
```

% This program takes acoustic data from the bioprobe which was % towed during the Apr 07 experiment at Rutgers Tuckerton Field
Figure A.60. The accelerometer data collected during the April 25, 2007 deployment in the x-direction. The unit ‘mG’ refers to milli-g force, where a 1 g is defined as an acceleration of the same magnitude as the nominal acceleration due to gravity on the Earth at sea level.

Figure A.61. The accelerometer data collected during the April 25, 2007 deployment in the y-direction.

% Station, and then compares it to data recorded by the glider % during the same experiment
<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>APR07probeglidercompare.m</td>
<td>prog.</td>
<td>compares the acoustic data recorded on the bioacoustic probe to that of the Slocum glider</td>
</tr>
<tr>
<td>APR07SpecgramSplit.m</td>
<td>prog.</td>
<td>splits up the bioacoustic probe data and creates wavefiles and specgrams of the split data</td>
</tr>
<tr>
<td>APR07SpecgramStitch.m</td>
<td>prog.</td>
<td>stitches the specgrams generated by APR07SpecgramSplit.m into one large specgram</td>
</tr>
<tr>
<td>MTRead.m</td>
<td>prog.</td>
<td>Written by Greeneridge Sciences, Inc. to access the stored files on the bioprobe</td>
</tr>
</tbody>
</table>

Table A.3. MATLAB programs included in this appendix.

clear all
close all

load('gliderdata')
load('glider_time_axis')
[BP_Pressure,BP_PressHeader,BP_PressInfo] = mtread('bp10.mt');
BP_Tmax = 7564/3600; % Convert total pressure-reading time to hours
BP_time_axis = linspace(0,BP_Tmax,7564);

% Correlate the time...Both pressure graphs were plotted, and the peaks were compared. The average of the difference of the first 13 peaks was found and added to the bioprobe time axis to make the data sync up
% Glider was turned on about 1.12 hrs before Bprobe
TimeDiff = 1.120423077;
BP_time_axis = BP_time_axis + TimeDiff;

BP_Pressure = BP_Pressure/max(BP_Pressure);
Glider_Pressure = gliderdata(:,381)/max(gliderdata(:,381));

figure
plot(glider_time_axis, -Glider_Pressure,'B')
hold on
plot(BP_time_axis,-BP_Pressure,'R')
ylabel('normalized pressure')
xlabel('mission time (hrs)')
% xlabel('Hours into mission')
title('Pressure comparison for selected data sample')
% Zoom in on our area of interest for entire experiment.
axis([1.25+TimeDiff, 1.75+TimeDiff, -1.1, 0.2])
legend('Glider','BProbe')

% Read and plot acoustic data for time of interest:
NFFT = 1024;
srate = 4096;
start_time = 1.25*3600;
end_time = 1.75*3600;
length = 200;
figure
subplot(3,1,[1 2])
for start = start_time:length:end_time,
    [Sound,SoundHeader,SoundInfo] = MTRead('bp00.mt',start,length);
    [B,F,T] = specgram(Sound,NFFT,srate);
    T = T/3600 + start/3600 + TimeDiff;
    hold on
    imagesc(T,F,20*log10(abs(B)));
    xlim([1.25+TimeDiff, 1.75+TimeDiff])
    ylim([0, 2000])
% axes('Tag','LeftAxes')
    title('Glider-towed hydrophone (PSD vs. time)')
% xlabel('Hours into mission')
% ylabel('frequency (Hz)')
end
colorbar

% plot glider depth over specgram
subplot(3,1,[1 2])
hold on
    depth = 2000-2000*gliderdata(:,382)/max(gliderdata(:,382));
    plot(glider_time_axis, depth, 'k.-')
% axes('Tag','RightAxes')
    xlim([1.25+TimeDiff, 1.75+TimeDiff])
    ylim([0, 2000])
% axes('Tag', 'DepthAxes')
% set(DepthAxes,'YDir','reverse')
% set(gca, 'YAxisLocation','right')

%
% UNCOMMENT THESE ONE AT A TIME IN ORDER TO PLOT SPECIFIC
% NOISE SOURCES
% plot potential noise sources
% Volume piston(ballast pump)
figure()
% subplot(3,1,3)
% hold on
% plot(glider_time_axis, gliderdata(:,260), 'r.')% ballast pump
% xlim([1.25+TimeDiff, 1.75+TimeDiff])
% xlabel('Hours into mission')
% ylabel('Volume Piston')
%
% Air pump
figure()
% subplot(3,1,3)
% hold on
% plot(glider_time_axis, gliderdata(:,451), 'k.')% air pump
% xlim([1.25+TimeDiff, 1.75+TimeDiff])
% xlabel('Hours into mission')
% ylabel('Air Bladder')
%
% Fin
figure()
% subplot(3,1,3)
% hold on
% plot(glider_time_axis, gliderdata(:,315), 'b.')% fin
% xlim([1.25+TimeDiff, 1.75+TimeDiff])
% xlabel('Hours into mission')
% ylabel('Fin position (rad)')
%
% Battery pitch
figure()
% subplot(3,1,3)
% hold on
% plot(glider_time_axis, gliderdata(:,280), 'g.')% bat. position
% plot(glider_time_axis, gliderdata(:,279), 'm.')% bat. control
% xlim([1.25+TimeDiff, 1.75+TimeDiff])
% xlabel('Hours into mission')
% ylabel('Battery position')
%
% plot all potential noise sources
subplot(3,1,3)
plot(glider_time_axis, -Glider_Pressure,'b.')
hold on
    % air pump
    plot(glider_time_axis, gliderdata(:,451)/max(gliderdata(:,451)),...
         'k.'
    )
    % fin
    plot(glider_time_axis, gliderdata(:,315)/max(gliderdata(:,315)),...  
         'b.'
    )
    % ballast pump
    plot(glider_time_axis, gliderdata(:,260)/max(gliderdata(:,260)),...  
         'r.'
    )
    % battery position
    plot(glider_time_axis, gliderdata(:,280)/max(gliderdata(:,280)),...  
         'g.'
    )
    % altimeter
    %    plot(glider_time_axis, gliderdata(:,182)/max(gliderdata(:,182)),
    %        'c.'
    %    )
    xlim([1.25+TimeDiff, 1.75+TimeDiff])
    ylim([-1.25 1.25])
    xlabel('mission time (hrs)')
    legend(‘Air Bladder’, ’Fin’, ’Vol Piston’, ’Battery Pos’, ’Location’,...  
           ’NorthOutside’, ’Orientation’, ’horizontal’)
    legend Boxoff
    caxis([40,110])
end{verbatim}

APR07SpecgramSplit.m -----------------------------------------------

\begin{verbatim}
\end{verbatim}

APR07SpecgramSplit.m -----------------------------------------------

\begin{verbatim}
\end{verbatim}
fig_save_dir = ['./figfiles/'];
sound_save_dir = ['./soundfiles/'];

[Pressure,PressHeader,PressInfo] = mtread('bp10.mt');
[Temp,TempHeader,TempInfo] = mtread('bp11.mt');
[Xaccel,XaccelHeader,XaccelInfo] = mtread('bp14.mt');
[Yaccel,YaccelHeader,YaccelInfo] = mtread('bp15.mt');

% Some info from the soundfile:
srate = 4096; % Sampling Rate
endlength = 7560; % Number of seconds in total file
NFFT = 1024; % Number of FFT points for specgram

% Break up file into 2 minute (120 second) sections:
length = 120;
for start = 0:length:endlength
    % Create Specgram
    [Sound,SoundHeader,SoundInfo] = MTRead('bp00.mt',start,length);
    adata = Sound; % . / 10000; % adata is acoustic data
    figure
    [B,F,T] = specgram(adata,NFFT,srate);
    imagesc(T,F,20*log10(abs(B)));
    axis xy
    title(['Towed Bioprobe, Specgram for start-time = ',...
          num2str(start), ' seconds'])
    print('-djpeg',[fig_save_dir,'Towed_specgram_',...
          num2str(start),'.jpg']);
    close(gcf)

    % Plot Power Spectral Density
    Fadata = fft(adata,512);
    PSD = Fadata.*conj(Fadata)/512;
    f = srate*(0:256)/512;
    figure
    plot(f,PSD(1:257))
    xlim([250,2050])
    title(['PSD for Specgram with start-time = ',...
          num2str(start), ' seconds'])
    xlabel('Frequency (Hz)')
    print('-djpeg',[fig_save_dir,'PSD_',num2str(start),'.jpg']);
    close(gcf)

    % Create Wave file
    wavwrite(adata,srate,32,[sound_save_dir,'Towed_starttime_',...
          num2str(start),'.wav']);
% This program takes acoustic data from the bioprobes which were
towed during the Apr 07 experiment at Rutgers Tuckerton Field
Station, and plots a specgram for all the data by stitching
small specgrams together. (Too much memory is required to do
a single specgram on the entire data)

clear all
close all

figure
% subplot(2,1,1)
length = 120;
endlength = 7560;
NFFT = 1024;
srate = 4096;
for start = 0:length:endlength,
    [Sound,SoundHeader,SoundInfo] = MTRead('bp00.mt',start,length);
    [B,F,T] = specgram(Sound,NFFT,srate);
    T = T/3600;
    % subplot(3,1,1)
    hold on
    imagesc(T+start/3600,F,20*log10(abs(B)));
    axis xy
    Xmax = (start + length)/3600;
    axis([0, Xmax, 0, 2048]);
    % title('Spectrogram of Glider Run')
    xlabel('Time (Hrs)')
    ylabel('Frequency (Hz)')
end
figure
% subplot(2,1,2)
[Pressure,PressHeader,PressInfo] = mtrread('bp10.mt');
Taxis2 = linspace(0,Xmax,7564);
plot(Taxis2,-Pressure)
XLim([0, Xmax])
% title('Pressure')
ylabel('Pressure (dBars)')
xlabel('Time (Hrs)')
axis([0, Xmax, -30, 2])
% function [P,HEADER,INFO] = MTRead(FILENAME,START,LEN)
% Reads a file that is in MT format.
% FILENAME is name of file to read.
% START is the number of seconds into the file to begin readin.
% (Default = beginning of file)
% LEN is the number of seconds worth of data to read.
% (Default = to end of file)
%
% function [P,HEADER,INFO] = MTRead(FILENAME,START,LEN,'P')
% Same as above, but START and LEN are in sample data points,
% rather than seconds.
% P is the array of data read from the file.
% HEADER is the information from the file’s MT header.
% (See datafile.h) All fields are stored as strings.
% INFO contains other data, calculated by this function.
% INFO.filename Name of file
% INFO.filesize Total size of file, in bytes
% INFO.when Date/Time in MATLAB 6-element form
% INFO.whenC Date/Time in C time_t form
% INFO.srate Sample Rate in Hz
% INFO.nsamp Number of sample points in file
% INFO.seconds Number of seconds in file
% INFO.count Number of sample points actually read
% and returned in P
%
% Note that the time reported in HEADER is at the beginning
% of the file, but that the time reported in INFO.when and
% INFO.whenC are at the beginning of data read; in other
% words, the time at the start of the file, plus START seconds.
%
% MODIFICATION HISTORY:
%
% 8/18/03 WCB Original Bob Blaylock internal code patched
% to work properly with strings that may have garbage after
% the null terminator.
4/11/04 WCB Renamed to MTRead(), all necessary functions incorporated into a single file, removed Blaylock comments warning about "obsolete" header data -- these only apply to the BGB extensions to MT format that the Bioacoustic Probe does not use. The necessary functions that had to be appended to this file were: c2mat_tm.m, mat2c_tm.m, contains.m, limits.m, and strtrim.m.

4/14/04 WCB Added check for malformed wordsize entry in the MT header; assumes 2 bytes per sample if the original value is not properly formed.

function [p,header,info] = MTRead(filename,start,len,slMode)
    if nargin < 4
        slMode = 's';
        if nargin < 3
            len = inf;
            if nargin < 2
                start = 0;
                end
        end
    end

    [f,msg] = fopen(filename,'rb');
    if f < 1
        fclose all;
        error([10 ' Sorry about this...' 10 ...
                ' But I can’t open this file.' 10 ' I get this error:'...
                10 10 ' filename ': ' msg 10 10]);
    end

    header.magicstring = MakeString(fread(f,8,'char'));
    if strcmp(header.magicstring,'DATA')
        fclose all;
        error([10 ' This is the wrong file!' 10 ...
                ' It’s not MacTrimpi format.' 10 ' I can do nothing!'...
                10 10 ' Trying to read '' filename ''', 10]);
    end

    header.totalhdrs = MakeString(fread(f,3,'char'));
    header.abbrev = MakeString(fread(f,8,'char'));
    header.stationcode = MakeString(fread(f,3,'char'));
    header.title = MakeString(fread(f,82,'char'));
    header.month = MakeString(fread(f,3,'char'));

123
header.day = MakeString(fread(f, 3, 'char'));
header.year = MakeString(fread(f, 5, 'char'));
header.hours = MakeString(fread(f, 3, 'char'));
header.minutes = MakeString(fread(f, 3, 'char'));
header.seconds = MakeString(fread(f, 3, 'char'));
header.msec = MakeString(fread(f, 4, 'char'));
header.sampling_period = MakeString(fread(f, 15, 'char'));
header.samplebits = MakeString(fread(f, 3, 'char'));
header.wordsize = MakeString(fread(f, 2, 'char'));

if str2num(header.wordsize) < (str2num(header.samplebits)/8)
    warning([' (Loading file "' filename '")' newl newl ...
        ' The samplebits field...' newl ...
        ' Does not fit the wordsize field.' newl...
        ' This file may be bad.' newl]);
end

header.typemark = MakeString(fread(f, 1, 'char'));
header.swapping = MakeString(fread(f, 1, 'char'));
header.signing = MakeString(fread(f, 1, 'char'));
header.caltype = MakeString(fread(f, 1, 'char'));
header.calmin = MakeString(fread(f, 15, 'char'));
header.calmax = MakeString(fread(f, 15, 'char'));
header.calunits = MakeString(fread(f, 40, 'char'));
header.recordsize = MakeString(fread(f, 6, 'char'));
header.sourcevers = MakeString(fread(f, 9, 'char'));

fseek(f, 0, 'eof');
info.filename = filename;
info.filesize = ftell(f);
close(f);
info.srate = 1/str2num(header.sampling_period);
info.when = str2num(['header.year ', 'header.month ', 'header.day...
    'header.hours ', 'header.minutes ', 'header.seconds ']);
info.when(6) = info.when(6) + str2num(header.msec)/1000;
if upper(slMode) == 'P'
    info.whenC = mat2c_tm(info.when) + start/info.srate;
else
    info.whenC = mat2c_tm(info.when) + start;
end
info.when = c2mat_tm(info.whenC);

% Some MT files have corrupted wordsize (no null terminator)
% -- if so assume 2-byte words
%
if (isempty(header.wordsize))
    header.wordsize = '2';
end
info.nsamp = (info.filesize - 512*str2num(header.totalhdrs))/...
    str2num(header.wordsize);
info.seconds = info.nsamp/info.srate;

if len > 0  % Only load data if it’s been asked for.
    if any(contains(header.swapping,'SLsl'))
        mode = 'ieee-le';
    else
        mode = 'ieee-be';
    end
    [f,msg] = fopen(filename,'rb',mode);
    if f < 1
        fclose all;
        error([10 ' Sorry about this...' 10 ...
            ' But I can''t open this file.' 10 ' I get this error:'...
            10 10 ' "' filename '": ' 10 msg 10 10]);
    end

    if upper(slMode) == 'P'
        status = fseek(f,round(512*str2num(header.totalhdrs) + ...
            round(start)*str2num(header.wordsize)),'bof');
    else
        status = fseek(f,round(512*str2num(header.totalhdrs) + ...
            round(start*info.srate)*str2num(header.wordsize)),'bof');
    end
    if status == 0
        if any(header.caltype == 'fF')
            if ~any(str2num(header.wordsize) == [4,8])
                fclose(f);
                error([10 ' Invalid word size!' 10 ...
                    ' Only valid Float sizes...' 10 ...
                    ' Are four or eight bytes.' 10 10]);
            end
            binType = ['float' num2str(str2num(header.wordsize)*8)];
        else
            binType = ['bit' num2str(str2num(header.wordsize)*8)];
            if any(contains(header.signing,'Uu'))
                binType = ['u' binType];
            end
        end
    end
if upper(slMode) == 'P'
    [p,info.count] = fread(f,len,binType);
else
    [p,info.count] = fread(f,round(len*info.srate),binType);
end
fclose(f);

calmax = str2num(header.calmax);
calmin = str2num(header.calmin);
if (length(calmin) == 1) & (length(calmax) == 1) & ...
    ((calmin + eps) < calmax) & ~any(header.caltype == 'fF')
    calmax = str2num(header.calmax);
calmin = str2num(header.calmin);
    if any(contains(header.signing,'Uu'))
        bitmin = 0;
        bitmax = (2^str2num(header.samplebits)) - 1;
    else
        bitmin = -(2^(str2num(header.samplebits)-1));
        bitmax = (2^(str2num(header.samplebits)-1)) - 1;
    end
    multiplier = (calmax-calmin)/(bitmax-bitmin);
p = (p - bitmin).*multiplier + calmin;
end
else
    p = [];
end
else
    p = [];
    info.count = 0;
end
return

% The standard is that the string is null-terminated,
% so we know there will be a null somewhere. Make the
% string out of everything up to the null.
%
% The standard also says that the rest of a field should
% be nulled, but in case it wasn’t and there is garbage
% after the terminating null, this will ignore the garbage.
%
% Note if the length of s is exactly 1 we just leave it
% alone. Only if it’s longer than one do we look for
% the null terminator.
% function s = MakeString(s)
s = char(s( :) ');
if (length(s) > 1) % Multi-char string?
    xx = find(s == 0); % Yes, look for null terminator
    if (length(xx) > 0) % Null terminator exists
        if (xx(1) > 1) % Is it not the first character?
            s = strtrim(s(1 : (xx(1) - 1)));
        else
            % Multi-char string but first character was a null!
            s = '';
        end
    else
        % Multi-char string but no null terminator found!
        s = ' ';% Multi-char string but no null terminator found!
    end
else
    % Single-char string
    if (s(1) == 0) % But is that single char a null?
        s = ''; % If so, this is a null string
    end
end
% xx = find(s = = 0);
% s = strtrim(s(xx));
return

% function s = strtrim(s)
% % Trims blanks and nulls from both ends of the string.

function s = strtrim(s)
if ~isempty(s)
    xx = limits(find(~isspace(s) & (s = = 0)));
    if isempty(xx)
        s = '';
    else
        s = s(xx(1) : xx(2));
    end
end
return

% function l = limits(x)
%
function l=limits(x)
    l = [min(x(:)) max(x(:))];
    return

function tm = c2mat_tm(tc)
    %
    % Where tc is a scalar containing a date/time as stored by C,
    % as the number of seconds past Midnight, January 1, 1970, this
    % function will return in tm a six-element row vector containing
    % the same date/time in MATLAB's format.
    %
    % The additional argument, fs, will be added to the seconds field
    % of the result. This is to allow times to be specified to fractions
    % of a second. If no second input argument is given, then the
    % fractional part of tc, if present, will be used.
    %
function tm = c2mat_tm(tc,fs)
    a = version;
    if (a(1) == 4) & (a(2) == '.
        error('Missing c2mat_tm.mex');
    else
        if nargin > 2
            tc = tc + fs;
        end
        tm = datevec((tc+6.216730560000000e+010)/(24*60*60));
    end

function tc = mat2c_tm(tm)
    %
    % Where tm is a 6-element row vector containing a date/time in
    % MATLAB's format, this function will return in tc a scalar
    % containing the same date/time in the standard C format, as the
    % number of seconds past Midnight, January 1, 1970.
    %
    % If the second output argument, fs, if given, then only an
    % integer value will be returned in tc, with the fractional part
    % of the seconds in fs.
function [tc,fs] = mat2c_tm(tm)
a = version;
if (a(1) == 4) & (a(2) == '.')
    error('Missing mat2c_tm.mex');
else
    tc = datenum(tm(1),tm(2),tm(3),tm(4),tm(5),tm(6))*(24*60*60) - ...
         6.216730560000000e+010;
    if nargout > 1
        fs = tc - fix(tc);
        tc = fix(tc);
    end
end

% X = contains(WHAT,WHERE)
% % For each element of WHAT, this function returns a 1 in the
% % corresponding element of X if that element is found in WHERE,
% % and a 0 if it is not.
% function x = contains(what,where,dummy)
% if nargin >= 3
%     dummy = dummy*dummy;
% end

if isempty(where)
    x = zeros(size(what));
    return;
elseif isempty(what)
    x = [];
    return;
end

x = logical(zeros(size(what)));
for ii = 1:prod(size(what))
    xx = any(what(ii) == where);
    if isempty(xx)
        xx = 0;
    end

    while prod(size(xx)) > 1
        xx = any(xx(:));
    end
    x(ii) = xx;
end

return

% Below is an obsolete version of this function. At some point,
% I realized I could do it as shown above, much more efficiently.
% The dummy argument in the above code is to avoid breaking any
% code which might have used the SORTED argument when calling the
% old version of this function.

% X = contains(WHAT,WHERE,1)
%
% Same as above, but specifies that WHERE is already sorted into
% ascending, order so this routine doesn’t need to waste time
% sorting it again.

%function n = contains(what,where,sorted)
% if nargin < 3
% sorted = 0;
% end
% %
% if ~sorted
% n = bSearch(what,sort(where(:))) ~= 0;
% else
% n = bSearch(what,where(:)) ~= 0;
% end
% end
APPENDIX B

Appendix for Manuscript 2

B.1 Additional Figures

B.1.1 Introduction

This section includes additional figures that were not appropriate to place in the body of the manuscript. Below are the additional spectrograms from the WHOI VLA/HLA recordings on Sept. 5.

Figure B.62. Spectrogram of received acoustic signal at distances 44.2 km and 45.6 m from the WHOI VLA/HLA.

Figure B.63. Spectrogram of received acoustic signal at distances 47.8 km and 49.1 m from the WHOI VLA/HLA.
B.2 Acoustical Society of America Meeting Abstracts
B.2.1 Introduction

Below are three abstracts submitted to the Acoustical Society of America (ASA) for presentations at their annual meeting. All three abstracts were accepted by the ASA and became the basis for the subsequent presentations.

June 2006 Meeting in Providence, RI

Effect of shelf break front on acoustic propagation Author list (James H. Miller, Kristy A. Moore, Gopu R. Potty, James F. Lynch)

The effect of a shelf break front on acoustic propagation is discussed in the context of the Shallow Water Experiment (SW-06) in the New Jersey Shelf. The primary effect is a horizontal analogue to the classical horizontal Lloyd’s mirror effect, produced by the fact that fronts can totally internally reflect sound incident upon them at low grazing angles. The direct and reflected modal rays add up to produce an interference pattern in range. It has been shown (Lynch et al., IEEE JOE, (2006)) based on simple calculations that this frontal effect has the potential to increase the maximum insonification level up to 6 dB. Noise measurements analyzed using the SWARM-95 data also provide some evidence to this effect. The present study explores this effect in more detail using a horizontal ray-vertical mode approach. Calculations were made using environmental parameters corresponding to the New Jersey Shelf area, where field measurements will be made in 2006 to explore this effect. [Work supported by Office of Naval Research].

December 2006 Meeting in Honolulu, HI

Results of 3D propagation effects during SW06 at NJ shelf break front Author list (Kristy Moore, James Miller, Gopu Potty, Scott Glenn)

Results from the Shallow Water Experiment (SW06) in the New Jersey Shelf were investigated for 3D propagation effects. This 3D propagation effect is a horizontal analogue to the classical Lloyd’s mirror effect. The Lloyd’s mirror effect
is produced by the fact fronts can totally internally reflect sound incident upon them at low grazing angles. The direct and reflected modal rays add up to produce an interference pattern in range. As was previously shown (Lynch et al., IEEE JOE, (2006)) with simple calculations, this frontal effect has the potential to increase the maximum insonification level up to 6 dB. Earlier the Lloyd’s mirror effect was studied using a horizontal ray-vertical mode approach, generating calculations from environmental parameters in the New Jersey Shelf. The results from SW06 verify the increase in the insonification level characteristic of Lloyd’s mirror and the horizontal ray-vertical mode model. [Work supported by Office of Naval Research]

June 2007 Meeting in Salt Lake City, UT

Investigation of 3D propagation effects at the New Jersey shelf break front

Author list (Kristy A. Moore, James H. Miller, Gopu R. Potty, James F. Lynch, and Arthur Newhall)

Signals recorded on the WHOI VLA/HLA from a ship-towed J15 source during the Shallow Water Experiment (SW06) in the New Jersey Shelf were analyzed for 3D propagation effects. The signal was a simple CW tone at 93 Hz and the source depth was approximately 50 meters. This 3D propagation effect is a horizontal analogue to the classical Lloyd’s mirror effect, where fronts can totally internally reflect sound incident upon them at low grazing angles. The direct and reflected modal rays can constructively interfere, having the potential to increase the intensity level by 6dB (Lynch et al., IEEE J. Ocean. Eng., 31(1) 33-48, (2006)). Trapping of sound between the shelf break front and an internal wave packet may reduce transmission loss by 10 to 20 dB. Bathymetric refraction is also a possible contributor to the reduced transmission loss. Modeling of the Lloyd’s mirror effect was carried out using the Kraken normal mode model with the environmen-
tal parameters of the New Jersey Shelf and J15 source. Analysis of the acoustic recordings of the J15 source and ship noise from the R/V Knorr is consistent with the modeling results. [Work supported by Office of Naval Research]

B.3 Matlab Code
B.3.1 Introduction

The following sections are the MATLAB programs and functions used in analysis and modeling in Manuscript 2: Investigation of 3D propagation effects at shelf break front. Table B.4 contains a list of the MATLAB programs in the order they are listed below.

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>plotbathy3.m</td>
<td>prog.</td>
<td>calculates bathymetry in the SW06 experimental area and processes the data from runtestsNJ.m</td>
</tr>
<tr>
<td>runtestsNJ.m</td>
<td>prog.</td>
<td>operates KRAKEN, allows alteration of the environmental and physical conditions</td>
</tr>
</tbody>
</table>

Table B.4. MATLAB programs included in this appendix.

plotbathy3.m

% to plot SW06 center area. tduda whoi 9 aug 06.
% 39.5182  38.8980 extent of lats from Larry via Tim
% -72.3624 -73.2319 extent of lons from Larry via Tim
close all
clear all
% J-15 3D area, too much for one load
lo1 = -73.1; lo2 = -72.5;
la1 = 39  ; la2 = 39.5;
% Gerstoft area, this one works
% lo1 = -73.1; lo2 = -72.9;
% la1 = 39  ; la2 = 39.2 ;
% larger area
% lo1 = -73.15; lo2 = -72.95;
% la1 = 39  ; la2 = 39.15 ;
% lo1 = -73.15; lo2 = -72.90;
% la1 = 39  ; la2 = 39.2 ;
% try a larger one
% lo1 = -73.15; lo2 = -72.75;
% la1 = 39 ; la2 = 39.35 ;

[LA,LO,Z]=loadgridmayer(lo1,lo2,la1,la2);
%decimate to manage memory issues
% LA = LA(1:10:end,1:10:end);
% LO = LO(1:10:end,1:10:end);
% Z = Z(1:10:end,1:10:end);
nan_locations = find(isnan(Z));
Z(nan_locations) = 0;
LA1=LA(:,1)';
LO1=LO(1,:);
% [dist,pangle]=sw_dist(LA1,LO1(:,1:251),'km');
% range = cumsum(dist);
% R=range*1000;
% R1=round(R);
Z(1,:)=Z(2,:);
Z(:,1)=Z(:,2);
a=size(Z);
for n=2:a(1)
    for m=2:a(2)
        if Z(n,m)==0
            Z(n,m) = Z(n-1,m);
        end
    end
end
for n=250:-1:1
    for m=301:-1:1
        if Z(n,m)==0
            Z(n,m)=Z(n+1,m);
        end
    end
end
Z(1,:)=Z(2,:);
Z(:,1)=Z(:,2);
Z(:,301)=Z(:,300);

LAd=diag(LA);
LOd=diag(LO);
for i=1:250; [dist(i),pangle(i)]=sw_dist([LAd(1,1) LAd(i,1)],...
    [LOd(1,1) LOd(i,1)],'km');
end;
d=dist*1000;
Zf = fliplr(Z);
Zd = diag(Zf);
D = flipud(Zd);
% D = D(1:2:250,1);
% d = d(1,1:2:end);
%
%
% % figure
% % pcolor(L0,LA,Z),caxis([75 90]); shading flat
% % imagesc([lo1 lo2],[la1 la2],Z); caxis([60 90]); axis xy
% % hold on
% % daspect([ 1 cos(mean([la1 la2])*pi/180) 1]);
% % ylabel('Lat'); xlabel('Long.')
% % colormap(flipud(jet))
% % colorbar
%
% % cd maps_new.dir
% % plotpeter
% % cd ..
% % trackbathy

run testsNJ.m

% clear all; close all; clc;
% slope configuration
% r : across the slope and toward the apex
% D : depth
% y : along the slope
%
% 3D mesh
% |----------------------------------|
% % Across | along the slope (Y)
% the |
% % Slope |
% (r) |
% (X) |
% V
% run plotbathy
run_kraken = 1 % if = 1, run kraken to calculate the modes.
% if = 0, not to, but the previous results will still be used in
% field3d.
run_field3d = 1 % if = 1, run field3d to calculate the 3D field.
if_plottri = 0 % if = 1, plot the triangular grids.
if plottl = 1 % if = 1, plot the TL curve.
if plotray = 1 % if = 1, plot the modal rays.

%try bathy in here

% r=LA1; % latitude from NJ Bathy
% D=Z; % depth from NJ Bathy
% r = linspace( 0.0, 20000, 101); %m
% D = linspace( 50, 115, 101 ); % m
% D( 101 ) = 1.0; Needed only if the depth goes to zeros
% r=range;
% D=Z(100,1:101);
% r=range(:,1:101);
% D=Z(1:101,1:101);

%%%%

if run_field3d,
    warning off
    try, delete krakenc.prt, catch, end
    try, delete field3d_Cart.prt, catch, end
    try, delete 3D_wedge.ray, catch, end
    try, delete 3D_wedge.shd, catch, end
    try, delete 3D_wedge.kbar, catch, end
    try, delete 3D_wedge.zbar, catch, end
    warning on
end

dy = 2*1000; %m
N_y=50;

% N_y = 51; % number of grid line along the slope,
% so the total length of the computed area along the slope is
% (Ny_y-1)*dy.
y = [0:(N_y-1)]*dy;

% y=L01; % Longitude from NY Bathy
% y=L01(1,1:251);

M = 2; % number of propagating modes
% source frequency and position and receiver positions
freq = 93;
rs = 5000; %m
ys = 0; %m
nsd = 1; sd = 50; % source depth (m)
ndr = 1; rd = [40 50]; % receiver depth (m)
n_tly = 501; tlymin = 0; tlymax = 60*1000; % number of receiver,
% receiver distance along the slope (m)
\[ n_{\text{tlx}} = 151; \text{tlx} = [0 \ 15000]; \text{ across the slope} \]
\[ \% \text{OPT=['GBTFMR'];} \%\text{ TL grids in Polar Coor.} \]
\[ \text{OPT=['GBCFMR'];} \% \text{TL grids in Cartesian Coord.} \]

\% gaussian beam info
\% Syntax:
\% \\begin{verbatim}
\alphal \alphal2 \nalp \ste \nstef \emult
\end{verbatim}
\% Description:
\% \alphal: First angle for beam fan (degrees).
\% \alphal2: Last " " " " "
\% \nalp: Number of beams in fan.
\% \ste: Step size (m).
\% \nstef: Number of steps.
\% \emult: Epsilon multiplier for beam initial conditions.

\alphal = 70; \alphal2 = 110; \nalp = 41;
\ste = 10; \nstef = 6000;
\emult = 0.3;
\emult = 0.6;

if run_kraken,
% write out the envfil across the slope
\text{fid} = \text{fopen( '3D_wedge.env', 'w' );}
\text{for iy = 1:length(r)}
\text{ for ir = 1:length( r )}
\text{ if r(ir) > 2000 \& r(ir) <= 12000,}
\text{fprintf( \text{fid}, \begin{verbatim}
\text{''Wedge problem #'} \text{int2str( ir )...}
\text{''\r
\text{n'] );}
\text{fprintf( \text{fid}, \text{'\%8.2f \ r\n', freq );}
\text{fprintf( \text{fid}, \text{'2 \ r\n' );}
\text{fprintf( \text{fid}, \text{''CVW .'' \ r\n' );
\text{fprintf( \text{fid}, \text{'500 0.0 %8.2f \ r\n', D( ir,iy ) );
\text{fprintf( \text{fid}, \text{' 0.0 1500.0 0.0 1.0 0.0 0.0 \ r\n' );
\text{fprintf( \text{fid}, \text{' %8.2f 1500.0 / \ r\n', D( ir,iy ) );
\text{fprintf( \text{fid}, \text{'1000 0.0 2000.0 \ r\n' );
\text{fprintf( \text{fid}, \text{' %8.2f 1700.0 0.0 1.5 0.5 0.0 \ r\n',...\r\n', D( ir,iy ) );
\text{fprintf( \text{fid}, \text{'} 2000.0 1700.0 / \ r\n' );
\text{fprintf( \text{fid}, \text{'V', 0.0 \ r\n' );
\text{fprintf( \text{fid}, \text{'}1400.0 5000.0 \ r\n' );
\text{fprintf( \text{fid}, \text{'0.0, ! RMAX (km) \ r\n' );
\text{fprintf( \text{fid}, \text{'1 ! NSD \ r\n' );
\text{fprintf( \text{fid}, \text{'180. ! SD(1) ... \ r\n' );
\end{verbatim}
\end{verbatim}}
\end{verbatim}}
\end{verbatim}}

\% gaussian beam info
\% Syntax:
\% \\begin{verbatim}
\alphal \alphal2 \nalp \ste \nstef \emult
\end{verbatim}
\% Description:
\% \alphal: First angle for beam fan (degrees).
\% \alphal2: Last " " " " "
\% \nalp: Number of beams in fan.
\% \ste: Step size (m).
\% \nstef: Number of steps.
\% \emult: Epsilon multiplier for beam initial conditions.

\alphal = 70; \alphal2 = 110; \nalp = 41;
\ste = 10; \nstef = 6000;
\emult = 0.3;
\emult = 0.6;

if run_kraken,
% write out the envfil across the slope
\text{fid} = \text{fopen( '3D_wedge.env', 'w' );}
\text{for iy = 1:length(r)}
\text{ for ir = 1:length( r )}
\text{ if r(ir) > 2000 \& r(ir) <= 12000,}
\text{fprintf( \text{fid}, \begin{verbatim}
\text{''Wedge problem #'} \text{int2str( ir )...}
\text{''\r
\text{n'] );}
\text{fprintf( \text{fid}, \text{'\%8.2f \ r\n', freq );}
\text{fprintf( \text{fid}, \text{'2 \ r\n' );}
\text{fprintf( \text{fid}, \text{''CVW .'' \ r\n' );
\text{fprintf( \text{fid}, \text{'500 0.0 %8.2f \ r\n', D( ir,iy ) );
\text{fprintf( \text{fid}, \text{' 0.0 1500.0 0.0 1.0 0.0 0.0 \ r\n' );
\text{fprintf( \text{fid}, \text{' %8.2f 1500.0 / \ r\n', D( ir,iy ) );
\text{fprintf( \text{fid}, \text{'1000 0.0 2000.0 \ r\n' );
\text{fprintf( \text{fid}, \text{' %8.2f 1700.0 0.0 1.5 0.5 0.0 \ r\n',...\r\n', D( ir,iy ) );
\text{fprintf( \text{fid}, \text{'} 2000.0 1700.0 / \ r\n' );
\text{fprintf( \text{fid}, \text{'V', 0.0 \ r\n' );
\text{fprintf( \text{fid}, \text{'}1400.0 5000.0 \ r\n' );
\text{fprintf( \text{fid}, \text{'0.0, ! RMAX (km) \ r\n' );
\text{fprintf( \text{fid}, \text{'1 ! NSD \ r\n' );
\text{fprintf( \text{fid}, \text{'180. ! SD(1) ... \ r\n' );
\end{verbatim}
\end{verbatim}}
\end{verbatim}}
\end{verbatim}}
\end{verbatim}}

\% gaussian beam info
\% Syntax:
\% \\begin{verbatim}
\alphal \alphal2 \nalp \ste \nstef \emult
\end{verbatim}
\% Description:
\% \alphal: First angle for beam fan (degrees).
\% \alphal2: Last " " " " "
\% \nalp: Number of beams in fan.
\% \ste: Step size (m).
\% \nstef: Number of steps.
\% \emult: Epsilon multiplier for beam initial conditions.

\alphal = 70; \alphal2 = 110; \nalp = 41;
\ste = 10; \nstef = 6000;
\emult = 0.3;
\emult = 0.6;

if run_kraken,
% write out the envfil across the slope
\text{fid} = \text{fopen( '3D_wedge.env', 'w' );}
\text{for iy = 1:length(r)}
\text{ for ir = 1:length( r )}
\text{ if r(ir) > 2000 \& r(ir) <= 12000,}
\text{fprintf( \text{fid}, \begin{verbatim}
\text{''Wedge problem #'} \text{int2str( ir )...}
\text{''\r
\text{n'] );}
\text{fprintf( \text{fid}, \text{'\%8.2f \ r\n', freq );}
\text{fprintf( \text{fid}, \text{'2 \ r\n' );}
\text{fprintf( \text{fid}, \text{''CVW .'' \ r\n' );
\text{fprintf( \text{fid}, \text{'500 0.0 %8.2f \ r\n', D( ir,iy ) );
\text{fprintf( \text{fid}, \text{' 0.0 1500.0 0.0 1.0 0.0 0.0 \ r\n' );
\text{fprintf( \text{fid}, \text{' %8.2f 1500.0 / \ r\n', D( ir,iy ) );
\text{fprintf( \text{fid}, \text{'1000 0.0 2000.0 \ r\n' );
\text{fprintf( \text{fid}, \text{' %8.2f 1700.0 0.0 1.5 0.5 0.0 \ r\n',...\r\n', D( ir,iy ) );
\text{fprintf( \text{fid}, \text{'} 2000.0 1700.0 / \ r\n' );
\text{fprintf( \text{fid}, \text{'V', 0.0 \ r\n' );
\text{fprintf( \text{fid}, \text{'}1400.0 5000.0 \ r\n' );
\text{fprintf( \text{fid}, \text{'0.0, ! RMAX (km) \ r\n' );
\text{fprintf( \text{fid}, \text{'1 ! NSD \ r\n' );
\text{fprintf( \text{fid}, \text{'180. ! SD(1) ... \ r\n' );
\end{verbatim}
\end{verbatim}}
\end{verbatim}}
\end{verbatim}}
\end{verbatim}}
\end{verbatim}}
\end{verbatim}}
\end{verbatim}}
\end{verbatim}}
fprintf( fid, '2001 ! NRD \n' );
fprintf( fid, '0. 2000.0 / ! RD(1) ... \n' );
else
fprintf( fid, ['''Wedge problem #' int2str( ir)... '''
'] );
fprintf( fid, '%8.2f \n', freq );
fprintf( fid, '2 \n' );
fprintf( fid, 'CVW .'' 
' );
fprintf( fid, '500 0.0 %8.2f \n', D( ir,iy ) );
fprintf( fid, ' 0.0 1550.0 0.0 1.0 0.0 0.0 \n' );
fprintf( fid, ' %8.2f 1550.0 / \n', D( ir,iy ) );
fprintf( fid, '1000 0.0 2000.0 \n' );
fprintf( fid, ' %8.2f 1700.0 0.0 1.5 0.5 0.0 \n', D( ir,iy ) );
fprintf( fid, ' 2000.0 1700.0 / \n' );
fprintf( fid, '1400.0 5000.0 \n' );
fprintf( fid, '0.0, ! RMAX (km) \n' );
fprintf( fid, '1 ! NSD \n' );
fprintf( fid, '180. ! SD(1) ... \n' );
fprintf( fid, '2001 ! NRD \n' );
fprintf( fid, '0. 2000.0 / ! RD(1) ... \n' );
end
end % next range
fclose( fid );
end

% 3D mesh
% |------------------------------>
% Across | along the slope (Y)
% the %
% Slope %
% (R) %
% (X) %
% V

if run_field3d,
Elt = [];
[Y,R] = meshgrid(y,r);
for idx_y = 1:length(y)-1;
    for idx_r = 1:length(r)-1;
        %1st element which corner is (idx_y,idx_r)
elt1 = [ sub2ind(size(R),idx_r,idx_y) ...
    sub2ind(size(R),idx_r,idx_y+1) ...
    sub2ind(size(R),idx_r+1,idx_y+1) ];
%2nd element which corner is (idx_y,idx_r)
elt2 = [ sub2ind(size(R),idx_r,idx_y) ...
    sub2ind(size(R),idx_r+1,idx_y+1) ...
    sub2ind(size(R),idx_r+1,idx_y) ];
Elt = [ Elt' elt1' elt2' ]';
end
end

% write field3d
fid = fopen( '3D_wedge.flp', 'w' );

fprintf( fid, [ '''3D Wedge problem'' ! TITLE \r\n' ] );
fprintf( fid, '''%s'' ! OPT \r\n', OPT );
fprintf( fid, '%d ! M (number of modes) \r\n', M );
fprintf( fid,...
'%.6f %.6f ! XS YS (source position)(km) \r\n',
rs/1000, ys/1000);
fprintf( fid, '%d \r\n', nsd );
fprintf( fid,...
'%.7f ',sd );
fprintf( fid, '/ !NSD, SD(1:NSD) (m) \r\n' );
fprintf( fid, '%d \r\n', nrd );
fprintf( fid,...
'%.7f ',rd );
fprintf( fid, '/ !NRD, RD(1:NSD) (m) \r\n' );
fprintf( fid, '%d \r\n', n_tly );
fprintf( fid,...
'%.7f %.7f / !NTLy, TLymin TLymax (km) \r\n',
tlymin/1000 , tlymax/1000 );
fprintf( fid, '%d \r\n', n_tlx );
fprintf( fid,...
'%.7f ', tlx );
fprintf( fid,...
'/ !NTHETA, THETA(1:NTHETA) (degree)\r\n' );
fprintf(fid,...
'%.d !Number of SSP''s (NSSP), (x,y) i = 1:NSSP (km) \r\n',
length(y)*length(r));
for idx_node = 1:length(y)*length(r);
    [idx_r,idx_y] = ind2sub(size(R),idx_node);
    fprintf(fid, '%5.2f %5.2f ''%s'' \r\n',
Y(idx_r,idx_y)/1000, sprintf('3D_wedge%4.4d',idx_r));
end
fprintf(fid, '%d !Nelts, Nodes of corners\r\n', size(Elt,1));
for idx_elt = 1:size(Elt,1);
fprintf(fid, '%d %d %d \r\n', Elt(idx_elt,:));
end
for idx_rd = 1 : nrd
fprintf( fid,...
' %7.3f %7.3f %d !ALPHA1 ALPHA2 NALPHA \r\n',...  
alpha1, alpha2, nalpha);
fprintf( fid,...
' %7.3f %d !STEP NSTEPS \r\n',...  
step, nsteps);
end
fclose(fid);
end

% run KRAKEN
% output file named as MODFIL$$$$
if run_kraken,
disp(['!krakenc.exe < 3D_wedge.env > krakenc.prt']);
warning off; try, delete MODFIL*, catch, end; warning on
dos('C:\MATLAB7\work\KrakenField3D\at\bin\krakenc.exe'...
' < 3D_wedge.env > krakenc.prt');
% disp(['kraken.exe < 3D_wedge.env > 3D_wedge.prt']);
% dos('kraken.exe < 3D_wedge.env > 3D_wedge.prt');
% change file name to XXXX.mod
modfil = dir('MODFIL*');
for idx_fil = 1 : length(modfil);
movefile ( modfil(idx_fil).name, sprintf('3D_wedge%4.4d.mod',...
    idx_fil) );
end
end

if if_plottri,
figure
plottri( '3D_wedge' );
axis tight;
xlabel('Distance Across the Slope (km)')
ylabel('Distance Along the Slope (km)')
end

% run field3d
if run_field3d,
disp(['!field3d_C.exe < 3D_wedge.flp > field3d.prt'])
warning off; try, delete SHDFIL, catch, end; warning on
dos('C:\MATLAB7\work\KrakenField3D\at\bin\field3d_C.exe'...
' < 3D_wedge.flp > field3d_Cart.prt');
try, movefile ('SHDFIL', '3D_wedge.shd'), catch, end;
try, movefile ('KBARFIL', '3D_wedge.kbar'), catch, end;
try, movefile ('ZBARFIL', '3D_wedge.zbar'), catch, end;
try, movefile ('RAYFIL', '3D_wedge.ray'), catch, end;
end

[ PlotTitle, freq, atten, Pos, pressure ] = read_shd('3D_wedge.shd');

%% plot results

% Plot the TL curve
if if_plottl,
    for i_rec = 1:nrd;
        figure; hold on;
        i_angle = find( Pos.r.depth == 9600 );
        if ~isempty(i_angle),
            plot(Pos.r.range-ys,20*log10(...
                (squeeze(abs(pressure(i_rec,i_angle,:))))),'k')
        end
        xlabel('Along the Slope (m)'); ylabel('TL (dB)');
        title([deblank( PlotTitle ) ' Receiver Depth: '...
            num2str(rd(i_rec)) 'm']);
        axis_p = axis;
        axis([25000 55000 -100 -50])
    end
end

% Plot Shade File
for i_rec = 1:nrd;
    figure;
    dist_acr = Pos.r.depth(:,);
    dist_aln = Pos.r.range(:,);
    TLL = 20*log10(squeeze(abs(pressure(i_rec,:,:))));
    pcolor(dist_acr/1000,dist_aln/1000,TLL');
    shading flat;
    caxis([-100 -40]);
    colorbar; view(2); title([deblank( PlotTitle )...'
    Receiver Depth: ' num2str(rd(i_rec)) 'm']);
    xlabel('Distance Across the Slope (km)');
    ylabel('Distance Along the Slope (km)')
end

% Plots the rays associated with horizontally-refracted modes.
if if_plotray, %OPT=='GBT',
    fid = fopen( '3D_wedge.ray' );
end

142
fscanf( fid, '%s', 1 );
hold on
for iray = 1:nalpha
    modes_read = 1;
    mode = 0;
    while modes_read,
        [Npts,count]= fscanf( fid, '%s', 1 );
        if count > 0,
            if Npts(1) == 'C',
                break;
            else
                Npts = str2num(Npts);
                mode = mode + 1;
            end
            temp = fscanf( fid, '%f', [ 2, Npts ] );
            if (mode <= 3),
                xray = temp( 1, : ) / 1000;
                yray = temp( 2, : ) / 1000;
                col = 'krwbymc';% colors to cycle through
                fprintf('Plotting the Gaussian Beam Trace'...%
                      'of mode #%d...
',mode)
                plot( xray, yray, col( mode ) );
            end
        else
            break;
        end
    end % next mode
drawnow
end % next ray
axis square;
end
fclose all;
end

%plot_phasespeed
APPENDIX C

Appendix for Manuscript 3

C.1 Additional Figures
C.1.1 Introduction

The following are figures that were not appropriate for the body of the manuscript. Included is the diagram of the experimental setup at the URI wave tank, some examples of calibrations from wave gauge data used to plot the wave height and period, and normalized acoustic intensity plots for an additional data set.

C.2 Additional Tables
C.2.1 Introduction

The following is an additional table which was not appropriate to be placed in the body of this manuscript. The table is of the Pierson-Moskowitz sea states used in the scaled experiment.

C.3 Matlab Code
C.3.1 Introduction

The following sections are the MATLAB programs and functions used in data collection and analysis in Manuscript 3: Acoustic Backscatter in Controlled Water Wave Fields. Table C.7 contains a list of the MATLAB programs in the order they are listed. Table C.8 contains a list of the MATLAB functions in the order they are listed as well.

C.3.2 MATLAB Programs

analysis2.m

% PROGRAM SPECTRAL CORRECTION
%
%---------------------------------------------------------------
<table>
<thead>
<tr>
<th>Sea State</th>
<th>V (kts)</th>
<th>$\eta$ (m)</th>
<th>T Range (s)</th>
<th>Avg. T (s)</th>
<th>Avg. $\lambda$ (m)</th>
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</table>

Table C.5. Pierson-Moskowitz sea state parameters of wind speed (V), wave height ($\eta$), wave period (T) ranges, average period and the average wavelength ($\lambda$) in an open ocean.
Figure C.64. Histograms of the dimensionless acoustic intensity in a regular sinusoidal wave field. The period is held constant between the different data sets in order to determine the effect wave amplitude has on acoustic intensity. (a) has a wave height of 0.04 m, (b) 0.06 m, (c) 0.08 m and (d) 0.10 m.

% Analysis of random wave elevation generated in a wavetank by % a wavemaker measured at N wave gages as a function of time at % frequency Fs (Hz) %
% Target spectrum is in file : results_f.bin (OMEGAN(1:NOMGATG) % SWAVE(1:NOMGATG) AMPN() PSIN()) % Wave data in file :
% 1. (commented out) elevation_t.bin (t(1:LTIME) eta1(1:LTIME) % eta2(1:LTIME) etaNETA(1:LTIME)) % 2. MAT file irregularwave3 stored (eta1(1:LTIME) eta2(1:LTIME) % etaETA(1:LTIME)), assumed sampled at 100 Hz %
%==============================================
Figure C.65. Histograms of the dimensionless acoustic intensity in a regular sinusoidal wave field. The wave height is held constant between the different data sets in order to determine the effect wave period has on acoustic intensity. (a) has a wave period of 1.0 s, (b) 1.25 s, (c) 1.5 s, (d) 1.75 s and (e) 2.0 s.
Figure C.66. Experimental setup at the URI wave tank.

clc; clear all; close all;
<table>
<thead>
<tr>
<th>GE</th>
<th>HSTARG</th>
<th>TPTARG</th>
<th>FETCH</th>
<th>U10</th>
<th>GAMMA</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.81</td>
<td>0.1</td>
<td>1.5</td>
<td>12000</td>
<td>0</td>
<td>3.3</td>
</tr>
<tr>
<td>NOMEQ</td>
<td>DEPTH</td>
<td>UCURR</td>
<td>Fu</td>
<td>exp2</td>
<td>GENER</td>
</tr>
<tr>
<td>128</td>
<td>1.3</td>
<td>0</td>
<td>100</td>
<td>15</td>
<td>0</td>
</tr>
</tbody>
</table>

Table C.6. The inputs from the *tank.dat* file called in *random.m*. GE is gravity \((m/s^2)\), HSTARG is the target significant height (m), TPTARG is the target peak spectral period (s), FETCH is the fetch of the wave field (m), U10 the wind speed 10 m off the water surface (m/s), GAMMA is the parameter \(\gamma\) used to calculate the wave spectra (see Equation 38), NOMEQ is the number of frequency intervals, DEPTH is the water depth (m), UCURR is the uniform current depth (m/s), Fu is the frequency for time series generation (Hz), exp2 is the power of two used to generate the time length in the voltage series of *random.m*, and GENER is either 0 or 1, determining if *tank.dat* is used to generate the wave spectra.

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>analysis2.m</td>
<td>prog.</td>
<td>adjusts collected wave spectrum closer to target wave spectrum</td>
</tr>
<tr>
<td>ArrivalTimeDiff.m</td>
<td>prog.</td>
<td>Calculates acoustic return times</td>
</tr>
<tr>
<td>GetJ.m</td>
<td>prog.</td>
<td>calculates dimensionless acoustic intensity</td>
</tr>
<tr>
<td>Godin1.m</td>
<td>prog.</td>
<td>calculates and plots travel time bias</td>
</tr>
<tr>
<td>Godin2.m</td>
<td>prog.</td>
<td>calculates PDF of propagation time difference and mean travel time difference</td>
</tr>
<tr>
<td>Godin3.m</td>
<td>prog.</td>
<td>calculates the acoustic intensity PDF</td>
</tr>
<tr>
<td>GodinPrep.m</td>
<td>prog.</td>
<td>calculates the T parameter from collected data</td>
</tr>
<tr>
<td>random.m</td>
<td>prog.</td>
<td>generates an irregular wave voltage series for the wavemaker</td>
</tr>
<tr>
<td>WGAdjust1.m</td>
<td>prog.</td>
<td>uses wave gauge calibrations to calculate wave heights from voltages</td>
</tr>
</tbody>
</table>

Table C.7. MATLAB programs included in this appendix.

global OMEGA1 OMEGA2 NOMEGT EPS

<table>
<thead>
<tr>
<th></th>
<th></th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>OMEGA1 = 0.35;</td>
<td>% Low Frequency cut off</td>
<td></td>
</tr>
<tr>
<td>OMEGA2 = 32;</td>
<td>% High frequency cutoff</td>
<td></td>
</tr>
<tr>
<td>NOMEGT = 1000;</td>
<td>% Number of frequencies for</td>
<td></td>
</tr>
<tr>
<td>% initial spect. analysis</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EPS = 0.005;</td>
<td>% Parameter for spectral</td>
<td></td>
</tr>
<tr>
<td>% truncation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NFIT = 3;</td>
<td>% degree of polynomial for</td>
<td></td>
</tr>
<tr>
<td>% removing trend in data</td>
<td></td>
<td></td>
</tr>
<tr>
<td>% Wave gage calibration constants c1 and c2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
fid1 = fopen('results_f.bin','rt');  % Target spectrum data from 
% previous analysis
fclose(fid1);
NOMGATG = length(AIN)/4;  % number of freq. in target spectrum
OMEGATG(1:NOMGATG) = AIN(1:NOMGATG);  % circ. f in target spectrum def.
SWAVETG(1:NOMGATG) = AIN(NOMGATG+1:2*NOMGATG);  % target spectrum

%fprintf(1,'%s
','Data read for target spectrum stored in results_f.bin');

%NETA = input('Enter number of wave gages : ?');  % User entry due to 
%binary string data

fid2 = fopen('results_t.bin','rt');  % Wave elevation data =>
% from measurement file in binary R*8
%B = fread(fid2, 'real*8');  % Data is stored column by 
%column of same length
fclose(fid2);
LTIME = length(B)/(NETA+1);  % number of data in time series
TTANK(1:LTIME) = B(1:LTIME);  % times of measurements
for j=1:NETA
  ETATK(1:LTIME,j) = B(LTIME*j+1:LTIME*(j+1));
% Wave elevation (m) (otherwise apply gage calibration)
end

% Wave Tank experiments

load voltage_wm.dat
%load waves.mat
%load IrreqWaves.mat
% A(:,2)=[],  % A(:,3)=[],
%A=waves;
A=voltage_wm;
[LTIME,NETA] = size(A);  % number of data in time series
TTANK(1:LTIME) = (0:LTIME-1)*0.01; % times of measurements
for j=1:NETA
    ETATK(1:LTIME,j) = A(1:LTIME,j)*c1(j) + c2(j) ;
    % Wave elevation (m) (otherwise apply gage calibration)
end

fprintf(1,'%s
',[\'Data read from file results_t.bin from '...
    num2str(NETA) ' gages\']);

% Remove slowly changing mean water level and perform statistics
%==============================================

% Detrend (using NFIT-order polynomoal fit) MWL variation
% (or seiching in tank)
for j=1:NETA
    p = polyfit(TTANK(:),ETATK(:,j),NFIT);
    ETAVEG(:,j) = polyval(p,TTANK(:));
end
ETATKC = ETATK - ETAVEG; % Corrected wave elevations

% Wave ZUC analysis for eta1 to get mean period and other statistics

[Height,dum1,dum2,Twave,istart,nwave] = zeroup(ETATKC(:,1),TTANK(:));

TM1 = mean(Twave); % Mean period in elevation % time series from ZUC analysis
etarms1 = sqrt(mean(ETATKC(:,1).^2)); % RMS wave elevation
Hs1 = 4*etarms1; % Significant wave height % from surface elevation analysis
Hrms1 = sqrt(mean(Height.^2)); % RMS wave height from ZUC analysis
H1s31 = sqrt(2)*Hrms1; % H1/3 ZUC
Hm1 = mean(Height); % Hm ZUC
H1s101 = 1.27*H1s31; % H1/10 ZUC

% Spectral analyses (based on Welsh method with standard features, 8
% =========== segments with Hamming windows at 50% overlap)
% TMAX = TTANK(LTIME);
DTAVG = TMAX/(LTIME-1); % mean sampling time step in time series
Fs = 1/DTAVG; % mean sampling frequency (Hz) is inverse mean time step
ne = floor(log(LTIME)/log(2) + 0.5); % Length of fft : nfft = 2^ne
nfft = 2^ne; % length of fft is always an even number
FRETG = OMEGATG/(2*pi);
FMINP = min(FRETG); % Same frequency axis as for target spectrum
FMAXP = max(FRETG);

for i=1:NETA
   [Pxx,freq] = pwelch(ETATKC(:,i),[],[],nfft,Fs);
   SWAVE(:,i) = Pxx(:)/(2*pi);
   % Observed power spectral density S(omega)=S(f)/2pi
end

fprintf(1,'Spectral analyses performed');

% Smoothing of the periodogram by averaging over the frequency bands
% centered on the specified frequencies in the target spectrum

delf = Fs/(nfft-1);
NFTG = length(FRETG);
f(1) = 1;
f(NFTG+2) = length(freq);
for n=1:NFTG
   nf(n+1) = round(FRETG(n)/delf);
   % Find location of target f in observed spectrum
end
for n=2:NFTG+2
   nfint(n-1) = round((nf(n-1)+nf(n))/2);
   % Find limits of frequency bands in observed spectrum
end
% Energy left in both tails
ETAILS(1:NETA) = trapz(freq(1:nfint(1))*2*pi,SWAVE(1:nfint(1),1:NETA))
   /(2*pi*delf*(nfint(1)-1)) + ... 
   trapz(freq(nfint(NFTG+1):nf(NFTG+2))*2*pi,SWAVE(nfint(NFTG+1):nf(NFTG+2),...
      1:NETA))
   /(2*pi*delf*(nf(NFTG+2)-nfint(NFTG+1)));
DETAILS = ETAILS/NFTG; % Average energy correction for each frequency band

for n=1:NFTG % Averaging by integral over frequency bands
   SWAVESM(n,1:NETA) = trapz(freq(nfint(n):nfint(n+1))*2*pi,...
      SWAVE(nfint(n):nfint(n+1),1:NETA))
   /(2*pi*delf*(nfint(n+1)-nfint(n))) + DETAILS;
end
freqSM(1:NFTG) = freq(nf(2:NFTG+1));

% Change of spectral shape of target spectrum to correct for observed
% differences in spectrum. Use nearest frequency in observed spectrum

ratfrt = zeros(1,NFTG);
for i=1:NEFA
    ratfrt(:) = ratfrt(:) + SWAVESM(:,i)./SWAVETG(:);
    % Average correction for NEFA gages
end
ratfrt = ratfrt/NEFA;

[STGMAX,ip] = max(SWAVETG);
icorrec = find(SWAVESM(1:NFTG) >= 0.15*STGMAX);
% Correct only parts of the spectrum >= 10% Smax (target)
ratfrt1 = ratfrt;
for j=1:length(icorrec)
    j0 = icorrec(j);
    j1 = j0-4;
    % only if icorrec(1) >= 4 and icorrec(length(icorrec)) <= NFTG-3
    j2 = j0+4;
    p = polyfit(FRETG(j1:j2),ratfrt(j1:j2),2);
    ratfrt1(j0) = polyval(p,FRETG(j0));
end
% New target spectrum is correcting for irregularities
SWAVETGN = SWAVETG;
SWAVETGN(icorrec) = SWAVETG(icorrec)./ratfrt1(icorrec);

% Correction for total energy based on m0

m0TG = trapz(OMEGATG,SWAVETG); % Target m0 moment
Hs0TG = 4*sqrt(m0TG); % Target Hs0 wave
m0C = trapz(OMEGATG,SWAVETGN);
Hs0 = 4*sqrt(m0C);
ratm0 = m0TG/m0C;
TP = 1/FRETG(ip); % Target peak period
SWAVETGN = SWAVETGN*ratm0;
% Correction of all freq. proportionally to m0TG/M0C
fprintf(1,'s\n','New target spectrum calculated');

% Plot smoothed observed spectrum versus target spectrum

figure;
plot(freqSM(:),SWAVESM(:,1:NEFA),FRETG,SWAVETG);
title(['Target vs obs. Spectr.: Hs0tg=' num2str(Hs0TG) ' m,...
    Hs0=' num2str(Hs0) ' m, Tp=' num2str(TP) ' s','fontsize',12);
axis([FMINP FMAXP 0 max(SWAVETG)]);
axis 'autoy';
xlabel('f (Hz)','fontsize',16);
ylabel('S (m^2. s)','fontsize',16);
figure
plot(FRETG,SWAVETG,FRETG,SWAVETGN);
title(['Target vs New Target Spectrum: Hs0tg=' num2str(Hs0) ' m,...
       Tp=' num2str(TP) ' s'], 'fontsize',12);
axis([FMINP FMAXP 0 max(SWAVETG)]);
axis 'autoy';
xlabel('f (Hz)','fontsize',16);
ylabel('S (m^2. s)','fontsize',16);

% Free surface representation by random phase method based on spectrum
%============================================================================

DOMEGA = OMEGATG(2)-OMEGATG(1);
AMPN = sqrt(2*SWAVETGN*DOMEGA); % amplitudes
PSIN = 2*pi*rand(1,NOMGATG); % phases

% Save binary results for new target spectrum in file results1_f.bin

fid1 = fopen('results1_f.bin','w'); % Various frequency domain results
out1=[OMEGATG' SWAVETGN' AMPN' PSIN'];
fwrite(fid1, out1, 'real*8');
close(fid1);

%-----------------------------------------------------------------

 ArrivalTimeDiff.m —————————————————
%-----------------------------------------------------------------
%Author: Kristy Moore
%Date: 06 27 2007
%Description: This program finds the peak voltage values associated
%with the direct and surface acoustic returns, and calculates the
%time of arrival difference between them.
%Name: ArrivalTimeDiff
%-----------------------------------------------------------------
clc;clear all;

load IrregAcoustics9.mat  %select data file

Fs=80000;  %sampling frequency
% channel with the received acoustical signal
R=A(:,4);

% creates time vector equal length to acoustics
% time=t/Fs; % using sampling frequency to put time into seconds

% removes first acoustic pulse
R=R(7000:800000);
R=R(1:792000);

% separates the data into 99 rows
Rr=reshape(R,8000,99);
ArrTime=[] % with each row containing reflection from one pulse
MaxAmp=[]

% first time amplitude exceeds .2 V
D=find(Rr(:,n)>0.2);
d1=D(1,1);

% first time amplitude exceeds .7 V
S=find(Rr(:,n)>abs(0.7));
if size(S)==[0,1] % isolates the beginning of the surface
    s1=1;
else
    s1=S(1,1);
    F=Rr(s1:s1+100,n);
    Amp=max(F);
    MaxAmp=[MaxAmp Amp];
end;

% for m=1:99
% F=Rr(s1:s1+100,m);
% [Amp,index]=max(F)
% MaxAmp=[MaxAmp Amp];
%
% t=[1:length(Rr)];
time=t/Fs;
t_diff=time(s1)-time(d1);
% saves all the time differences between the direct and surface
% reflected pulses.
ArrTime=[ArrTime t_diff];
end;

% save('Time_Difference.mat','ArrTime')

i=find(ArrTime<0.5e-3);
ArrTime(:,i)=[];

% figure()
% hist(ArrTime*1000)
%
% axis([.88 1.14 0 30])
% xlabel('Travel Time (ms)')
% ylabel('Number of Returns')
% axis([0.85e-3 1.2e-3 0 30])
% xlabel('travel time difference (s)')
% ylabel('number of occurrences')
% h = findobj(gca,'Type','patch');
% set(h,'FaceColor','r','EdgeColor','k')

GetJ.m ————————————————————–

close all;
clear all; clc

load Amp_Flat  %voltage from flatwater

Io=MaxAmp;

load Amp_SS6  %voltage from a wave field

I=MaxAmp;

for n=1:86
    J(n)=I(1,n)/Io(1,n); % dimensionless intensity
end;
figure()
hist(J)
axis([0.4 2.8 0 35])
xlabel('Dimensionless Intensity')
ylabel('Number of Returns')
title('Regular Wave Field - Sea State 6')

Godin1.m ————————————————————–

% Code to plot equation 57 ; Godin 2003 paper

clear
close
%sigma=2;       %rms surface elevation=2m
sigma=3.5
theta=0;
z_s=100;       % source depth
z_p=0:1:100;   % receiver depth
%rho_x=200;    %correlation length
rho_x=240;
c=1450;

% equation 57

asq=(z_s*z_p)/rho_x^2;
temp1=(2*sigma^2)./(c.*(z_s+z_p));
temp2=(sin(theta*pi/180))~2*cos(theta*pi/180);
temp3=(asq*(1+(cos(theta*pi/180))~2))/cos(theta*pi/180);
deltat=temp1.*(temp2-temp3);
plot(z_p,deltat*1000)

theta=15;
asq=(z_s*z_p)/rho_x^2;
temp1=(2*sigma^2)./(c.*(z_s+z_p));
temp2=(sin(theta*pi/180))~2*cos(theta*pi/180);
temp3=(asq*(1+(cos(theta*pi/180))~2))/cos(theta*pi/180);
deltat=temp1.*(temp2-temp3);
hold on;plot(z_p,deltat*1000,'r--')

theta=30;
asq=(z_s*z_p)/rho_x^2;
temp1=(2*sigma^2)./(c.*(z_s+z_p));
temp2=(sin(theta*pi/180))~2*cos(theta*pi/180);
temp3=(asq*(1+(cos(theta*pi/180))~2))/cos(theta*pi/180);
deltat=temp1.*(temp2-temp3);
hold on;plot(z_p,deltat*1000,'g:')
xlabel('Receiver Depth (m)')
ylabel('Travel Time Bias')
title('Travel Time Bias - Source Depth=100m')
%axis([0 1000 -0.18 0.01])
legend('theta = 0', 'theta = 15', 'theta = 30')

Godin2.m ————————————————————

% Code to plot equation 57 ; Godin 2003 paper
%clear
close all

tau=0:0.05:6;
deltat=tau*(sigma/1450);
t1=deltat+9.867e-4;
t1=t1*1000;
%t1=t1+3e-4;
% equation 34;35

T=1;
%T=0.4844
%T=1.0414
psi=T*exp(-tau.^2/2);
w1=tau.*psi.*exp(-psi);
plot(tau,w1,'k');hold on
%plot(t1,w1);hold on

T=10;
%T=0.6421
%T=0.8835;
psi=T*exp(-tau.^2/2);
w1=tau.*psi.*exp(-psi);
plot(tau,w1,'b')
%plot(t1,w1,'r')

T=100;
%T=TT(3);
%T=1.0579
%T=0.6761
psi=T*exp(-tau.^2/2);
w1=tau.*psi.*exp(-psi);
plot(tau,w1,'r')
%plot(t1,w1,'g')

T=1000;
%T=TT(4);
%T=0.5148
psi=T*exp(-tau.^2/2);
w1=tau.*psi.*exp(-psi);
plot(tau,w1,'g')
%plot(t1,w1,'k')

xlabel('dimensionless travel time difference')
%xlabel('Travel Time (ms)')
ylabel('PDF of travel time difference')
title('Propagation time PDF for spherical incident wave - first arrival')
%legend('Irreg 2','Irreg 6', 'Irreg 7', 'Irreg 9')
% Mean Travel Time Difference vs. T

% tau case for T>>1
T=1.0:10:1000;
temp1=sqrt(2*log(T));
temp2=0.577/sqrt(2*log(T));
tau_mean=temp1+temp2;
figure
semilogx(T,tau_mean)
hold on;

% tau case for T~1
T1=0.1:.1:11;
temp1=sqrt((4*log(T1).^2)+1)+(2*0.577);
temp2=2*pi*T1.^2;
temp3=(1./temp1)+(1./temp2);
tau_mean1=(temp3).^(-.5);
semilogx(T1,tau_mean1)
hold on;

% tau case for T<<1
T2=0.01:0.001:0.1;
tau_mean2=sqrt(2*pi)*T2;
semilogx(T2,tau_mean2);
hold on;
xlabel('dimensionless parameter T')
ylabel('Mean travel time difference')
title(' Mean travel time difference - first arrival')

% tau case for T>>1
T=0.01:10:10000;
temp1=sqrt((4*log(T).^2)+1)+(2*0.577);
temp2=2*pi*T.^2;
temp3=(1./temp1)+(1./temp2);
tau_mean=1./sqrt(temp3);
figure
semilogx(T(2:100),tau_mean(2:100))

%
% % T1=0.01:0.01:1;
% % temp1=sqrt((4*log(T1).^2)+1)+(2*0.577);
% % temp2=2*pi*T1.^2;
% % temp3=(1./temp1)+(1./temp2);
% % tau_mean1=1./sqrt(temp3);
% % %tau_mean1=sqrt(2*pi)*T1;
% % hold on; semilogx(T1,tau_mean1)
% %
% % T2=1:0.1:10;
% % temp1=sqrt((4*log(T2).^2)+1)+(2*0.577);
% % temp2=2*pi*T2.^2;
% % temp3=(1./temp1)+(1./temp2);
% % tau_mean2=1./sqrt(temp3);
% % %tau_mean1=sqrt(2*pi)*T1;
% % hold on; semilogx(T2,tau_mean2)
% % xlabel('dimensionless parameter T')
% % ylabel('Mean travel time difference')
% % title(' Mean travel time difefrence - first arrival')
\end{equation}

**Godin3.m** -------------------------------------------------------------

%!lstinputlisting{Godin3.m}
\begin{verbatim}
\begin{verbatim}
clear
%close
tau=0:0.06:6;
J=0:0.01:1.0;

% J=0:0.02:2.0;
% %tau=0:0.03:6;
% tau=0.5:0.01:1.5

% equation 34;35
T=1;
for ii=1:length(J)

psi=T*exp(-tau.^2/2);
w1=tau.*psi.*exp(-psi);
[w]=godin4(tau);
[w_j_tau]=Godin5(J(ii),tau);
w_1_tau_j=(w1.*w_j_tau)/w;
pdf_j(ii)=trapz(w_1_tau_j)*0.05;
end
figure()
plot(J,pdf_j,'k');hold on

% T=.5;
% for ii=1:length(J)
% 
% psi=T*exp(-tau.^2/2);
% w1=tau.*psi.*exp(-psi);
% [w]=godin4(tau);
% [w_j_tau]=Godin5(J(ii),tau);
% w_1_tau_j=(w1.*w_j_tau)/w;
% pdf_j(ii)=trapz(w_1_tau_j)*0.05;
% 
% end
% plot(J,pdf_j,'m');hold on

T=100;
for ii=1:length(J)

psi=T*exp(-tau.^2/2);
w1=tau.*psi.*exp(-psi);
[w]=godin4(tau);
[w_j_tau]=Godin5(J(ii),tau);
w_1_tau_j=(w1.*w_j_tau)/w;
pdf_j(ii)=trapz(w_1_tau_j)*0.05;
end
plot(J,pdf_j,'r');hold on

T=10;
for ii=1:length(J)

psi=T*exp(-tau.^2/2);
w1=tau.*psi.*exp(-psi);
[w]=godin4(tau);
[w_j_tau]=Godin5(J(ii),tau);
w_1_tau_j=(w1.*w_j_tau)/w;
pdf_j(ii)=trapz(w_1_tau_j)*0.05;
end
plot(J, pdf_j); hold on

T=1000;
for ii=1:length(J)

psi = T * exp(-tau.^2/2);
w1 = tau.*psi.*exp(-psi);
[w]=godin4(tau);
[w_j_tau]=Godin5(J(ii), tau);
w_1_tau_j=(w1.*w_j_tau)./w;
pdf_j(ii)=trapz(w_1_tau_j)*0.05;
end
plot(J, pdf_j, 'g'); hold on

xlabel('J')
ylabel('Intensity PDF - first arrival')
title('Intensity PDF of first arrival')

T=1.0
T=10
T=100
T=1000

GodinPrep.m ———————————————————
clear all
close all
clc

filename='ElevationSS7.mat'
load Heightp2h4 % loads surface elevation recorded on wave gauges
H=1.0; % tank water typically 10-12 deg C
H=1.0; % 1.0 m from hydrophone to surface

vp=sqrt(9.8*H); % phase velocity shallow water assumption d<L/11
t=[1:length(WG1_height)];
time=t/800; % makes time series

[height, ampc, ampt, period, istart, nw] = zeroup(WG1_height, time);
% calculates the characteristics of the individual waves in the data set period

L=period*vp;  % find wavelength for each wave

for i=1:length(L)
    slope(i)=height(i)/(L(i)/2);  % finds the positive slope for each wave
end

sigma2=mean((height*100).^2)
sigma21=sigma2/100
sigma=sqrt(sigma2)/100
gamma2=mean((slope*100).^2)
gamma2=gamma2/100

% calculates the dimensionless parameter T from Godin and Fuks
% for ii=1:length(sigma)
%    T(ii)=(gamma2(ii)*H)/(sqrt(2*pi)*sigma(ii));
% end

T=(gamma2*H)/(sigma*sqrt(2*pi))

tau=height/sigma

%--------------------------------------
% Prototype calculations

Hp=100;
Vpp=sqrt(9.8*Hp);
Periodp=10*period;
Lp=Periodp*Vpp;
heightp=100*height;
% finds the positive slope for each wave
for i=1:length(Lp)
    slopep(i)=heightp(i)/(Lp(i)/2);
end

sigma2p=mean((heightp).^2)
sigmap=sqrt(sigma2p)
gamma2p=mean((slopep*100).^2)
gamma2p=gamma2p

Tp=(gamma2p*H)/(sigmap*sqrt(2*pi))
% PROGRAM RANDOM
%
%======================================================================
% Random wave generation in a wavetank by a wavemaker
% if GENER = 1 then read spectrum from file results1_f.dat
% else :
% PM: FETCH = -1; HSTARG = 0 => use OMEGAP, find U10 and HS0 for TPTARG
% <>0 => use HSTARG, find U10 and OMEGAP, TPTARG
% JS: FETCH <>0 (1st guess), U10=0 => use OMEGAP, find U10, HS0
% => iterate on FETCH,U10 to match HSTARG
% <>0, U10<>0=> use U10, find OMEGAP, HS0
%
%9 March 07 S. Grilli, Ocean Engng. Dept., Univ. of Rhode Island
%
clc; clear all; close all;

global GE FETCH U10 HSTARG EPS GAMMA

global OMEGMIN OMEGMAX OMEGA1 OMEGA2 NOMEGT DOMEGA

OMEGA1 = 0.35; % Low Frequency cut off
OMEGA2 = 32; % High frequency cut off
NOMEGT = 1000; % Number of frequencies for initial spect. analysis
EPS = 0.005; % Parameter for spectral truncation
GAMMA = 3.3; % JS (use averag value)

% INPUT GENERAL DATA (tank.dat) and definitions

filein = 'tank.dat'; % General wave generation data
fid1 = fopen(filein,'rt'); % gravity
GE = fscanf(fid1,'%f',1); % Target significant wave height
HSTARG = fscanf(fid1,'%f',1); % Target peak spectral period
TPTARG = fscanf(fid1,'%f',1); % Fetch (m)
FETCH = fscanf(fid1,'%f',1); % Wind speed at 10 m
U10 = fscanf(fid1,'%f',1); % Parameter Gamma for JS (1-7),
GAMMA = fscanf(fid1,'%f',1); % 3.3 if given 0
NOMEG = fscanf(fid1,'%f',1); % Number of frequency intervals
DEPTH = fscanf(fid1,'%f',1); % Water depth (m)
UCURR = fscanf(fid1,'%f',1); % Depth uniform current (m/s)
Fu = fscanf(fid1,'%f',1); % Frequency for time series
    % generation (Hz)
exp2 = fscanf(fid1,'%f',1); % Power of 2 for time series
    % generation (Hz)
GENER = fscanf(fid1,'%f',1); % 1: spectrum exists in file
    % result1_f.bin
    % 0: generate spectrum based on data in
    % tank.dat
fclose(fid1);

% Wave spectrum generation
%%%%%%%%%%%%%%%%%%%%%%%%%%%%
if(GENER == 1) % Read spectrum from file
    fid1 = fopen('results1_f.bin','rt');
    A = fread(fid1, 'real*8');
    fclose(fid1);
    NOMEG = length(A)/4;
    OMEGAN(1:NOMEG) = A(1:NOMEG);
    SWAVE(1:NOMEG) = A(NOMEG+1:2*NOMEG);
    AMPN(1:NOMEG) = A(2*NOMEG+1:3*NOMEG);
    PSIN(1:NOMEG) = A(3*NOMEG+1:4*NOMEG);
    OMEGAP = 2*pi/TPTARG; % PEAK TARGET SPECTRAL FREQUENCY
    m0 = trapz(OMEGAN,SWAVE);
    HS0 = 4*sqrt(m0);
    fprintf(1,'%s
','Target spectrum read from file results1_f.bin');
else % Generate spectrum
    OMEGAP = 2*pi/TPTARG; % PEAK TARGET SPECTRAL FREQUENCY
    % For JS with U10 = 0 and Fetch <> 0 => HS0
    % U10 <> 0 and Fetch = -1 => HS0
    % For PM with HSTARG = 0 and U10 = 0 => HS0
    if (GAMMA == 0)
        GAMMA = GAMAM; % Mean JS parameter by default
    end
    % PM or JS spectrum generation
    [AMPN,PSIN,SWAVE,OMEGAN,HS0] = spectre(OMEGAP,NOMEG);
    %
    fprintf(1,'%s
','Target spectrum generated');
end

% spectral wavenumber for DEPTH and UCURR=0 (LWT)
[KN0] = kdis(OMEGAN,DEPTH);
%
% Time series correction due to current

if (UCURR ~= 0)
    CEL0 = OMEGAN./KNO;  % Celerity without current
    CG0 = (CEL0/2)./(1+2*KNO*DEPTH./sinh(2*KNO*DEPTH));
    % Group velocity without current
    [KN] = kudis(OMEGAN,UCURR,DEPTH);
    % spectral wavenumber for DEPTH and UCURR (LWT)
    
    OMEGAPN = OMEGAN - KN*UCURR;  % Apparent wave pulsation due to current
    CEL = OMEGAPN./KN;  % Celerity with current
    % Group velocity with current
    CG = (CEL/2)./(1+2*KN*DEPTH./sinh(2*KN*DEPTH));
    CELRAT = CEL./CEL0;
    OMERAT = OMEGAPN./OMEGAN;
    
    KS = sqrt(((CELRAT.^2).*OMERAT.*CG0./(UCURR+CG));
    AMPN = AMPN.*KS;
    
    hold on;
    SWAVEP = AMPN.^2/(2*DOMEGA);  % New spectrum with current
    OMEGAN = OMEGAPN;  % New wave frequency distribution
    [SPMAX,iS] = max(SWAVEP);
    OMEGAP = OMEGAN(iS);  % New peak spectral frequency
    
    TP = 2*pi/OMEGAP;  % Target spectral peak period (s) without current !!!
    % one shouldm redo a spectral analysis
    % here to verify after time series generation
end

% Generate wave time series at frequency Fu Hz by linear superposition
Sec = (2^exp2 - 1)/Fu; \% Length (s) of Random Signal -> 2^15-1 at Fu Hz

\[ t = [0:1/Fu:Sec]; \% \text{ time vector} \]

\[ \text{tum} = \text{length}(t); \% \text{ length of time vector} \rightarrow 2^15-1 \]

% elevation time series

\begin{verbatim}
for m = 1:tum
    Wave(m) = sum(AMPN.*cos(OMEGAN.*t(m) + PSIN));
end
\end{verbatim}

% Wave ZUC analysis

\begin{verbatim}
[Height,dum1,dum2,Twave,istart,nwave] = zeroup(Wave,t);
% -----
\end{verbatim}

% Surface elevation and statistics

etarms = sqrt(mean(Wave.^2));
% Significant wave height from surface elevation analysis
Hz = 4*etarms;
Hrms = sqrt(mean(Height.^2)); \% RMS wave height from ZUC analysis
H1s3 = sqrt(2)*Hrms; \% H1/3 ZUC
Hm = mean(Height); \% Hm ZUC
H1s10 = 1.27*H1s3; \% H1/10 ZUC

% Mean period in elevation time series from ZUC analysis
Tm = mean(Twave);

figure
plot(t,Wave);
title(['Random wave: Hs0=' num2str(HS0) ' m, Hs=' num2str(Hs)...
' m, Tp=' num2str(TP) ' s, Tm=' num2str(Tm) ' s'],'fontsize',12);
xlabel('t (s)','fontsize',14);
ylabel('eta (m)','fontsize',14);

fprintf(1,'%s
','Surface elevation generated');

% Wavemaker stroke/voltage generation
%====================================

% Calculate Stroke transfer function for flap wmk. (TRANS = S/H
% => STROKEN = S/2)

OMEGAT = 2*pi./Twave; \% pulsation of individual waves

\begin{verbatim}
[KT] = kudis(OMEGAT,UCURR,DEPTH);
% -----
\end{verbatim}
[Strans] = flap(KT,DEPTH);  % Flap wavemaker transfer function
 % ----
 % Transform individual waves to maximum strokes H -> So
 STROKET = Height.*Strans;

[Vtran] = voltage(Twave,STROKET)./STROKET;
% Voltage transfert function Vmax(So,T)/So
% calculated for each stroke So -> Vmax
% -----

% Apply stroke and voltage transfer functions to each individual
% wave in time series

iout = 1;
Vout = zeros(1,tum);  % initialize time series to zero
% first partial wave data
Vout(iout:istart(1)-1) = Wave(iout:istart(1)-1)*Strans(1)*Vtran(1);
iout = istart(1);
for ns=1:nwave  % next nwave data
    mb = istart(ns);
    me = istart(ns+1)-1;
    istrlegt(ns) = me - mb + 1;
    % voltage time series
    Vout(iout:iout+istrlegt(ns)-1) = Wave(mb:me)*Strans(ns)*Vtran(ns);
    iout = iout + istrlegt(ns);
end
% last partial wave data
Vout(iout:tum) = Wave(iout:tum)*Strans(nwave)*Vtran(nwave);
figure
plot(t,Vout);
title(['Random wave: Hs0=' num2str(HS0) ' m, Hs=' num2str(H1s3) ...
        ' m, Tp=' num2str(TP) ' s, Tm=' num2str(Tm) ' s'], 'fontsize',12);
xlabel('t (s)','fontsize',14);
ylabel('Volt','fontsize',14);

fprintf(1,'%s
','All wave and voltage time series calculated');

% Save results
%===============
% Voltage time series at frequency Fu (Hz)
fid2 = fopen('voltage_wm.dat','w');
out2=[Vout'];
fprintf(fid2,'%10.5f
',out2);
fclose(fid2);
% Various times series results in ascii
fid3 = fopen('results_t.dat','w');
for m=1:tum
    out3=[t(m) Wave(m) Vout(m)];
    fprintf(fid3,'%10.5f %10.5f %10.5f
',out3);
end
fclose(fid3);
% Various times series results in binary R*8
fid3p = fopen('results_t.bin','w');
out3p=[t' Wave' Vout'];
fwrite(fid3p, out3p, 'real*8');
close(fid3);
% Various frequency domain results in binary R*8
fid4 = fopen('results_f.bin','w');
out4=[OMEGAN' SWAVE' AMPN' PSIN'];
fwrite(fid4, out4, 'real*8');
close(fid4);

WGadjust1.m ————————————————

clc;clear all;close all;
CalFs = 1;  % wave gauge calibration sampling frequency....
% KEEP AT 1 Hz
Fs = 1;    % data file sampling frequency (user-defined)
Twave = 1.3;  % wave period in seconds as inputted into wave1.vi
Hwave = 0.137;  % wave height in m as inputted into wave1.vi
load('WGCal1')
WG1Cal1 = A(:,1);  % channel 1 = wave gauge #1 is a large
%(20 cm) gauge
WG2Cal1 = A(:,2);  % channel 2 = wave gauge #3 is a small
%(15 cm) gauge
% WG3Cal1 = A(:,3);  % channel 3 = wave gauge #3 is a small
% (15 cm) gauge
% WG4Cal1 = A(:,4);  % channel 4 = wave gauge #4 is a large
%(20 cm) gauge
WG1Cal1_ave = mean(WG1Cal1);
WG2Cal1_ave = mean(WG2Cal1);
% WG3Cal1_ave = mean(WG3Cal1);
% WG4Cal1_ave = mean(WG4Cal1);
clear A
load('WGCal2')
WG1Cal2 = A(:,1);
WG2Cal2 = A(:,2);
% WG3Cal2 = A(:,3);
% WG4Cal2 = A(:,4);
WG1Cal2_ave = mean(WG1Cal2);
WG2Cal2_ave = mean(WG2Cal2);
% WG3Cal2_ave = mean(WG3Cal2);
% WG4Cal2_ave = mean(WG4Cal2);
clear A
load('WGCal3')
WG1Cal3 = A(:,1);
WG2Cal3 = A(:,2);
% WG3Cal3 = A(:,3);
% WG4Cal3 = A(:,4);
WG1Cal3_ave = mean(WG1Cal3);
WG2Cal3_ave = mean(WG2Cal3);
% WG3Cal3_ave = mean(WG3Cal3);
% WG4Cal3_ave = mean(WG4Cal3);
clear A % clear A because DAQVIEW software saves variable A for every .mat file
load('WGCal4')
WG1Cal4 = A(:,1);
WG2Cal4 = A(:,2);
% WG3Cal4 = A(:,3);
% WG4Cal4 = A(:,4);
WG1Cal4_ave = mean(WG1Cal4);
WG2Cal4_ave = mean(WG2Cal4);
% WG3Cal4_ave = mean(WG3Cal4);
% WG4Cal4_ave = mean(WG4Cal4);
clear A % clear A because DAQVIEW software saves variable A for every .mat file
% load('WGCal5')
WG1Cal5 = A(:,1);
WG2Cal5 = A(:,2);
% WG3Cal5 = A(:,3);
% WG4Cal5 = A(:,4);
WG1Cal5_ave = mean(WG1Cal5);
WG2Cal5_ave = mean(WG2Cal5);
% WG3Cal5_ave = mean(WG3Cal5);
% WG4Cal5_ave = mean(WG4Cal5);
clear A % clear A because DAQVIEW software saves variable A for every .mat file
%
load('WGCal6')
%
WG1Cal6 = A(:,1);
WG2Cal6 = A(:,2);
% WG3Cal6 = A(:,3);
% WG4Cal6 = A(:,4);
WG1Cal6_ave = mean(WG1Cal6);
WG2Cal6_ave = mean(WG2Cal6);
% WG3Cal6_ave = mean(WG3Cal6);
% WG4Cal6_ave = mean(WG4Cal6);
clear A % clear A because DAQVIEW software saves variable A for %every .mat file
%
load('WGCal7')
WG1Cal7 = A(:,1);
WG2Cal7 = A(:,2);
% WG3Cal7 = A(:,3);
% WG4Cal7 = A(:,4);
WG1Cal7_ave = mean(WG1Cal7);
WG2Cal7_ave = mean(WG2Cal7);
% WG3Cal7_ave = mean(WG3Cal7);
% WG4Cal7_ave = mean(WG4Cal7);
clear A
%
load('WGCal8')
WG1Cal8 = A(:,1);
WG2Cal8 = A(:,2);
% WG3Cal8 = A(:,3);
% WG4Cal8 = A(:,4);
WG1Cal8_ave = mean(WG1Cal8);
WG2Cal8_ave = mean(WG2Cal8);
% WG3Cal8_ave = mean(WG3Cal8);
% WG4Cal8_ave = mean(WG4Cal8);
clear A
%
%x=[-.10:.02:.10];
x=[-.10:.0285:.10];
%x3=[-.075:.015:.075];
x3=[-.075:.021:.075];
y1=[WG1Cal8_ave WG1Cal7_ave WG1Cal6_ave WG1Cal5_ave WG1Cal4_ave...
    WG1Cal3_ave WG1Cal2_ave WG1Cal1_ave];
y2=[WG2Cal8_ave WG2Cal7_ave WG2Cal6_ave WG2Cal5_ave WG2Cal4_ave...
    WG2Cal3_ave WG2Cal2_ave WG2Cal1_ave];
%y3=[WG3Cal8_ave WG3Cal7_ave WG3Cal6_ave WG3Cal5_ave WG3Cal4_ave...
%WG3Cal3_ave WG3Cal2_ave WG3Cal1_ave];
%y4=[WG4Cal8_ave WG4Cal7_ave WG4Cal6_ave WG4Cal5_ave WG4Cal4_ave...
%WG4Cal3_ave WG4Cal2_ave WG4Cal1_ave;
 Fit2=polyfit(y2,x,1);
 %Fit3=polyfit(y3,x3,1);
 %Fit4=polyfit(y4,x,1);
 Fit1=polyfit(y1,x,1);
%

% Data File
[eventFilename, pathname] = uigetfile('*.mat', 'Pick the data file');
cd(pathname)
load(eventFilename) % loading event data file
df = 1/Fs; % delta frequency
t = [df:df:(length(A(1:100:end,1)))*df]; % time array
WG1 = A(1:100:end,1); % channel 1 = wave gauge #1
WG2 = A(1:100:end,2); % channel 2 = wave gauge #2
%WG3 = A(1:100:end,3); % channel 3 = wave gauge #3
%WG4 = A(1:100:end,4); % channel 4 = wave gauge #4
% Receiver = A(:,5); % channel 5 = Receiver (hydrophone)
% %ReceiverGaindB = 10*log10(ReceiverGain);
% Amount of receiver gain in dB (e.g. 100x linear = 20 dB)
% Source = A(:,6); % channel 6 = Source (pinger)
clear A

% Wave Field Data

% Plotting Raw (with Bias) Wave Gauge Signals
figure(1)
subplot(2,2,1)
plot(t,WG1,'r')
hold on
plot(t,WG2,'b')
%plot(t,WG3,'m')
%plot(t,WG4,'g')
grid on
axis([0 max(t) -10 10])
title('Raw Wave Data')
xlabel('Time (s)')
ylabel('Amplitude (V)')
legend('WG #1','WG #4')
%
% Plotting WG calibration curves
figure(1)
subplot(2,2,2)
plot(x,y1,'ro',x,-y2,'bo')
axis([-0.10 0.10 -10 10])
grid on
title('Wave Gage Calibration')
xlabel('Displacement (m)')
ylabel('Amplitude (V)')
legend('WG #1','WG #4')

% Applying Wave Gauge Calibration
for k = 1:length(WG1)
    WG1_height(k)=WG1(k)*Fit1(1)+Fit1(2);
    WG2_height(k)=WG2(k)*Fit2(1)+Fit2(2);
    %WG3_height(k)=WG3(k)*Fit3(1)+Fit3(2);
    %WG4_height(k)=WG1(k)*Fit4(1)+Fit4(2);
end
% Gain1=mean(WG1_height);
% WG1_height2=WG1_height-Gain1;
% Gain3=mean(WG3_height);
% WG3_height2=WG3_height-Gain3;
% Gain4=mean(WG4_height);
% WG4_height2=WG4_height-Gain4;
figure(1)
subplot(2,2,3)
% plot(t,WG1_height2,'r')
plot(t,WG1_height,'r')
hold on
plot(t,WG2_height,'b')
% plot(t,WG3_height2,'m')
% plot(t,WG4_height2,'g')
% % plot(t,WG2_height,'b')
%plot(t,WG3_height,'m')
%plot(t,WG4_height,'g')
grid on
axis([0 max(t) -0.15 0.15])
title('Surface Elevation')
xlabel('Time (s)')
ylabel('Surface Elevation (m)')
legend('WG #1','WG #4')
% % WG1_height_ZeroRef = WG1_height2 + abs(min(WG1_height2));
% WG3_height_ZeroRef = WG3_height2 + abs(min(WG3_height2));
% WG4_height_ZeroRef = WG4_height2 + abs(min(WG4_height2));
```
WG1_height_ZeroRef = WG1_height + abs(min(WG1_height));
WG2_height_ZeroRef = WG2_height + abs(min(WG2_height));
%WG3_height_ZeroRef = WG3_height + abs(min(WG3_height));
%WG4_height_ZeroRef = WG4_height + abs(min(WG4_height));
figure(1)
subplot(2,2,4)
plot(t,WG1_height_ZeroRef,'r')
hold on
plot(t,WG2_height_ZeroRef,'b')
%plot(t,WG3_height_ZeroRef,'m')
%plot(t,WG4_height_ZeroRef,'g')
grid on
axis([0 max(t) 0 0.30])
title('Wave Height')
xlabel('Time (s)')
ylabel('Wave Height (m)')
legend('WG #1', 'WG #4')

C.3.3 MATLAB Functions

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>flap.m</td>
<td>func.</td>
<td>wavemaker transfer function</td>
</tr>
<tr>
<td>Godin4.m</td>
<td>func.</td>
<td>calculates the propagation time PDF and passes to Godin3.m</td>
</tr>
<tr>
<td>Godin5.m</td>
<td>func.</td>
<td>calculates the modeled acoustic intensity and passes to Godin3.m</td>
</tr>
<tr>
<td>kdis.m</td>
<td>func.</td>
<td>generates the spectral wavenumber based on linear dispersion relationship</td>
</tr>
<tr>
<td>kudis.m</td>
<td>func.</td>
<td>calculates wavenumber corrected for current</td>
</tr>
<tr>
<td>spectre.m</td>
<td>func.</td>
<td>generates a Pierson-Moskowitz or Jonsswap wave spectrum</td>
</tr>
<tr>
<td>voltage.m</td>
<td>func.</td>
<td>voltage transfer function</td>
</tr>
<tr>
<td>zeroup.m</td>
<td>func.</td>
<td>computes zero up crossing height from collected data</td>
</tr>
</tbody>
</table>

Table C.8. MATLAB functions included in this appendix.

```

function [TRANS] = flap(k,d)

%9 March 07  S. Grilli, Ocean Engng. Dept., Univ. of Rhode Island
%===================================================================
% depth to arm of hydraulic jack in meter (URI wavemaker)
dt = 1.925;
```
arg1 = k.*d;
arg2 = 2.*arg1;

% trans = So/H = So/(2A) as a function of (k,d) for linear flap
% hinged wavemaker (A=H/2) and So is stroke amplitude

TRANS = (arg2 + sinh(arg2))./(4.*sinh(arg1).*sinh(arg1)+
(1 - cosh(arg1))./arg1));

% dt/d accounts for difference in water level d and hydraulic
% jack location

TRANS = TRANS.*dt./d;

Godin4.m ————————————————————

function [w]=godin4(tau)
% calculates w - equation 54 and sends back to Godin3.m
% tau=2;

temp1=erfc(-tau/2);
temp2=erfc(-tau/sqrt(2));
temp3=exp(-3*tau.^2/4);
temp4=exp(-tau.^2);
temp5=exp(-tau.^2/2);

w=0.5*sqrt(3/pi)*((temp3.*temp1)+((tau/sqrt(pi)).*temp4)+
(((tau.^2-1)/sqrt(2)).*temp5.*temp2));

Godin5.m

function [w_j_tau]=Godin5(J,tau);
% calculates w(tau,J) - equation 53 in Godin2007
% and sends back to Godin3

% tau=2;
% J=2;

temp1=exp((1/J)-(3*tau.^2/4));
temp2=erfc(sqrt(2/J)-(tau/2));
temp3=(1/(2*J^3))*sqrt(3/pi);

w_j_tau=temp1.*temp2.*temp3;
function [K] = kdis(omega,d)

%0 KDISF  ldis
%1 Purpose  ldis computes the wavenumber k using the linear dispersion
%1 relation : k tanh(k*d) = (omega)**2 / ge in the form
%1 L = Lo tanh(k*h), with Lo=g T**2/2 pi
%2 Method  Newton-Raphson iteration method with relative error EPS
%2 Computations assume SI, i.e., MKS units.
%2 Uses : x = k*h; k=2 pi/L
%2 x(n+1) = x(n) - F(x(n))/DF(x(n))
%2 F(x(n)) = x(n) - D/tanh(x(n))
%2 DF(x(n)) = 1 + D/sinh(x(n))**2
%2 Number of iterations is limited to ITERM=50
%3 CALL arg. omega: circular wave freq. (r/s)
%3 d : Depth of the sea (m)
%3 RET arg. L : Wavelength (m)
%3 OTHERS GE : Acceleration of gravity (m/s^2)
%E ERRORS The number of iterations is too large
%9 Sept. 06 S. Grilli, Ocean Engng. Dept., Univ. of Rhode Island

% global GE
EPS = 0.000001;
ITERM = 50;

DE = (omega.^2) .* d ./ GE;
ITER = 0;
ERR = 1;

%.....Initial guess for nondimensional solution X
if (DE >= 1)
    X0 = DE;
else
    X0 = sqrt(DE);
end

%.....Solution using Newton-Raphson method
while ((ERR > EPS) & (ITER <= ITERM))
    F = X0 - DE./tanh(X0);

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DF = 1 + DE./(sinh(X0).^2);
X1 = X0 - F./DF;
ERR = abs((X1-X0)./X0);
X0 = X1;
ITER = ITER + 1;
end

if (ITER > ITERM)
    fprintf(1, 'convergence failed\n');
else
    K = X1 / d;
end

kudis.m ————————————————————

function [K] = kudis(omega,U,d)

% KDISF ldis
% Purpose ldis computes the wavenumber k using the linear dispersion relation : g*k tanh(k*d) = (omega - k*U)**2 (the apparent frequency)
% Method Newton-Raphson iteration method with relative error EPS
% Computations assume SI, i.e., MKS units.
% Uses : x = k*h; omegab = omega *sqrt(d/g) ; ub = U/sqrt(g*d)
% x(n+1) = x(n) - F(x(n))/DF(x(n))
% F(x(n)) = x(n) - (omegab - ub*x(n))^2/tanh(x(n))
% DF(x(n)) = 1 + ((omegab - ub*x(n)).^2/sinh(x(n))**2)*
% (1+ ub*sinh(2*x(n))/(omegab - ub*x(n)))
% Number of iterations is limited to ITERM=50
% CALL arg. omega: circular wave freq. (r/s) (could be a vector)
% d : Depth of the sea (m) (scalar)
% U : depth uniform current velocity (m/s) (scalar)
% >0 co-flowing; <0 flowing against wave
% RET arg. L : Wavelength (m)
% OTHERS GE : Acceleration of gravity (m/s^2)
% ERRORS The number of iterations is too large
% %
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% %
% global GE
% EPS = 0.000001;
% ITERM = 50;
OMEGAB = omega * sqrt(d/GE);
DE = OMEGAB.^2;
UB = U/sqrt(GE*d);
ITER = 0;
ERR = 1;

%......Initial guess for nondimensional solution X
% if (DE >= 1)
  X0 = DE;
else
  X0 = sqrt(DE);
end

%......Solution using Newton-Raphson method
% while ((ERR > EPS) & (ITER <= ITERM))
  F = X0 - (OMEGAB - UB*X0).^2./tanh(X0);
  DF = 1 + ((OMEGAB - UB*X0).^2./((sinh(X0).^2))... 
       *(1 + UB*sinh(2*X0)/(OMEGAB - UB*X0)));
  X1 = X0 - F./DF;
  ERR = abs((X1-X0)./X0);
  X0 = X1;
  ITER = ITER + 1;
end

% if (ITER > ITERM)
  fprintf(1,'convergence failed\r');
else
  K = X1 / d;
end

spectre.m

function [AMPN,PSIN,SWAVE,OMEGAN,HS0] = spectre(OMEGAP,NOMEG)
%===================================================================
% PM: FETCH = -1; HSTARG = 0 => use OMEGAP, find U10 and HS0
%     (for TPTARG)
% <>0 => use HSTARG, find U10 and OMEGAP,
% TPTARG
% JS: FETCH <>0 (1st guess), U10=0 => use OMEGAP, find U10, HS0
%     => iterate on FETCH,U10 to match
%     HSTARG
% <>0, U10<>0=> use U10, find OMEGAP, HS0 <> HSTARG
%
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%
%===================================================================
global GE FETCH U10 HSTARG EPS GAMMA
global OMEGMIN OMEGMAX OMEGA1 OMEGA2 NOMEGT DOMEGA

TOLHSI = 0.975; % For JS, mn and max tolerance on HS0 = HSTRAG
TOLHSA = 1.025;
% Max nb. iterations for iterative correction of Hs0 in JS
ITMAX = 15;

if U10 == 0
  if FETCH == -1 % FDS
    ALPHA = 0.0081; % PM
    if HSTARG == 0
      U10 = 0.797*GE/OMEGAP;
      HS0 = 0.21*U10^2/GE;
    else
      U10 = sqrt(GE*HSTARG/0.21);
      OMEGAP = 0.797*GE/U10;
      HS0 = HSTARG;
    end
    st = 1;
  else
    U10 = 10648*GE*GE/(FETCH*OMEGAP^3); % JS
    ALPHA = 0.57/sqrt(GE*FETCH/U10^2);
    st = 2;
  end
else
  if FETCH == -1 %FDS
    ALPHA = 0.0081; % PM
    OMEGAP = 0.797*GE/U10;
    HS0 = 0.21*U10^2/GE;
    st = 1;
  else
    ALPHA = 0.57/sqrt(GE*FETCH/U10^2); % JS
    OMEGAP = (22*GE/U10)/((GE*FETCH/(U10^2))^(1/3));
    st = 3;
  end
end
ALPHA = ALPHA*GE^2; % Spectrum generation at given frequencies
% Calculate spectrum over pre-fixed interval [OMEGA1, OMEGA2]
% with max number of frequencies NOMEGT

OMEGAM(1:1:NOMEGT) = OMEGA1 + (0:1:NOMEGT-1) * (OMEGA2 - OMEGA1) / (NOMEGT - 1);
SOL = ALPHA .* exp(-1.25 .* (OMEGAP ./ OMEGAM).^4) ./ OMEGAM.^5;
if st >= 2
    sig0L(1:NOMEGT) = 0.09;
    nlittle = find(OMEGAM <= OMEGAP);
    sig0L(nlittle) = 0.07;
    SWAVEL = SOL .* GAMMA.^(exp(-(OMEGAM - OMEGAP).^2 / (2 .* sig0L.^2 * OMEGAP^2)));
else
    SWAVEL = SOL; % PM
end

% Find frequency interval [OMEGMIN, OMEGMAX] for spectrum > % EPS its maximum

[Smax, iSmax] = max(SWAVEL);
ismall = find(SWAVEL >= Smax * EPS);
OMEGMIN = min(OMEGAM(ismall));
OMEGMAX = max(OMEGAM(ismall));

% Recalculate spectrum in selected interval and its zero-th % moment with reduced number of frequencies NOMEG

DOMEGA = (OMEGMAX - OMEGMIN) / (NOMEG - 1);
OMEGAN(1:1:NOMEG) = OMEGMIN + (0:1:NOMEG-1) * DOMEGA;
S0 = ALPHA .* exp(-1.25 .* (OMEGAP ./ OMEGAN).^4) ./ OMEGAN.^5;
if st >= 2
    sig0(1:NOMEG) = 0.09;
    nlittle = find(OMEGAN <= OMEGAP);
    sig0(nlittle) = 0.07;
    SWAVE = S0 .* GAMMA.^(exp(-(OMEGAN - OMEGAP).^2 / (2 .* sig0.^2 * OMEGAP^2)));
else
    SWAVE = S0; % PM
end

% Zero-th moment of spectrum by integration
m0 = trapz(OMEGAN(1:NOMEG), SWAVE(1:NOMEG));
HS0 = 4 * sqrt(m0);
% Iterative fine tuning of FETCH for JS to match targeted Hs
if st == 2
    beta = HSO/HSTARG;
    iter = 1;
    while (beta < TOLHSI | beta > TOLHSA) & iter <= ITMAX
        % Corrects wind speed prop. to sqrt(Hs0)
        U10C = U10/sqrt(beta);
        FETCHC = 10648*GE*GE/(U10C*OMEGAP^3);
        ALPHAC = 0.57/sqrt(GE*FETCHC/U10C^2);
        S0 = ALPHAC.*exp(-1.25.*(OMEGAP./OMEGAN).^4)./...
            OMEGAN.^5;
        SWAVE = S0.*GAMMA.*(exp(-(OMEGAP-OMEGAN).^2./(2.*...
            sig0.^2*OMEGAP^2)));
        mOC = trapz(OMEGAN,SWAVE);
        HSOC = 4*sqrt(mOC);
        beta = HSOC/HSTARG;
        U10 = U10C;
        iter = iter + 1;
    end
    FETCH = FETCHC;
    U10 = U10C;
    HS0 = HS0C
end

% Free surface representation by random phase method based
% on spectrum

AMPN = sqrt(2*SWAVE*DOMEGA); % amplitudes
PSIN = 2*pi*rand(1,NOMEG); % phases
TP = 2*pi/OMEGAP; % Actual apsctral peak period (s)

figure
plot(OMEGAN(1:NOMEG)/(2*pi),SWAVE(1:NOMEG));
title([‘Ocean wave spectrum’ ’ Hs=’ num2str(HS0) ...%
    ’ m, Tp=’ num2str(TP) ’ s’],’fontsize’,16);
xlabel(‘f (Hz)’,’fontsize’,16);
ylabel(‘S (m^-2. s)’,’fontsize’,16);

voltage.m ———————————————————–

function [Vout] = voltage(T,So)

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%==================================================================
% This function creates the voltage signal to drive the wave tank.  
% Calibration is strictly based on sinusoidal motion of period \( T \)  
% and stroke

\[
A0 = 1.1586; \\
A1 = 28.978; \\
A2 = -1.8555; \\
A3 = -11.8; \\
A4 = 8.938; \\
A5 = 0.7059;
\]

\[
V_{\text{out}} = A0 + A1 \cdot s_{\text{o}} + A2 \cdot T + A3 \cdot s_{\text{o}} \cdot T + A4 \cdot s_{\text{o}}^2 + A5 \cdot T^2;
\]

zeroup.m ————————————————————-

function [height, ampc, ampt, period, istart, nw] = zeroup(f, t);
%
%==============================================================
% zeroup.m: computing zero-up crossing height from data
%%
% Input -  f: time series
%         t: time values
%
% Output - height: time series of height
%          ampc : time series of crest amplitude
%          ampt : time series of trough amplitude
%          period: time series of period
%          istart: start index of each wave (length nw+1)
%          nw : number of data
%
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%==============================================================
%

n = length(f);
nw = 0;
iflag = 0;
fmax = 0;
fmin = 0;

for i=1:n-1
    fmax = max(f(i+1), fmax);
    fmin = min(f(i+1), fmin);
    if ( f(i) < 0 ) & ( f(i+1) >= 0 )

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t0 = t(i) - (t(i+1)-t(i))/(f(i+1)-f(i))*f(i); % time of ZUC
if iflag == 0;
    iflag = 1;
    tstart = t0;
    istart(1) = i+1;
    fmax = 0;
    fmin = 0;
else
    nw = nw + 1;
    height(nw) = fmax - fmin;
    ampc(nw) = fmax;
    ampt(nw) = fmin;
    fmax = 0;
    fmin = 0;
    tend = t0;
    period(nw) = tend - tstart;
    tstart = tend;
    istart(nw+1) = i+1;
end
end
end
BIBLIOGRAPHY


