

UNDERWATER ACOUSTIC PROPAGATION MODELING AND UTILIZATION FOR
MARINE HYDROKINETIC DEVICES

by

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A dissertation submitted in partial fulfillment
of the requirements for the degree

of

Doctor of Philosophy

in

Engineering

MONTANA STATE UNIVERSITY
Bozeman, Montana

January 2024

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ACKNOWLEDGEMENTS

This work was sponsored by Sandia National Laboratories Water Power Technology department and by the Department of Energies Wind and Water Power Technologies Office. Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under Contract No. DE-NA0003525. All experimental data, bathymetric data, and environmental data collected for the various project locations required for this was provided by Integral Consulting, Inc. out of Santa Cruz, CA. Computational efforts were performed on the Tempest High Performance Computing System, operated and supported by University Information Technology Research Cyberinfrastructure at Montana State University. The work presented in this thesis would have have been completed without help from the following people:

Sandia National Laboratories, Albuquerque, NM: Jesse Roberts, Leiph Preston, and Jenny Harding.

Integral Consulting, Inc., Santa Cruz, CA: Kaus Raghukumar, and Craig Jones.

Montana State University: Dr. Erick Johnson, Dr. Joel Cahoon, Dr. Kathryn Plymessenger, Dr. Matt Blank, Nate Johnson, and Wyatt Gray.

Thank you to everyone who provided data, helped facilitate questions, and provided guidance. It would not have happened without you.

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NOMENCLATURE

$*$	Perturbative values
$^{\circ}$	Ambient value OR degree
η	Entropy
θ	Absolute temperature
κ	Material bulk modulus
κ_x	Dampening variable
λ	Bulk viscosity OR wavelength
μ	Dynamic viscosity OR micro
ξ	Entropy production
ρ	Density
σ	Normal Stress
τ	Shear Stress
Ψ	Memory variable
ω	Frequency
$\mathbf{a}$	Acceleration vector
a_x	Dampening variable
A	Area
b_x	Dampening variable
B	Pressure amplitude
c	Sound speed
e	External Energy density
$\mathbf{F}$	Resultant force vector
$\mathbf{g}$	Gravity force vector
$\mathbf{I}$	Identity matrix
$\mathbf{n}$	Normal vector
n	Distance counter
$\mathbf{m}$	Moment density tensor
m	Mass
$\mathbf{P}$	Linear momentum vector
p	Pressure
r	Radius
$\mathbf{s}$	Entropy flux
S	Salinity
t	Time
T	Temperature
$\mathbf{v}$	Velocity vector
w	Waveform

NOMENCLATURE – CONTINUED

dB	Decibel
Hz	Hertz
kg	Kilogram
m	Meter
Pa	Pascal
PCU	Salinity unit
s	Second
APL/JHU	Applied Physics Laboratory of Johns Hopkins University
ARL	Applied Research Laboratory
CEC	Current Energy Converter
CMPL	Convolutionally Perfectly Matched Layer
CPT	Columbia Power Technologies
CTD	Conductivity, Temperature, Salinity Measurements
DNMS	Drifting Noise Measurement System
DOE	Department of Energy
DSC	Deep Sound Channel
EMEC	European Marine Energy Centre
FDM	Finite Difference Method
FEM	Finite Element Method
FFT	Fast Fourier Transform
FWH	Ffowcs-Williams and Hawkings
GPL	General Public License
GTWT	Garfield Thomas Water Tunnel
HICI-FT	High Intensity Controlled Impedance – Fluid filled wave Tube
MHK	Marine Hydrokinetic
MMPA	Marine Mammal Protection Act
NNMREC	University of Washington Northwest National Marine Renewable Energy Center
NOAA	National Oceanic and Atmospheric Administration
NPAL	North Pacific Acoustic Laboratory
NRL	Naval Research Laboratory
NWEI	Northwest Energy Innovations
ORPC	Ocean Renewables Power Company
PCHIP	Piecewise Cubic Hermite Interpolating Polynomial
PAM	Passive Acoustic Monitoring
PE	Parabolic Equations

NOMENCLATURE – CONTINUED

PNNL	Pacific Northwest National Laboratories
PTS	Permanent Threshold Shift
RANS	Reynolds Average Navier Stokes
RITE	Roosevelt Island Tidal Energy
RMS	Root Mean Square
SAMS	Scottish Association for Marine Science
SEL	Sound Energy Level (dB)
SNL	Sandia National Laboratories
SPL	Sound Pressure Level (dB)
SURGE	Simple Underwater Renewable Generation of Electricity
SWARM	Shallow Water Acoustics in Random Medium
SWIFT	Surface Wave Instrumentation Float with Tracking
TDDAPS	Time Domain Acoustic Atmosphere Suite
TL	Transmission Loss (dB)
TTS	Temporary Threshold Shift
UD	University of Delaware
WEAP	Wave Equation Analysis for Piles
WETS	Wave Energy Test Site
WEC	Wave Energy Converter
WHOI	Woods Hole Oceanographic Institution

ABSTRACT

Over the last two decades, there has been growing concern surrounding the increase in underwater anthropogenic sounds as expanding human populations interact with marine life and look for alternative energy production methods. That concern has led to a significant push worldwide to understand how propagated sound interacts with the surrounding marine environment. Marine hydrokinetic (MHK) devices are an alternative source of renewable energy available, which generate electricity from the motion of tidal and ocean currents, as well as ocean waves. Sounds produced by MHKs tend to overlap the frequency range common to both marine fauna communication and behavior. Preliminary measurements indicate that sound level values fall near the total sound decibel limitations presented by regulatory bodies. To date, the power optimization of MHK arrays has been prioritized over how its sound is produced, directed, and may impact the marine soundscape. There is a gap in knowledge regarding how marine fauna may respond to these sounds and what their physical and behavioral impact may be, and an absence in measured levels from in-situ MHK deployments. A model for predicting the propagation of sound from an array of MHK sources in a real environment is essential for understanding potential impacts on a surrounding system.

This work presents a fully three-dimensional solution to a set of coupled, linearized velocity-pressure equations in the time-domain as applied to underwater systems, and is an alternative sound propagation model to the Helmholtz and wave equation methods. The model is validated for a single source located within a series of increasingly complex two-dimensional and three-dimensional shallow water environments and compared against analytical solutions, examples from literature, and recorded sound pressure levels collected from Sequim Bay, WA. An uncertainty analysis for an array of MHK devices is presented to further understand how multiple turbine signals interact with one another in increasingly complex systems. This research presents a novel use of the velocity-pressure equations to analyze the variability associated with sound sources as sound propagates through a selected environment to inform the design and deployment of a MHK device or array of devices to minimize potential future impacts.

CHAPTER 1: INTRODUCTION

Every object has the potential to produce sound. That sound propagates away from an initial source and can be described through its frequencies and their amplitudes, as well as if the sound profile is continuous or a pulse. All sound waves continue to interact with the surrounding environment, generally dissipating energy as they expand through the environment and are attenuated by irreversible losses. However, total sound levels may increase in specific locations within the soundscape by combining with sound produced by other sources or through a sound wave interacting positively with its own reflections. Sound is typically thought of as being generated by moving objects, such as a running car engine, a vibratory compactor on a construction site, a rotating wind turbine, or vocal chords vibrating. Sound may also be created by stationary objects disrupting and interacting with fluid flowing around or within them. Due to the increased density as compared to air and near incompressibility of water, sounds generated underwater can travel for significantly greater distances than they would in air. Moreover, the unique relationship between temperature, salinity, and density in the oceans can create a focusing beam, the Deep Sound Channel (DSC), that allows sounds to travel even further.

Over the last two decades, there has been growing concern surrounding the increase in underwater anthropogenic sounds as the expanding human populous interact with marine life or looks for alternative ways to produce energy. That concern has led to a significant push worldwide to understand how propagated sound interacts with the surrounding marine environment. The United States Department of Energy (DOE) in particular has set aggressive goals for clean energy generation by 2030 with additional goals of having a net-zero carbon impact by 2050 [5, 14]. This second goal is mirrored by the International Energy

Agency in 2021 as well [6]. Technologies that harness energy from waves and currents in United States waters had a potential technical capacity of generating an average of 1560 TWhr/yr of electricity [74]. However, a study conducted in 2021 revealed that number to have increased to 2300 TWhr/yr of electricity with the continued research in alternative energy production, which is approximately 57% of the current electrical need produced by the United States [59]. These technologies are collectively referred to as marine hydrokinetic (MHK) devices and use the motion of the water to produce energy. The type of water motion leveraged differentiates current energy converters (CECs), which harness energy from river, tidal, and ocean currents, from wave energy converters (WECs), generating power from the various wave motions. In addition to generating electricity, these devices also produce noise from, as examples, the mechanical components, mooring lines, power takeoff, and their physical obstruction of the flow field. Dependent upon where these devices are deployed, they may enter a marine environment that is already noise-saturated from shipping, recreational activities, factories, or power-plants. MHK devices may be deployed individually or in arrays to minimize the spatial disturbance of a deployment location depending on the area selected. This allows for an abundance of options for clean energy generation that is customizable to a specific location to reduce a potential impact on an environment. Adding MHK devices to an array will increase the electricity generated and reduce its cost; however, the sound from each device will be compounded together increasing the array's sound contribution to the environment. Further, power performance hinges on the number and type of devices, size of the devices, location within an environment, and their orientation to the fluid motion. To date, the power optimization of MHK arrays has been prioritized over how its sound is produced, directed, and may impact the marine soundscape.

Environmental concerns over the potential impact that MHK devices, and really any additional anthropogenic sound sources, to the marine ecosystem are currently addressed through regulatory constraints. The Marine Mammal Protection Act (MMPA) in the USA

presently limits the total noise levels for disturbance and injury for MHKs specifically with regard to various species and types of sound disturbances [115]. Sounds produced by CECs and WECs tend to overlap both the frequency range common to marine mammal and fish communication and behavior and early measurements indicate they fall near the total sound decibel limitations presented by the MMPA [23]. Additionally, the MMPA provides a strict regulatory guideline that was created and imposed by the USA for not just any permitting required for the construction and operation of MHKs, but for the construction and operation of any project operating within the waterways of the USA. However, noise is prevalent in all countries around the world, which has led to many world governments using the MMPA as an example for their own set of guidelines or regulatory standards. There is a gap in our knowledge as to how marine fauna may respond to these sounds and what their physical and behavioral impact may be. Potential impacts would include communication, feeding, short- and long-term hearing damage, and pressure damage to swim bladders or soft tissue. Since MHK deployments will generate a new, continuous noise, rather than a periodic or intermittent sound, there is also uncertainty surrounding how these responses are affected over the months, years, and lifespan of a deployment.

To support the deployment and operation of MHK technologies, quantify sound levels emitted from these devices, and help reduce potential environmental impacts, an assessment of the type and level of noise produced is necessary. At this time, the amount of recorded sound data for CECs and WECs from known experimental and in-situ measurements and predictions from numerical results is very limited due to the lack of MHK installments, appropriate test facilities, and the complexity of the simulations, especially those with pressure data sets collected over periods of weeks or months. Data collected over longer periods of time are useful to quantify operational changes over the life cycle of a turbine as well as potential impacts to the marine life in an area. Each device produces a unique sound profile that may change to be louder or softer as the operational conditions vary with

time. How that sound spectra moves through a deployment site will affect the surrounding environment and depends on the sound generated from a singular device, or an array of devices, the location and configuration of the array, and all environmental properties of the area. Most deployment sites under consideration in the near term are in shallow water environments for ease of deployment and access for maintenance. However, shallow water environments already include a multitude of noise sources, such as shipping traffic, breaking waves, sediment/debris transport, and sounds contributed by marine life in a constrained space [15, 16, 17, 35, 36]. It should be noted that anthropogenic and natural sound sources are not only found in shallow water environments; however, the shape of these environments tend to heighten the interactions of the different sound sources to create an overall noisier environment than a deep ocean. The addition of new MHK sources adds to the total sound of the system and has the potential to push the total level over regulatory and environmental limits, which may adversely affect the surrounding marine fauna. Some areas are already operating at conditions over the set limitations for historical or other regulatory reasons. A further understanding in sound propagation and sound interaction from an array of turbines may lead to a change in design for already deployed system, decreasing the sound in those areas as well.

Numerical solutions provide a promising way to investigate this interplay between the environmental impacts of MHK deployments and optimizing the power generated. Modeling different MHK sources and array types may demonstrate designs that minimize the sound produced. This is completed by optimizing the layout of the sources so that the sound generated by each source in an array interacts with one another and results in an overall level that falls below ambient. This allows the overall noise produced by the array to be effectually 'silenced' and serve to fill the previously discussed gap in recorded data. Simulated data, especially when it is compared to any available recorded data to validate a model, is an effective tool to further understand the interaction of additional sound sources

in a marine environment. There is a long history of sound propagating algorithms for underwater acoustics that can be leveraged to resolve the sound environment in underwater systems. These algorithms may be used to connect the design of MHKs and subsequent sound generation with potential environmental affects[55]. However, the most common methods to predict the propagation of sound underwater are currently solved in the frequency domain with various approximations to the Helmholtz wave equation. The choice of which model to use is based upon approximations to the frequency range and whether the solution domain is allowed to have variations in depth and/or distance direction. They almost exclusively solve a single frequency at one location within a 1D or 2D domain [37]. The current field of underwater acoustics has continued to focus on high-frequency, short-range or low-frequency, long range applications. The conditions posed with MHK devices sit outside the strengths of the existing algorithms as the sounds from CECs and WECs are anticipated to fall in the low to mid frequency values, 50 - 1,500 Hz, have complex, time-varying sound profiles, and will often be deployed in locations where the 3D reflections may matter.

This work chooses to use a finite-difference, time-domain solution to the three-dimensional Cauchy's equations of motion, which are linearized into a coupled velocity-pressure system (ParAcousti) [8, 9]. This approach can model the simultaneous noise propagation from an array of sources with individual, time-varying sound signatures in domains that allow for the 3D variation of its physical properties. Complex domains may include fluid and solid regions, which would permit investigations of sound propagation through material interfaces. The combined discretization of both the fluid and solid domains enables varying properties in all spatial coordinates to be used, as measurements or simulation data becomes available. Sound-source profiles are evaluated as moment tensors, allowing combinations of monopole, dipole, and quadrupole forces [7, 61]. These characteristics make the velocity-pressure solution the most flexible, single-model for the prediction of sound propagation from marine hydrokinetic energy deployments. Simulated

sound pressure, as well as particle velocities, generated by ParAcousti may help to provide both a substitute for a lack of experimental MHK data in the field and an optimization tool for MHK array design. ParAcousti is meant to be a tool suited to model and help understand the interaction of sound as it propagates within, and interacts with, a fully 3D environment for complex, multi-directional sources that may overlap with frequencies relevant to marine fauna.

The primary goal of ParAcousti is that it is a tool that MHK designers, regulatory agencies, and marine biologists alike can use to understand the potential effect sound sources may have on an environment before a design is finalized and deployed. Within this document, a background on properties of sound, the general state of knowledge surrounding MHK modeling, effects of sound on marine fauna, and experimental data sets are presented in Chapter 2. Chapter 3 presents the theory behind ParAcousti and the derivation of the velocity-pressure equations, which are used to predict sound propagation in the marine environment. The development of ParAcousti is then followed, in Chapter 4, with a validation of the equations and additional comparisons against known analytic and standard underwater acoustic solutions. Chapter 5 presents a real-world validation of ParAcousti against a pulsed series of frequencies that were recorded in Sequim Bay, WA. Chapter 6 demonstrates how ParAcousti can be used to model source variability within an array of MHK devices across a range of deployment locations, and that this results in uncertainty about the sound pressure field. Operating conditions vary continuously for an environment resulting in uncertainty within the sound source parameters. ParAcousti allows for an assessment of that uncertainty in any array arrangement or environment further allowing designers, regulators, and biologists to determine how sound will propagate and interact with a particular environment.

This work contributes to the fields of underwater acoustics, numerical models, and engineering by:

- Validating and applying a novel 3D model to a shallow underwater sound system, which was developed for seismic modeling. This research demonstrates that ParAcousti could in fact be leveraged for and applied to underwater systems. Additionally, this research demonstrates that ParAcousti has the capability to model complex sound systems in time and provide a user with both pressure and particle velocity data.
- Applying ParAcousti to model a real-world environment and comparing the 3D and 2D model data to the analyzed experimental data. This research uses a unique, fully 3D model to determine the differences between 3D and 2D models to understand the impact on simulated data and which type more effectively captures the real-world effects present in experimental data. This is especially necessary for shallow water environments where variation within the bathymetry contributes heavily to how sound interacts and propagates in an environment. This research further catalogues sound reflections, travel times, and interactions between the sound source and boundary conditions that are not present in standard models.
- Further the understanding of how multiple turbine signals interact with one another in a multitude of environments that replicate increasingly complex systems. This culminates in a model with real-world bathymetry and illustrates how multiple signals interact, build, and destroy each other. The research demonstrates a novel use of delta functions within ParAcousti to conduct an uncertainty analysis to analyze the variability associated with the sound sources as the sound propagates through the selected environment. This data provides information as to array design and allows for a range of operational conditions to be understood and brought into the design of a CEC array before deployment, minimizing any environmental impacts.

ParAcousti is an open-source, finite-difference model developed by Sandia National Laboratories (SNL) that is an open-source model. This work has allowed ParAcousti to

become an accepted acoustic model within the modeling community and provides data that continues to further the understanding of sound propagation in an underwater environment. ParAcousti was released to the public in the fall of 2018 under a GPL license SCR#1643.1 through SNL on Git-Hub. Documentation, tutorials, and access to the source-code can be found at: <https://snl-waterpower.github.io/ParAcousti/>.

CHAPTER 2: BACKGROUND

ParAcousti provides a connection between sound propagation modeling and the biologic assessment of the interaction between marine life and anthropogenic sounds generated in an underwater environment. The background surrounding these two subjects may be divided into three distinct topics: the physics of sound, characteristics of marine renewable energy, and the perception of sound. The physics of sound describes the physical understanding and how we model and represent an acoustic source as well as current analytical solutions, numerical solutions, and geophysics. Any simulated or recorded sound profile is generated by a sound source. This body of research is concerned with sound either directly generated and recorded by a MHK source or created to mimic a MHK source or array. Marine renewable energies vary in location, type, and size as well as the type of experimental and numerical data that is available. Experimental data is necessary for any model validation or direct comparison, but is unique to a particular environment and source layout. MHKs in particular vary greatly in type and orientation in an environment. Additionally, MHKs occupy a frequency range which overlaps significantly with the sound produced by many species of marine fauna and may have behavioral implications aside from potential physical impacts. A biologic assessment of the potential impacts of MHK devices requires an understanding of the third topic, the perception of sound. This involves how marine fauna interact with and are potentially impacted by additional sound sources within the underwater environment and how fauna perceive and react to sound behaviorally and physically. Perception of sound does not strictly affect marine mammals. A clear understanding of the sound produced by MHK devices and the potential environmental impact directly affects the construction and deployment of the devices as well as the actualization of regulatory standards. Regulations within the United States and Internationally directly impact the use of MHK devices. Research on these devices greatly affects how these potential alternative energies are viewed

by the public, researchers, and administrators, as well as how they are designed and established in a marine environment. A general background about each of these three topics is provided in this chapter.

Physics of Sound

Sound is created from vibrations, which travel through a fluid medium, until those vibrations can be heard or perceived. Typically air is the only medium considered when people think of sound; however, vibrations may occur and travel through any medium containing matter such as water and soil. Those vibrations are created when energy is imparted to a physical system where particles at equilibrium now have a periodic resonance that decays with time as the system returns to equilibrium. Waves are used to define, model, and understand sound as it travels through a medium, but are not necessarily limited to a perfect oscillatory structure. Rectangular pulses, spikes, and noise are all valid forms of sound waves. To further incorporate these forms of waves that often are part of acoustics research, waves may be described as the movement of a disturbance, or piece of information, from one point to another in a medium which takes place at a finite and measurable speed. As the disturbance moves with reference to the medium, the shape of the sound wave is arbitrary. Sound waves and geophysical waves, also known as compressional elastic waves and P waves, move parallel to the direction of propagation and are so labeled longitudinal waves [24].

Sound waves generated in underwater environments typically move in sinusoidal pattern which defines the waves movement from positive to negative pressures as the wave moves through a particular environment. Two sinusoidal waves are shown below in Figure 2.1 and are defined by $y = \cos t$ and $y = \sin t$. This example of the wave function starts with the maximum value at $t = 0$ for the $\cos$ function while the $\sin$ function is shifted and has a value of $y = 0$ at $t = 0$. The location of the maximum value of the wave may be shifted

depending on when the wave form was emitted in time. Sound waves are described with respect to frequency, amplitude, and phase. Frequency is the number of times per second that the wave repeats itself or it's defined function. Amplitude is the maximum value of y for the defined function and is often thought of as the relative strength of a sound wave. Finally, phase is the amount that the waveform has been shifted along the x plane from it's relative starting point, ranging in values from 0 to $2/\pi$. In the example Figure 2.1, the amplitude is $1m$, the phase is 0, and the frequency in an underwater system where the sound speed is equal to $1500m/s$ is $238.1Hz$. Wavelength is the measured length of one waveform before it repeats. Frequency, wavelength, and sound speed are related through $\omega = c/\lambda$, where ω is the frequency at the source, c is the sound speed of the medium that the sound is propagating through, and λ is the wavelength.

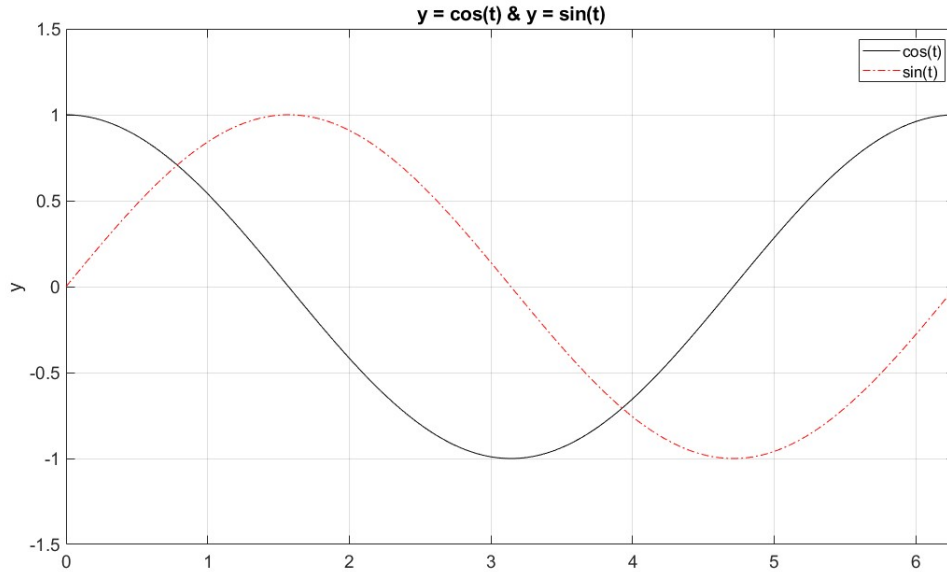


Figure 2.1: This figure shows a basic cosine wave form, which is the basis for most underwater sound wave models. The functions shown are $y = \cos x$ and $y = \sin x$.

Sound waves propagate outward through and interact with an environment. Sound is traditionally thought of as moving through air, as that is the medium in which humans

interact the most. With respect to air, sound speed is related to density and compressibility. This work revolves around sound traveling in underwater environments, where water is nearly incompressible. This changes the relationship, such that sound speed is additionally related to the salinity, static pressure, and temperature of the water. Underwater systems are complex and the sound wave will interact with the water surface and any structure within the area of interest. This would include the sea floor and any other sound waves produced by other sound sources. As indicated earlier, all objects have the ability to produce sound. This is accomplished either through directly emitting noise or by interacting with the environmental around it. For example, water moving over a sediment layer has a noise associated with that movement, as do waves hitting the shoreline, or a turbine spinning underwater to generate electricity. Any objects present within a system or changes in medium may be represented by changes in density that the sound wave interacts with. Any change in density affects the sound speed that the wave may travel and additionally the wave length. All interactions, including for a continuous propagation in a consistent medium result in a reduction of energy as the sound moves away from the source which eventually results in the sound wave dissipating entirely. When the sound wave interacts with a large change in medium, the wave will either reflect off due to the change in density or refract and continue propagating through the different medium. Again, whenever a sound wave interacts, energy is lost to the surrounding system. Note that loss indicates irrecoverable sound, usually through attenuation in the system. The sound source reduces in sound level as it propagates away from the source.

Propagated sound is expressed as a pressure in units of a pascal, Pa, or $1 \frac{N}{m^2}$. For this work, the root mean squared (RMS) pressure is used to calculate averages of pressure-values in time as necessary. The RMS pressure, P_{rms} is calculated by,

$$P_{rms}(x, y) = \sqrt{mean_t(P(x, y, t)^2)} \quad (2.1)$$

where $P(x, y, t)$ is the pressure value at any given point in a domain in time. Sound pressure level, (SPL), and transmission loss, (TL), are the typical values of interest with respect to pressure in a solution. Both equations are in units of decibels, (dB), which are referenced to a standard pressure value. Equations for SPL and TL are presented in equations 2.2 and 2.3.

$$SPL = 20 \log_{10} \frac{P_{rms}}{1e-6} \quad (2.2)$$

$$TL = 20 \log_{10} \frac{P_{rms}}{P_{rms}(relm)} \quad (2.3)$$

SPL uses a standard pressure value of $1e-6Pa$ for underwater acoustics while TL uses the RMS pressure 1 m away from the source as a reference, or $relm$. SPL gives a sense of the magnitude of sound while TL is non-dimensionalized with respect to its source strength. TL may be subtracted from the source SPL value to determine the SPL at a given location and is a way of visualizing energy loss. SPLs are always referenced to $1e-6Pa$ or $1\mu Pa$. The value of which is with respect to water as opposed to a reference value of $20\mu Pa$ for air. Pressure levels decay at a rate of $\frac{1}{r}$, where r is the radius of a standard sphere. The sphere may be thought of as the general environment that the sound is propagating outward in with the radius being a general measurement of distance or range.

Common Sound Propagation Solution Methods

Understanding how sound waves interact and propagate through various underwater environments is key to predicting how sound may potentially impact an area as well as how our world physically works. Various sound propagation models have been used throughout history to determine how sound waves move through an environment and how the associated energy of the wave form dissipates [37]. In acoustics, there are two main equations which are used to describe sound propagation through different mediums. These equations are the

wave equation and the Helmholtz equation, both of which were derived to describe acoustics propagating through any kind of medium. The equations discussed below were developed specifically for underwater sound propagation as opposed to in air.

The use of the wave equation has a long history in the numerical solutions of sound. This is due to an accessibility of simplified solutions which are relatively easy to calculate. However, while the wave equation does provide a solution for the full propagation of waves, it is non-trivial to solve for a complex model domain and a time-history for a non-continuous source. This simplification comes at the cost of flexibility across a range of applications [37]. Models derived from the Helmholtz wave equation have been used to predict underwater sound propagation in a breadth of applications including modeling earthquake p-waves, sonar models, whale songs, and single source explosions. The various Helmholtz-derived models are often solved in a way that computes 2D solutions in a plane in depth and range, where 3D solutions are then resolved as a collection of azimuthal slices radiating from a source.

Various underwater sound propagation models have been used throughout history, but Helmholtz derived equations remain the most applied to date [55]. However, approximations required to solve the Helmholtz equations self-limit many applications. Solution approaches disallow out-of-plane sound reflections and have the potential to create areas where SPLs overlap or shadow zones which do not occur in complex, shallow environments. MHK devices will be deployed in domains where energy generation may be maximized. Potential deployment locations often overlap with those type of environments restrictive to Helmholtz models. Few examples of MHK modeling exist; however, research has been completed in comparative fields with respect to potential environmental impacts. A normal modes model called KRAKEN demonstrated a methodology to investigate the noise impact from MHKs on marine species [92]. The range of audibility, behavioral disturbance, and injury were obtained through dolphin and harbor porpoise audiographs with disturbances extending out to 4 km [83]. Pile driving has proved to be a fairly extensive area of research, with Rossington et al.

using a parabolic equation model to explain an increase in fish travel time when subjected to sound recorded from a single pile driving event with the sound level ranging from 140 to 249 dB re 1 μPa , ambient and peak noise respectively [101]. These modeling approaches will be discussed further in this document.

The Wave Equation The wave equation is considered the foundation for most solutions for underwater acoustic propagation modeling. The wave equation provides simplified solutions that are relatively easy to calculate and may be applied to model the full propagation of waves. However, the solution of the equation becomes non-trivial to solve for a complex model domain in a complete 3D environment. The standard 3D wave equation is derived for an ideal fluid through hydrodynamics and the adiabatic relationship between pressure and density. Specifically, the equation for conservation of mass, Euler's form of the momentum equation, and the adiabatic equation of state are combined with the idea that sound speed (c) squared is equal to the change in pressure with respect to the change in density, where the partial derivatives are taken at a constant entropy, S [55]. The equations are listed below as (2.4), (2.5), and (2.6).

$$\frac{\delta \rho}{\delta t} = -\nabla \cdot \rho \mathbf{v} \quad (2.4)$$

$$\frac{\delta \mathbf{v}}{\delta t} + (\mathbf{v} \cdot \nabla) \mathbf{v} = -\frac{1}{\rho} \nabla p(\rho) \quad (2.5)$$

$$p = p_0 + \rho' \left[\frac{\delta p}{\delta \rho} \right]_S + \frac{1}{2} (\rho')^2 \left[\frac{\delta^2 p}{\delta \rho^2} \right]_S + \dots \quad (2.6)$$

where ρ is density, t is time, $\mathbf{v}$ is the particle velocity vector, p is pressure, and values with either a $_0$ or $'$ represent an ambient or perturbative quantity, respectively. If perturbations are assumed to be small and a linear approximation is made, which is conducted for the acoustic

wave equation, then the first terms of equations 2.4, 2.5, and 2.6 are retained. The ambient or background pressure is assumed to be zero. The speed of sound squared is substituted in for the change in pressure with respect to the change in density. In addition, the background properties and sound speed are assumed to be independent of time as the time scale of the ocean is considered to be vastly larger than that of the induced perturbations from a sound wave. Finally, the equations are thought of as for a singular moment in time, where density is constant for a particular domain and the prime ($'$) is dropped from the pressure variables, resulting in equation 2.7, which is written specifically for pressure calculations, but may be reformulated to solve for particle velocity [55]

$$(\nabla^2)p - \frac{1}{c^2} \frac{\delta^2 p}{\delta t^2} = 0 \quad (2.7)$$

As the wave equation is presented, it assumes that all values of density, sound speed, and pressure are constant for a particular model domain and remain constant in time as a pressure perturbation is introduced as a sound source and allowed to move through that model domain. To allow for internal boundary conditions and to handle any changes in environmental values as indicative of a real environment, where density, sound speed, and pressure values change with location and depth, either the Finite Difference Method (FDM) or the Finite Element Method (FEM) may be applied to solve the wave equation. The FDM directly discretizes in space and time whereas the FEM discretizes the domain and time into small blocks which each have a selected set of boundary conditions or degrees of freedom which allows for a linear system of equations to be formed and solved. Note that as a sound source is modeled as a wave form, either solution method will require that the system be discretized into segments significantly smaller in length than that of the source wave length to accurately describe the wave form as it propagates outward from a source [55]. An example of a FEM solution was one proposed in 2018 by Gao out of Los Alamos National Laboratory

for a time-domain solution. The solution overlaid multiple grid domains over top each other in order to interpolate physical parameters onto a courser grid to solve and solutions were demonstrated for contrived 2D and 3D problems [41]. Additionally, a fully 3D model was proposed in 2022 by Petris where the wave equation was solved using a 2nd order accurate FDM and applied to a 20 Hz monopole, dipole, and quadropole sources. The model used what is termed a hard source, where a pressure value is effectively manually set at the start of the calculations to create an explicit solution. Results were close to that of the recorded data, only varying by approximately 1 dB [85].

The Helmholtz Equations The Helmholtz equation is a frequency-based form of the wave equation derived by introducing a frequency-time Fourier transform pair. Helmholtz-derived models were developed to compute a 2D solution plane in depth and range (distance in the x-axis). 3D solutions have traditionally been resolved from a collection of azimuthal slices instead of a full solution. Models derived from the Helmholtz wave equations are generally grouped into three different variants; Ray Theory, Normal Modes, and Parabolic Equations [55]. Each has been used to predict underwater sound propagation for a number of applications and are generally organized by how they address range dependence, sound frequency levels, and domain depth [37]. The Helmholtz equation written in the frequency domain is shown below as equation 2.8, where k is the medium wave number at a radius, $\mathbf{r}$, and at a radial frequency, ω . $\Psi(\mathbf{r}, \omega)$ is defined as the displacement potential with respect to particle velocity.

$$[\nabla^2 + k^2(\mathbf{r})]\Psi_{\mathbf{r}, \omega} = f(\mathbf{r}, \omega)k(\mathbf{r}) = \frac{\omega}{c(\mathbf{r})} \quad (2.8)$$

The function described as $f(\mathbf{r}, \omega)$ represents the environmental body forces located within the domain of interest. Forces such as gravity and magnetism are found to have no significant impact on acoustic propagation other than the effect of gravity on sound

speed variation in depth over very long distances ($x > 10,000km$). Acoustic sources are the main remaining contributor to body forces as they are required to generate sound in an environment. Background perturbations are already assumed to be zero, so sound sources are assumed to be localized and identifiable, which results in $f(\mathbf{r}, \omega)$ going to zero as well. Pressure and the displacement potential may be related through Hooke's Law for an ideal, linearly elastic fluid resulting in equation 2.9.

$$p = -\rho \left(\frac{\delta^2 \Psi}{\delta t^2} \right) \quad (2.9)$$

The Helmholtz equation is a 3D elliptic, partial-differential equation in which the solution process is primarily determined by the medium properties or boundary conditions of a problem. Individual models are commonly split between how they address, 1) range dependence (1/2/3D varying properties and topology), 2) low- and high-frequency sounds, and 3) shallow- and deep-water domains [37]. Although these equations provide a sufficient solution for many problems, they are self-limiting due to the approximations necessary to solve. Additionally, these approaches limit sound from being reflected out-of-plane and have the potential to smear or blend SPLs and create shadow or caustic zones in complex tidal and river domains where renewable energy technologies will initially be deployed.

Ray methods separate the sound source into a number of singular rays emitting out and refracting through an infinite number of layers within an environment as it moves through the model domain. The solution method leverages Snell's Law, $k_1 \cos \theta_1 = k_2 \cos \theta_2$, where k is the particular layer and θ is the angle of refraction. The Ray method is effective for high frequencies. However, as the sound source is approximated in this method, the use can lead to a reduction in accuracy as the ray trajectories are very sensitive to the environment and the numerical discretization of the problem. Errors pertaining to this are accentuated over long distances [55].

The second accepted solution to the Helmholtz equation is a method called Normal Modes. Normal modes uses a depth dependent equation to separate the sound source into it's primary modes of vibration. Each of those modes is modeled separately and weighted in accordance to the source depth. The energy contribution from each mode is summed together to produce a complete acoustic field. This method is for 1D systems and handles both high and low frequency sound sources, and is primarily used for shallow water systems. It was widely used by Pekeris as a standard solution to a single source sound profile over a flat bottom channel [55, 84]. Patricio et al. used normal modes, within a program called KRAKEN [92], to demonstrate a methodology for investigating the impact of noise from WECs on marine species, and used dolphin and harbor porpoise audiographs to determine zones of audibility, behavioral disturbance, and injury. Zones of behavioral disturbance were shown to extend 4 km [83]. Additionally, Normal modes were applied using a single receiver in a shallow water environment off the coast of New England in 2018 to determine the type of modes demonstrated in a 20 - 440 Hz source [25].

Parabolic Equations, or the PE method, comprises the third standard solution for the Helmholtz equations. This method was introduced in the 1970s by Hardin and Tappert to devise a solution based on fast Fourier transforms. The PE method may be solved for 2D or 3D systems. The PE method was derived for a constant density medium in cylindrical coordinates and is appropriate for low angle propagation angles of 10° to 15° off of the horizontal. The equations may be applied to higher value propagation angles with a reduction in accuracy. The model is additionally appropriate only for frequency values less than 1KHz [55]. Further solution has have been proposed to increase the valid angle for a 3D system. In 2012, a 3D solution to the PE method was proposed by Lin at Woods Hole Oceanographic Institution which further increases the solution angle to 32.5° by retaining cross-multiplier operator terms which were previously neglected [65]. A similar model produced by Lin in 2019 was successfully used to simulate Block Island Wind Farm off the coast of Road Island

over a range of frequencies from 750 - 1250 Hz, but was applied as a 2D model solved over a range of degrees to capture a 3D system and was not a full 3D solution [66]. A wide angle solution was proposed and applied in 2012 to a rough surface, high frequency (10 - 15 kHz) underwater environment with a singular source. The method correctly predicted arrival times for the source, but struggled with matching energy readings and was consistently low by 2 - 10 dB [103]. One of the earlier examples by Sturm in 2005, which presented a fully 3D solution for a narrow angle slope in an underwater system with frequencies of 25 and 40 Hz [109]. Rossington et al. coupled a parabolic equation model with a fish movement model to investigate cod feeding, noting a 7-day increase in travel time to local feeding grounds when modeled fish were subjected to sound recorded from a single pile driving event with the sound level ranging from 140 to 249 dB re 1 μPa corresponding to ambient and peak noise from pile driving, respectively [101].

Typically for all three of the solutions, if a 3D model domain is required, a 2D model will be created for every degree of rotation throughout a 3D plane to make a pseudo representation of a fully 3D environment. Few full, stable 3D solutions exist and fewer are applied due to the complexity of the solution as well as computational costs.

Characteristics of Marine Renewable Energy

MHK devices use the motion of water to produce energy. These devices include both CECs, which harness energy from river, tidal, and ocean currents, and WECs. In addition to generating electricity, these devices also produce noise from, as examples, the mechanical components, mooring, power takeoff, and their obstruction of the flow field. Dependent upon where these devices are deployed, they may enter an already noise-saturated marine environment from shipping, recreational activities, factories, or power-plants. Additionally, as more devices are added in an array to lower the levelized cost of electricity, the total sound will be compounded. Regulatory constraints and environmental concerns over the

sound produced by these devices may be a hurdle to their deployment and operation. The Marine Mammal Protection Act in the USA presently limits total noise levels for disturbance and injury below 120 dB and 180 dB re 1 μ Pa, respectively [115]. Due to these concerns, the particular noise profiles produced by CECs and WECs are of great interest in order to discern their effects on the marine life present on location where the devices are to be deployed, or are already located.

In order to support the deployment and operation of MHK technologies, while also ensuring regulatory requirements are met, an assessment of the type and level of noise produced is necessary. This review details the known experimental and in-situ measurements and numerical results of the noise generated by WECs and CECs. As is evidenced, very few data presently exist and in lieu of new measurement campaigns, surrogate technologies where acoustic work has progressed are noted. A large amount of the existing experimental data documented in this paper fails to adequately characterize the surrounding environmental conditions to differentiate individual contributors from each device, i.e. the portion of noise associated with the power take-off, mooring cables, etc., which are needed to validate any modeling techniques used to predict the noise generated from these devices and how the sound propagates through the environment.

An insufficient amount of experimental data for WEC and CEC noise sources has been recorded from projects in the United Kingdom, United States, Portugal, Denmark, and New Zealand. Additionally, much of this data is either unavailable for use outside of the particular project or may be contaminated with environmental and other anthropogenic noises. Several reports on the state of available experimental data have been published since 2005 when Marine Energy Turbines deployed one of the first SeaFlow tidal energy conversion systems off the coast of the British Isles, including a report by Robinson and Lepper [100]. This report provides one of the most comprehensive reviews and was leveraged for the OES-IS Annex IV report [30], a state of the science report for MHK devices around the world, published in

2016 [13, 29, 30, 97, 100, 111]. One of the first WEC testing centers was established off the coast of Azores Island at the Pico Power Plant in Portugal in 2010. Initially, ambient noise measurements were collected followed by the installation and monitoring of the WaveRoller WEC in 2013 [31, 106]. The system was tested in 2014 revealing that values measured at 220 m away varied from 115 dB to 121 dB re $1 \mu\text{Pa}$ [31]. The US Navy and the University of Washington tested one of the largest US WEC projects, the Azura, at the Wave Energy Test Site (WETS) off the coast of Hawaii. The Azura WEC was a 1:2 scale point absorber designed by Northwest Energy Innovations (NWEI) that began operating in May 2015. Initial data shows that Azura is operating within a frequency range of 150 Hz to 1.5 kHz with a max recording of 87 dB re $1 \mu\text{Pa}^2/\text{Hz}$ [89].

The European Marine Energy Centre in the UK has one of the largest databases of MHK projects and provides a tidal test site off the coast of Scotland. Namely, projects have been centered around collecting ambient sound data as well as additional noise inputs from construction and ship traffic [48]. OpenHydro was monitoring several CEC projects at that location as well beginning in 2008 [48], while at the same time, Scotrenewables Tidal Power Ltd. introduced a 250 kW tidal turbine and monitored the construction noise. Construction noise was recorded and an effective radiated noise level of 162 dB re $1 \mu\text{Pa}$ at 1 m, including noise from boat engines, was derived using a spreading law [19]. In 2012, Ocean Renewables Power Company (ORPC) installed a CEC unit off the coast of Cobscook Bay in Maine, following a successful prototype test for a cross-flow turbine mounted to a barge as a demonstrator project in 2012 and ambient noise recordings [80]. When the turbines were rotating as part of the TidGen Power System, increases in sound levels were noticeable for frequencies at approximately 105 Hz and 210 Hz, and 2.8 kHz where harmonics occurred, but SPL did not exceed 120 dB re $1 \mu\text{Pa}^2/\text{Hz}$ for any frequency. Energy levels were primarily recorded between 50 and 200 Hz [80]. Other projects exist in Admiralty Inlet in Puget Sound; New York; Iguigig, Alaska; Sandia National Laboratories, New Mexico; and Omaha

Bay, New Zealand [4, 19, 28, 39, 68, 87, 88]. Additionally, construction sources, ships, and wind turbines may all be used as supplemental experimental data when MHK data is lacking [20, 27, 35, 36, 43, 46, 51, 52, 62, 67, 76, 77, 112, 114].

Several reports on the state of available experimental data have been published since 2005 when Marine Energy Turbines deployed one of the first SeaFlow tidal energy conversion systems off the coast of the British Isles. Robinson and Lepper provided the most comprehensive review in 2013, which was directly used in the Annex IV, a state of the science report for MHK devices around the world, published in 2016 [30, 100]. A report published in 2009 by the Oregon Wave Energy Trust specifies a set of guidelines for the appropriate methods for collecting and recording acoustic data [13]. Additionally, QinetiQ, the European Commission, and Ocean Energy Systems also prepared summary reports for the environmental assessment or impacts of MHK devices, including acoustic propagation and data analysis [29, 97, 111]. Projects are separated into two categories, wave energy converters and current energy converters. Most documents refer to CECs as Tidal Energy Converters because tidal sites are the predominant testing and deployment locations to date. It is assumed that the devices discussed are full-scale, unless otherwise denoted.

Noise from Wave Energy Converters & Current Energy Converters

The Billia-Croo wave test site off the coast of Scotland has been used to collect ambient noise data for a range of conditions in order to develop an acoustic baseline for the area. Subsequently, a methodology for the collection of operational data for any WECs located at the test site was developed and implemented for the Pelamis P2 system. The Pelamis P2 system is composed of a distributed series of noise sources that extend outward in a line which floats on the surface to produce energy. Operational measurements included four seabed mounted recorder units for a period of 30 hours and for separate broadband drift trials of a measurement system located on a boat with a maximum measurement distance of

2.4 km. Data shows the 10 minute, one-third octave band level at the midpoint of the device to be 120 dB re 1 $\mu Pa^2/Hz$ at 1 m for the band 10 Hz to 2 kHz and the maximum observed average level for the 1 kHz band to be 181 dB re $\mu Pa^2/Hz$ at 1 m for low and medium sea states, respectively [63, 64]. A second device, the Oyster 801 developed by Aquamarine Power, Ltd., was installed in the testing site in 2012. The drilling noise for pile installation was measured by Kongsberg Maritime Ltd as decreasing from 120dB to 100 dB re 1 μPa over a range of 400 m to 5 km. Data shows a SPL of 140 dB re 1 μPa at a location of 200 m from the source [2]. Operational acoustic data for the Oyster is not currently available. At Falmouth Bay in Cornwall, Exeter University conducted a trial of a point absorber WEC in 2013 developed by FaBTest, collecting the construction and operational noise at a range of 200 m from the device by a data recorder and logger (AMAR Generation 2). Data showed an effective radiated noise level of 154.4 dB at 176 Hz at 1 m while an acoustic reading from the WEC during operation was undetectable [3].

In Denmark, Aarhus University collected ambient and operational data in 2013 for the Wavestar A/S system off the Danish North Sea coast. Received levels were measured at a range of 10 to 20 m from the device using an autonomous recorder and data logger. A median SPL of 106-109 dB re 1 μPa , 1-2 dB above background noise, in the range of 125-250 Hz, was recorded during operation with 121-125 dB re 1 μPa at 250 Hz during shutdown and startup [113]. Uppsala University in Sweden measured operational data for two point-absorbing WECs called the L12 Lykesil and WESA projects, respectively, located at the Lykesil Testing Site. The two systems were measured using autonomous submersible data loggers in various sea states from April to the end of May in 2011 at a depth of 24 m from 20-40 m in distance from the sources. Most of the data was corrupted due to overload distortion; however, max and average SPL values at 20 m were 133 dB re 1 μPa and 129 dB re 1 μPa , respectively. The report states that SPL values were corrected to a range of 1 m in the band of 20 to 1000 Hz, but values were not specified [44]. The Wave Energy

Test Center in Portugal was one of the first to have a testing site at the Pico Wave Plant off the Coast of Azores Island and was used to collect data the Wave Energy Oscillating Water Column device. Ambient data was collected in 2010 off the coast of Peniche, Portugal as part of the Simple Underwater Renewable Generation of Electricity (SURGE) project in conjunction with the Waveroller WEC [106], which was installed and tested in September 2013 [31]. Broadband SPLs varied between 86 and 119 dB re 1 μPa . The system was tested again in 2014. Hydrophones were used to measure acoustic data at distances from 165-1200 m from the Waveroller at frequencies between 50 Hz and 20 kHz. Values measured at 220 m varied from 115 dB to 121 dB re 1 μPa decreasing as the distance from the source increased [31].

In the United States, Columbia Power Technologies (CPT) tested its SeaRay 1/7th scale WEC in West Point, Puget Sound, WA in conjunction with University of Washington Northwest National Marine Renewable Energy Center (NNMREC). Ambient levels were measured in November, 2009 and found to be an average of approximately 117 dB re 1 μPa with a peak value at 135 dB re 1 μPa at a frequency band of 20 Hz to 30 kHz; this peak included ship traffic in the area [16]. The SeaRay was monitored for 14 months from March 2011 to April 2012 using drifting hydrophones (APL-UW SWIFT) at depths of 5 and 15 m drifting to a maximum distance of 1.5 km and a single autonomous device drifting at 1 m near the source. SPL received levels for the SeaRay were 126 dB re 1 μPa without ship traffic present and levels were not distinguishable with ship traffic present [18, 28].

Dr. Brian Polagye, from the University of Washington, is currently working on a project off the coast of Hawaii at the US Navy WETS. The Azura WEC is a 1:2 scale point absorber designed by NWEI that has been operating since May 2015. A drifting instrumentation system using the Surface Wave Instrumentation Float with Tracking (SWIFT) platform and OceanSonics icListen HF has additionally been monitoring the Azura during this period. Initial data shows that Azura is operating within a frequency range of 150 Hz to 1.5 kHz

with a max reading of 87 dB re 1 $\mu Pa^2/Hz$ [89].

A large amount of the available data for CEC noise measurements comes from the European Marine Energy Centre (EMEC) Tidal Test Site off the coast of Scotland. Two studies published by the Scottish Association for Marine Science (SAMS) in 2010 detail the ambient noise for the Fall of Warness Tidal Energy Test Site for both ebb and flood conditions, as well as having captured the sound produced by a jack-up barge and cable laying operation. No turbines were present at this time and mean ambient levels were recorded as 132 to 91 dB re 1 $\mu Pa^2/Hz$ for ebb tide and 132 to 97 dB re 1 $\mu Pa^2/Hz$ for flood tide for frequency values of 25 Hz and 46 kHz respectively. Recorded values for the frequency range between 25 Hz and 46 kHz scale between 132 and 91 dB re 1 $\mu Pa^2/Hz$ or 132 and 97 dB re 1 $\mu Pa^2/Hz$ for ebb and flood tide, respectively. Also present were strong contributions from ship traffic [118, 119, 121]. EMEC conducted further monitoring in September 2011 and March 2012 to clarify ambient noise levels in the area using three separate drifting acoustic recorders (hydrophone) surveys. During the two monitoring periods, the report states that turbine noise data is included, operating at the main frequencies of 300 and 500 Hz, but the type or location of the turbine is not clarified [49].

OpenHydro, in coordination with EMEC, placed a single, non-operating turbine 6 m in the same area in 2008. Ambient noise levels were pulled from previous reports and drifting autonomous data recorders were used to measure the operational noise. Data about the turbine is limited; however, broadband SPL received levels ranged from 116-127 dB re 1 μPa and effective radiated noise levels were 125-148 dB re 1 μPa at 1 m. Readings were below ambient SPL at ranges greater than 200 m [120]. Additionally, a 250 kW tidal turbine was installed at the same test site by Scotrenewables Tidal Power Ltd. Construction noise was recorded and an effective radiated noise level of 162 dB re 1 μPa at 1 m, including noise from boat engines, was derived using a spreading law [19].

Marine Current Turbine's SeaGen tidal stream energy device is located at Strangford

Lough, Northern Ireland, and consists of two 16 m open-bladed rotors attached to a pile in the seabed. It has an average water depth of 26 m. Construction noise was measured at distances of 28-2,130 m resulting in one second RMS SPLs varying from 105 to 139 dB re 1 μPa . An effective source level was calculated to be 162 dB re 1 μPa referenced to 1 m for the construction noise [75]. The ambient noise levels recorded show a large amount of interference due to turbulence in the system. Operational recordings were taken later from a boat-based hydrophone over a range of 150-2,937 m from the source. A broadband received level of 141 dB re 1 μPa (SPL) at a range of 311 m and a broadband effective radiated noise level of 174 dB re 1 μPa referred to 1 m were measured. The data is not publicly available [100].

As public data is lacking for a full-scale turbine at Strangford Lough, researchers from the Marine Research Group in coordination with Queens University Belfast, Northern Ireland, measured operational acoustics for the SCHOTTEL Instream Turbine as part of the MaRINET testing campaign. The project is based in Portaferry, North Ireland at the very end of Strangford Lough, and testing was completed in 2014. A M24 Hydrophone was mounted to a buoy system and data sets were taken from 9 m to 450 m from the turbine for three modes: power generation, freewheeling, and application of brakes. Ambient background noise was recorded at times when the turbine was not running in the same area for different sea states and ranged from 62 to 72 dB re $\mu Pa^2/Hz$ for a frequency range of 200-2,000 Hz. The maximum broadband source level for the one-third octave spectral levels calculated for the turbine after correcting for any drifting occurring during data collection was 120 dB re $\mu Pa^2/Hz$ at 1 m around 300 Hz and 100 dB re $\mu Pa^2/Hz$ at 1 m at 10 kHz [102].

A study was conducted in 2005 to measure the operating noise of the Marine Current Turbines tidal current generator near Lynmouth in the Bristol Channel. A boat-measured system was used to collect data at a range of 100 m to 1 km over a period of four hours on

March 9th, 2005. Ambient noise was collected at times when the turbine was not running; however, the amount of data recorded for ambient noise does not characterize the variation seen when the turbine is being operated. The effective source level was back calculated to a value of 166 dB re 1 μPa reference to 1 m [97].

Akvaplan-niva AS monitored a 300 kW Hammerfest Strom tidal turbine in 2009 located at Kvalsund, Norway. Ambient noise was not measured and operational noise was collected via a boat assembly. The one-third octave band of received SPL near the turbine were recorded as 130-150 dB re 1 μPa [1]. Very little other information is available on this project. The Wave Energy Test Centre carried out a number of tests on a turbine system in May of 2010 for one of the first monitoring programs at the Pico Wave Plant. The data shows distinct harmonic acoustic components associated with the turbine's rotational speed and impulsive noise. During the testing process, the harmonics were analyzed for various rotational speeds. Received SPL values did not exceed 126 dB re 1 μPa at 10 m in front of the turbine [106].

ORPC performed a prototype test for a cross-flow turbine mounted to a barge as a demonstrator project in 2012. Noise was measured by a buoy-based hydrophone at an operational range of 10m. Results show a received SPL of less than 100 dB re 1 $\mu Pa^2/Hz$ [28]. A larger unit was installed in 26 m of water in Cobscook Bay, Maine, USA in 2012 called the TidGen project. Ambient and operational data for the system in freewheel and generating modes were collected for Cobscook Bay and ambient noise was also collected for the Western Passage. For Cobscook Bay, ambient readings had an average of 94 dB re μ^2 for a 1/3 octave bandwidth with a range of 0 to 16 kHz. There was a spike in readings up to 110 dB re μ^2 at the 32 Hz frequency bandwidth. Ambient noise levels for the Western Passage measured at an average of 90 dB re μ^2 for a range of 1/3 octave bandwidths from 0 to 16 kHz. Noise levels were monitored using ORPC's Drifting Noise Measurement System (DNMS) which varied in range from 20 to 300 m from the TidGen unit and data was collected

over a period of three days in April of 2013. When the turbine was rotating, increases in sound levels were visible for frequencies at approximately 105 Hz, 210 Hz, and 2.9 kHz, but SPL did not exceed 120 dB re 1 $\mu Pa^2/Hz$ for any frequency. A frequency tone of 5 kHz was associated with the turbine while generating electricity. Integrated root mean square levels from 20 Hz to 20 kHz also did not exceed 120 dB re 1 μPa^2 [79]. ORPC intended to follow this installment with another two turbines.

The Roosevelt Island Tidal Energy (RITE) Energy project has been operating in the East River in New York by Verdant Power. Verdant Power deployed six tidal turbines in 10 m of water as part of this project in 2011 [68, 69]. Each turbine is a three-bladed system mounted to the riverbed. Transects were made using hydrophones parallel to the shore in order to collect ambient and operating acoustic data for the turbines. At the time of the testing, one turbine had a damaged blade and another was not operational. Resulting SPL were reported as measuring up to 145 dB re 1 μPa reference to 1 m. However, this was measured as less or comparable to the ambient noise present due to the subway traveling under the East River at that location. Interestingly, acoustic data was compared to the SPL known to cause injury in 14 species of fish. Of those species, one was reported to suffer potential injury [28].

Researchers at Washington State University conducted a project in Admiralty Inlet in Puget Sound in 2013 using previously collected EMEC operating 6 m OpenHydro turbine data from 2010 superimposed on the site [19]. The project was meant to assess the effects of the proposed installation of two 6 m OpenHydro tidal turbines in 55 m of water in Admiralty Inlet. Bottom mounted acoustic Doppler current profilers and hydrophones were used to determine tidal current movement and ambient turbine noise for the system. The maximum noise source level for two turbines in Admiralty Inlet was assumed to be 172 dB re 1 μPa referenced to 1 m for both proposed turbines. It was estimated that the probability of a marine mammal detecting the turbine noise would fall below 25% within a kilometer of

the site [88].

A second ORPC project, consisting of a RivGen turbine, near Iguigig, AK in the Kvichak River was monitored. The RivGen turbine consists of two 4.1 m long rotors supported on a pontoon frame and was located centrally in the river under 2.5 m of water. Acoustic data was measured using autonomous drifting spar buoys (SWIFTs), each with a hydrophone attached. Over a period of 9 days in August 2014, 178 data sets were collected as the buoys were allowed to float over the turbine which ran in one of three modes: freewheeling, generating power, or breaking. Most frequencies over 1,000 Hz were masked by the sound of the turbulence in the river itself. Frequencies of interest ranged from 10 to 1,000 Hz. Ambient data was not collected and it was assumed that the brake condition would be closest to that of the system without a turbine present. The turbine helps to supply power to the local village and so could not be removed. For an optimally operating turbine in the one-third octave band centered at a frequency of 100 Hz, the sound level produced is approximately 40 dB above that of the braking condition. At higher frequencies, this drops to 10 dB. The braking condition was measured to have an SPL of 100 dB re 1 μPa at 1 m for a 1/3 octave bandwidth with frequencies of 100-400 Hz, 110 dB re 1 μPa re 1 m for 400-900 Hz, and 115 dB re 1 μPa at 1 m for 900-1000 Hz, where the measurements stopped [4].

Sandia National Laboratories conducted a project testing a 1:8.7-scale axial-flow water turbine in a water tunnel. The turbine was a three bladed, horizontal-axis rotor system model of the 5 m diameter MHKF1 rotor. Testing was completed in the Penn State University/Applied Research Laboratory (ARL) Garfield Thomas Water Tunnel (GTWT). The tunnel test section is 1.22 m in diameter by 4.27 m in length and was run at a constant velocity of 4.0 m/s. Acoustic monitoring was completed using hydrophone embedded in a paraboloid housing attached to a tunnel window in the center of the tunnel section and was located 206 mm from the turbine center. Point measurements were taken for a range of

frequencies from 0 to 100 kHz. Using 1/3 octave bands, the maximum recorded reading was just over 130 dB re 1 $\mu Pa^2/Hz$ at 1 m at a frequency of approximately 6.4 kHz when the turbine was running at 531 rpm. Background noise was also collected for this project [39].

A final study completed by the Institute of Marine Science at the University of Auckland in New Zealand in 2012 wished to use CEC experimental data for comparison to a spreading model, but was unable to acquire any data from operators. Instead, measurements were taken in July and August 2012 in Omaha Bay, New Zealand using an omnidirectional HTI-96 hydrophone. The source was created using a single (monopole source) and later a second additional (twin monopole source) underwater loudspeaker located centrally in the Bay. Measurements were taken ranging from 0 to 5,000 m from the source. The loudspeaker projected the acoustic signal of a tidal turbine operating at a water velocity of 3 m/s and an SPL output of 154 dB re 1 μPa at 1 m per loudspeaker. The acoustic signal was composed of a single sound file compiled on the computer using Adobe Audition acoustic software. Measurements were taken for frequencies between 100 Hz and 24 kHz. Observed data showed a SPL of 3-41 dB re 1 μPa greater than those predicted by standard geometric spreading models for both the single and double sources. Ambient noise measurements were taken for a period of 7 minutes for data comparison. Measured SPLs did not fall below 120 dB re 1 μPa until after approximately 8,000 m for either case [87].

Noise from Current Energy Converters

Experimental data relating to MHK devices is limited and has been recorded from projects in the United Kingdom, the United States, Portugal, Denmark, and New Zealand. A large portion of this data is either proprietary or contaminated with environmental or other anthropogenic noises. Marine Energy Turbines deployed one of the first SeaFlow tidal energy conversion systems off the coast of the British Isles in 2005 generating several comprehensive reports on the state of data such as the OES-IS Annex IV report, published

in 2016 [13, 29, 30, 97, 100, 111]. Within these reports, there are two main categories of MHK devices; WECs and CECs. Since 2005, several WEC testing centers or sites have been constructed including one off the coast of Azores Island at the Pico Power Plant in Portugal in 2010. An installation and monitoring of the WaveRoller WEC in 2013 generated ambient noise measurements followed by further testing in 2014. Sound levels were measured as 115 dB to 121 dB re 1 μPa 220 m away [31].

The US Navy and the University of Washington are currently testing one of the largest US WEC projects, the Azura, at the WETS off the coast of Hawaii. The Azura WEC is a 1:2 scale point absorber designed by NWEI that has been operating since May 2015. Initial data shows that Azura is operating within a frequency range of 150 Hz to 1.5 kHz with a max recording of 87 dB re 1 $\mu Pa^2/Hz$ [89]. Since 2005, the EMEC in the UK has provided and maintained one of the largest databases of MHK projects centered around collecting ambient and induced sound data from construction noise and ship traffic. The EMEC additionally provides a tidal test site off the coast of Scotland [47]. In 2012, a CEC was installed off the coast of Cobscook Bay in Maine by the ORPC following a successful deployment and testing of a cross-flow prototype turbine mounted to a barge along with ambient noise readings. Turbines were installed as part of a TidGen Power System, where increased sound levels were noticeable for frequencies at approximately 105, 210, and 2,800 Hz due to harmonics in the system. SPLs did not exceed 120 dB re 1 $\mu Pa^2/Hz$ for any frequency tested [80].

Several other data sets were considered for the validation analysis of ParAcousti that were readily available and directly recorded from an MHK device. Columbia Power Technologies (CPT) tested its SeaRay 1/7th scale WEC in West Point, Puget Sound, WA in conjunction with University of Washington Northwest National Marine Renewable Energy Center (NNMREC). Ambient levels were measured in November, 2009 and found to be an average of approximately 117 dB re 1 μPa with a peak value at 135 dB re 1 μPa at a frequency band of 20 Hz to 30 kHz for this shallow water system [18]. The Azura WEC has

been operating since May of 2015 at the US Navy Wave Energy Test Site in Oahu, Hawaii and is a 1:2 scale point absorber designed by NWEI. Sound data was collected from April to October of 2015 with recordings taken up to 200 m from the WEC. Operating frequencies ranged from 150 Hz to 1.5 kHz with a max reading of 87 dB re 1 $\mu Pa^2/Hz$ [89]. Several other data sets mimic MHK sources, but are not directly recorded from an MHK source. From 2009 to 2011, the North Pacific Acoustic Laboratory (NPAL) conducted three major data collection projects to study long-range, deep water broadband acoustic propagation in the North Pacific, specifically the northern Philippine Sea. Water levels were greater than 5,000 m in places and frequencies were 200 - 335 Hz. NPAL generated sound using recorded MHK signatures with an average power level of 182 dB re 1 μPa at 1 m rms [122]. In 1995 and 2006, acoustic and environmental data was collected by investigators from the Naval Research Laboratory (NRL), Woods Hole Oceanographic Institution (WHOI), the University of Delaware (UD), and the Applied Physics Laboratory of Johns Hopkins University (APL/JHU) to form a project called SWARM (Shallow Water Acoustics in Random Medium). Data was collected 100 mi off the coast of New Jersey, USA using two pipe tomography sources producing levels of 181 and 183 dB re 1 μPa at 1 m for frequencies ranging from 224 - 500 Hz [10, 78]. All potential locations except for NPAL's recordings were taken in what is considered shallow water locations.

Ambient Noise Levels

Ambient recordings for most WEC and CEC projects suffer from a lack of sheltering from prominent single sources, which dominate the sound profile such as ship traffic. The University of Washington has completed research on the influence of sediment generated noise and that individual sources may dominate a sound profile, leading to an ambient reading which may obscure any MHK contribution or not be useful for experimentation at a later date [15, 17]. The Pacific Northwest National Laboratory went as far as to complete

a study analyzing the influence of turbulence on acoustic measurements, including MHK and ambient sound profiles, and created a set of guidelines for how to handle acoustic data measured from a system with increased turbulence [99].

EMEC has two other testing sites, the first of which is Shapinsay Sound Tidal Energy Test Site located at Shapinsay Sound, Orkney. Acoustic measurements were made at this location between September 2011 and May 2012 for a total of four surveys in order to characterize the ambient noise data for the area and for a range of tidal conditions. EMEC's 'Drifting Ears' hydrophone equipment was used for the monitoring. The average reading for the area was approximately 65 dB re 1 μPa at a frequency of 2.5 kHz. Values up to 100 dB re 1 μPa in a 1 Hz bandwidth were recorded from passing small boats and a 'seal scarer' was recorded as contributing upwards of 90 dB re 1 μPa in a 1 Hz bandwidth for the area [49].

The second testing site is the EMEC nursery wave test site in Scapa Flow, Orkney. This project was intended to provide ambient acoustic data in order to provide a baseline to aid future developers of WEC devices deploying to the site. Measurements were conducted between September 2011 and March 2012 using a fixed hydrophone and recorder package provided by Wildlife Acoustics, Inc. Three surveys were conducted in total with a frequency range of 0 to 16 kHz. Acoustic data was recorded for a range of sea states; the average depth is approximately 25 m. Mean spectra data showed a range of approximately 55 to 95 dB re 1 μPa depending on the weather condition, peaking at 500 Hz and having the lowest values at 16 kHz. Values were on average 20 dB higher when it was raining as compared to a calm condition. SPLs for the quiet conditions tended to drop off around 2 kHz. Ship noise resulted in SPLs over 100 dB at 500 Hz [49].

A third ambient acoustic study was performed in Grand Passage, NS, Canada by the Department of Oceanography at Dalhousie University in Halifax, NS. The main purpose of this study was to assess the feasibility of Passive Acoustic Monitoring (PAM) for Grand

Passage using moored and drifting hydrophones. A drifting underwater sound projector was used to determine the maximum observed detection range, which resulted in being 700 m with a false alarm rate of 50 percent. Ambient noise was recorded for four different frequency bands: 0-2 kHz, 2-20 kHz, 20-50 kHz, and 50-200 kHz. For frequencies below 2 kHz, recorded data showed SPL values of about 48 dB re 1 μPa at slack water and 67 dB re 1 μPa at peak tidal flow. Above 2 kHz, the data from the drifting hydrophone showed a marked dependence on position in the channel compared any tidal variation exhibited by the moored hydrophone [72].

Marine Hydrokinetic Noise: Surrogate Technologies

Without sufficient measured data from MHK sources, there are technologies in use, and operations performed, underwater that are similar and can provide guidance on anticipated noise spectra, levels, and impacts. This includes ship design and propulsion, construction activities, offshore platforms, acoustic measurements for SONAR and geologic surveys. As all of these activities are governed by domestic and international regulations, and much research has gone into reducing their contribution to anthropogenic noise in the water environment. While many references exist that detail measured values for each of these surrogate sources, a 2009 OSPAR Commission report summarizes the principal noise levels of these surrogate applications and their impact on the environment [43]. And while the operating medium is different, noise measurements from wind turbines may also be used. The following is a synopsis of a few areas of study that pertain to MHK acoustics as well as contain data that may be used in lieu of MHK experimental data for simulation validation and comparison. Areas of study include noise generation and propagation from ship vessels and propellers [36], pile driving events used in the offshore oil and gas and wind energy industries [35], and wind turbines, both off and onshore [51, 62].

Wind Turbines Wind turbines are the most direct analog to CECs, both horizontal-axis and cross-flow designs. Operating conditions for offshore windfarms have been measured anywhere from 90 dB re 20 μPa to 130 dB re 20 μPa at 1 m [43, 76, 77, 112]. The large size of these devices, as compared to proposed CECs, will have lowered the principal frequencies and the smaller density of air will prevent the sound from propagating as far as it would in water. Unlike air, MHK devices will have to consider the addition of cavitation as a noise source.

Hay et al. developed an analytic model based on a Green's function approach for sound radiating in a water column by pulsating a cylindrical structure embedded in horizontally stratified layers of viscoelastic sediment [51]. The model was extended to include relaxation and viscous losses in seawater and empirical loss factors for sedimentary layers. The analytic model is coupled to a parabolic equation code, allowing for range dependent scenarios, to include varying bathymetries, sediment types and tower array configurations.

Lee et al. numerically modeled aerodynamic noise originating from a wind turbine in the time domain [62]. An analytic trailing edge noise model is used to determine the unsteady pressure on the blade surface which serves as an input to a far field propagation model using the acoustic analogy theory. A time domain solution is of interest to examine the dependence on observer location and time rather than a frequency domain solution. Results indicate that despite constant operating and atmospheric parameters, acoustic characteristics can differ drastically with change in distance and direction from the wind turbine. Validation of the model for a two-dimensional flow was carried out with an experiment by Brook et al. displaying good agreement with the results [27].

Ships and Propellers Ship hulls will interact with the surrounding water to generate hydrodynamic and structural noise sources, similarly to the structures of both CECs and WECs. Particularly, as WECs become larger their design may benefit from practices in naval

architecture, as these predominately low frequency noises may travel further than higher frequency contributions from machinery and propellers. Propellers share a lot in common with CEC designs. Though propellers use energy to move a body and CECs remove energy from the flow, the design and operation will result in similar noise contributions. Propeller size and design, operating conditions, and the local environment will ultimately dictate the type of noise produced and potential for cavitation; however, noise from small to large vessels can be in the range of 150-190 dB re 1 μPa at 1 m [43, 107]. Unlike ships, MHK devices are expected to operate continually in a single location.

Ianniello et al. claim to be the first to conduct acoustical analysis on a complete scaled ship model [52]. The acoustic analogy, a technique in numerical acoustics to reduce sound sources to simple emitter types, i.e. Lighthill- and Ffowcs Williams-Hawkings- analogy, is used to predict the underwater noise generation from a complete scaled ship model on a steady course. A coupled incompressible Reynolds Average Navier Stokes (RANS) code, with a level-set approach to account for the fundamental time evolution of the free surface, and a Ffowcs-Williams and Hawkings (FWH) based hydroacoustic solver designed to handle large amounts of data from a full-unsteady hydrodynamic solution was utilized. Results of pressure signatures indicate very good agreement and functionality between the RANS and FWH solvers. Effective demonstration and robustness of this numerical approach to assess a ship's underwater noise and identify the main noise generating mechanisms is claimed by the authors [52]. The authors also claim that a reliable underwater noise prediction through the direct approach is numerically unfeasible due to the intrinsic limitations of the RANS simulation and the very fine spatial discretization requirements. Additionally, the quadrupole noise sources from a propeller must be included in a FWH-based hydroacoustics analysis as there is a significant amount of contribution to the acoustical characteristics. The noise generation from a ship's propeller is analogous to an MHK turbine and a similar analysis of a MHK device could be conducted and provide detailed, accurate, and robust

acoustical characterizations [52].

Industrial & Construction Sources Noise produced during pile driving events for the installation of offshore wind turbines and oil and gas activities as well as other construction and industrial sources will be similar to those in construction of fixed MHK platforms. This type of noise source will also be similar to systems reaching mechanical limits, such as the extension of the damping-plate of a point absorber. While the cyclic on and off noise source, due to repetitive impacts of the pile driver, differs from a normally continuously operating MHK source, these measurements will also serve as an appropriate surrogate for the propagation of anthropogenic noise in a marine environment.

Lippert et al. utilized a two-component, coupled model for the prediction of noise generation and propagation from pile driving events at offshore wind farm construction sites [107]. A basic FEM model represented the pile itself and 50 m around the pile. The results from the FEM model were used to generate acoustic source properties as input to a wavenumber integration code, an alternative form of the normal mode technique, which was the main propagation method used for long ranges in this study. Feasible simplifications to the pile's acoustic source were investigated and researchers suggested including an accurate method to reduce the acoustic source of the entire pile to a set of point sources. The wavenumber integration code and FEM model results were compared in the 50 m overlapping region between the two models. Good agreement between the two techniques were observed, verifying the validity of the wavenumber integration code at long ranges [67].

Trimoreau et al. utilized a similar coupled, two-component model for prediction of noise during pile driving events as Lippert et al with an additional semi-empirical technique [114]. The coupled model makes use of a customized stress-Wave Equation Analysis for Piles (WEAP) and a vibro-acoustic finite element algorithm. WEAP is a geotechnical tool that calculates the stress wave in hammer-pile systems and its results are used as inputs to

the vibro-acoustic FEM model. A separate semi empirical approach is established that uses empirical data of sound levels emitted by an air gun at long ranges in an actual site and a sound transmission model to extrapolate the sound level at the source. Once the source is reconstructed, a wave number integration propagation code is used to calculate propagation of sound at long ranges. Two test cases of actual pile driving events were utilized for both modeling techniques; results from the models were compared to hydrophone data taken at both sites. Good agreement between both the numerical and semi-empirical techniques and the data were observed [114].

Halvorsen used a High Intensity Controlled Impedance – Fluid filled wave Tube (HICI-FT) in a laboratory experiment at the Pacific Northwest National Laboratory in Washington to create a source profile similar to that produced by pile driving. SPL levels were achieved though operating device over a number of strikes (similar to pile driving) near a tank of Chinook salmon. Two cases were completed. The first of which produced an average cumulative SPL of 210 dB re 1 μPa^2s for 1920 strikes and a second which produced the same SPL value but for 960 strikes. The Salmon tested were all exposed to a SPL resulting in types of physical injury [46].

Noise measurements were recorded at the Fall of Warness test site in Scotland during the summer of 2010 during jack-up operations as well as for drilling noise during the installation of a monopole at the Voith Hydro test berth. Measurements were taken by Aquatera for Voith Hydro. Measurements were taken with a hydrophone system and included SPL received levels of 135-140 dB re 1 μPa at 500 m. A broadband effective source level of 168 dB re 1 μPa at 1 m was calculated using spreading laws. Background noise was estimated to be 122-126 dB re 1 μPa for frequencies up to 22 kHz mainly due to local ship traffic [11, 12].

The Penguin WEC, owned by Wello, is designed to react to waves in a pitching and rolling motion of ocean waves. Currently, the system is outfitted with a secondary cooling system comprised of two fans and one pump. In 2012, a study was completed to analyze

the underwater acoustic signature of the cooling system while the Penguin was moored at Hoy Island in Orkney, Scotland. The study did not include the operational noise produced by the WEC and any noise from the movement of the device while moored was made part of the ambient recordings. A sonobuoy collected acoustic water 4 m under the water surface where the total water depth was approximately 10 m. Ambient data was measured as a range of SPLs from 104 to 112 dB rms re 1 μPa , excluding ship traffic. The cooling fan yielded frequency peaks at 15, 45, 90, 140-150, and 250-300 Hz with a SPL of 140.5 rms re 1 μPa at 1 m. Ambient levels were reached within 10 m of the device [20].

More noise measurements will become available as the number of MHK developers and their technologies increase in technology readiness. However, at the present time there is an insufficient amount of detailed acoustic MHK measurements to support the industry, regulators, and researchers in understanding its impact on the marine environment. This lack of data also prevents validation of any predictive models for the noise generated. The measurements that do exist rely on different techniques and instrumentation and the reported values are highly dependent upon the in-situ environmental conditions. The data that is available in literature and from individual developers and researchers indicate individual device noise levels that will nearly reach domestic regulations. That said, the mechanisms of propagation may rapidly decay these levels and sufficient surrogate data can be leveraged to support the MHK industry until more measurements become available.

Perception of Sound

Sound not only interacts with the environment, but it is also perceived by the animals living in that environment. Sound introduced to that system will interact with the noise already present within an environment. This may increase sound levels, or if the energy level is low enough, it will fall below ambient levels and have no significant impact. Sound which falls above ambient may adversely affect any marine fauna living in a particular location.

Marine Fauna Interactions with Sound

Environmental concerns have been raised about the use of MHK devices and their effect on the surrounding fish and marine mammal populations when in use. This is exemplified by the implementation of sound regulations by US agencies [115] and the publishing of Annex IV 2016 State of the Science Report aimed at quantifying environmental effects from MHK devices [30]. Several studies indicate that at low sound levels fish species can increase their swimming speeds, move away from the sound source and swim in cohesive groups. In more extreme, high-intensity sound levels, detrimental effects include temporary or permanent damage to a species ability to hear sound or other physical damage such as bursting of the swim bladder in fish [45, 73, 90]. Fish species may suffer complete hearing loss from increased anthropogenic noise levels, completely disrupting the fish’s ability to communicate or feed effectively [105].

Several researchers have used predictive underwater noise models to map zones of influence for marine species based on dB thresholds [45, 83, 101]; however, many of these underwater noise models are over-simplified and range-independent solutions that lack the complex 3D interactions. These interactions are generated from bathymetry, attenuation, varying sound speed, temperature, salinity, and density profiles. Additionally, most of these works do not predict how a species may react behaviorally to noise and only calculate zones of influence. Rossington et al. [101] have taken these shortcomings into consideration and developed an eco-hydro-acoustic tool. This modeling tool has been designed to predict the response of marine species to underwater sound by combining a range dependent (pseudo) 3D Parabolic equation acoustic propagation model with data from a hydrodynamic model, which in turn generates data for an ecological response model for an individual species. Each “fish” is represented as a particle that is subject to both advection and behavioral rules and allows response to the environment. This response includes transport by the naturally moving currents of the marine environment including any striking with land, way points of

navigation that the species tends to move towards, noise avoidance measures, and correlated random changes in direction and speed. A case study using this tool was performed for an offshore wind farm pile driving event in Liverpool Bay near the mouth of the River Mersey for a specific species of cod that travel through the site to their feeding grounds. The individual based model (specific for one kind of species) results indicate the fish that could “hear” noise took seven days longer to reach their destination than the control “deaf” fish. It should be noted this model, like all other models, is only as accurate as the accuracy of the input data and formulations. While the ecological response model may not detail every possible fish interaction, it serves as a good statistical approach. As more ecological response information is made available and incorporated into the tool, the accuracy and reliability of the tool increases.

Pressure disturbances due to acoustical noise are a concern as it may produce negative impacts to marine wildlife and the environment. Behavioral disturbances may have a negative effect if impacted areas are important to the life cycle of the species, limit access to food, or simply cause stress. Many marine species also use sound as a form of communication, orientation, or detection of a predator or prey and additional sound, or sound of particular frequencies, in an area may limit or alter these abilities [34]. Anthropogenic noise can cause direct harm, injury, or even death to fish and marine mammals. As an example, under large pressure loads fish swim bladders, gas-filled organs that allow fish to control their buoyancy, or capillaries can burst [45, 46, 71] A study involving underwater turbines in coastal sites reported a reduction in area usage of Harbour seals by 11 - 41 % for up to 500 m from the recorded sound source [50]. Halvorsen determined that Chinook salmon would experience tissue damage leading to adverse physiological damage when exposed to a cumulative sound energy level of 210 dB re $1 \mu Pa^2 \cdot s$. The overall extent of these impacts is unclear at this point, largely due to a limited number of operational MHK devices in the environment. However, accurate prediction of the acoustical landscape from a potential MHK operation

is important in understanding impacts and ensuring environmental regulations are met. Additionally, the interaction of the emitted sound from an MHK and the sound produced by a particular species would limit a species' abilities to communicate, especially if all sound was concentrated in a singular, overlapping frequency band [34, 104]. [104] in particular indicated a temporary threshold shift (TTS), or a temporary disturbance in behavior, for seals when SELs of 207 and 191-195 dB re 1 μPa^2s for frequencies of 100 and 400 Hz, respectively. For the same species, [86] found that listening space reductions were in excess of 80 % within 60 m for harbour seals and over 55 % within 10 m of a tidal energy device for harbour porpoises.

The response of fish and other marine wildlife to anthropogenic influences is a complex and often hard to predict. Studies have been conducted on the effects of sound on fish and invertebrates. For example, Wale, [117], showed that the feeding behavior of the common shore crab is affected by decreasing foraging time in response to a stimuli of noise from an active ship. Fewtrell and Lokkeborg, [38] and [70], demonstrated that when underwater noise is detected, fish species can increase their swimming speeds, move away from the sound source and swim in more cohesive groups. In more extreme, high-intensity sound levels, detrimental effects include a total avoidance of an area previously frequented by a species [45, 73, 90]. Lucke, [71], collected data from five different studies, which calculated SELs from 2007 - 2017. All studies were interested in which SELs would result in a TTS for cetaceans in a tidal area. Within these data sets, SELs varied 0.9 to 19 dB within comparable data sets with highs around 165 dB re 1 μPa^2s for a sound gun [71]. This indicates that even within collected data sets, there is a sizable variability within what level is considered to affect a cetacean. Accurate predictions of the sound environment altered by a singular, or array of, MHK device(s) would help in the understanding and minimization of any potential impacts while ensuring that a device design meets regulations.

Regulatory Considerations

As with other anthropogenic noise sources within our waterways, regulations are used to govern successful permitting of WECs and CECs, respectively. However, regulatory constraints and environmental concerns over the SPLs produced by these MHK devices are a hurdle to their deployment and operation. The Marine Mammal Protection Act in the USA, for example, limits cumulative sound exposure levels specifically for pinnipeds and cetaceans [115]. Of the five classifications of marine fauna of concern, high-frequency cetaceans are determined to be the most sensitive with a cumulative sound exposure level of 153 dB and 173 dB re $1 \mu Pa^2 s$, prior to experiencing a temporary and permanent change to their hearing, respectively. Maximum allowed decibel levels are separated into temporary and permanent threshold shifts as well as a limit for behavioral disturbance with a continuously operating source, which is set generally at 120 dB re $1 \mu Pa$ rms. MHK devices have the potential to produce a SPL greater than acceptable levels as defined by NOAA and other regulatory bodies in the USA. The regulations set by the Marine Mammal Protection Act, which is additionally monitored by the National Marine Fisheries Service as well as NOAA has influenced several other regulatory bodies. These include the Federal Maritime and Hydrographic Agency and the MMWG or recommendations of the working group for marine mammals and underwater noise in Denmark. SEL values for each of those regulations for Harbour Seals and Harbor porposie vary from 160 - 170 dB re $1 \mu Pa^2 s$ and 140 - 164 dB re $1 \mu Pa^2 s$, respectively for TTS and 185 - 200 dB re $1 \mu Pa^2 s$ and 155 - 183 dB re $1 \mu Pa^2 s$, respectively for permanent damage [108]. This indicates that even within regulatory bodies agreed upon levels are not consistent further contributing to the need for recorded data and applicable acoustic models for underwater systems.

CHAPTER 3: THEORY

In contrast to the traditional approaches described in chapter 2, this chapter discusses a method for investigating the propagation of sound in an underwater environment. This research uses an alternative 3D solution to the velocity pressure equations proposed by Aldridge and Ostashev in 2002 and 2005, respectively [8, 9, 81]. With the large increase in available computational capabilities, a fully 3D, time-domain solution of the governing velocity-pressure equations can be solved as an alternative to the wave equation and Helmholtz models. This is advantageous for MHK acoustic propagation, where the often, shallow-water shape and bathymetric composition of early installation sites will contribute significantly to how noise moves through the system by focusing and dispersing the sound field. Similar effects will be present in deep-water domains, but are expected to have a less-pronounced impact on propagation since the energy within the pressure wave will travel longer distances prior to significant interactions. In an unconstrained environment, the energy from sound dissipates primarily through spreading and conversion to heat. Any conversion to heat is neglected in the solution presented within this chapter. The following velocity-pressure equations make similar assumptions to that of the wave equations by modeling an ideal fluid under adiabatic conditions and handles both shallow- and deep-water environments equally well. However, unlike the wave equations, body and perturbative external forces are included in the velocity-pressure solution. Grid spacing and time steps of velocity-pressure equations have the potential to become quite small for high frequency sources, increasing computational demands. However, past work suggests that the majority of the energy in a MHK device falls below 1500 Hz and of that energy of it is mostly contained in lower principle frequency ranges [4, 18, 39, 58, 64, 68, 80, 89]. The velocity-pressure equations are capable of modeling complex bathymetry, which is important for understanding all the interactions in MHK-relevant domains. All of these effects will impact the distance

that sound levels propagate before falling below a given threshold level, such as those designated by regulations. Additionally, the velocity-pressure equations are capable of being parallelized, which reduces computational time associated with the increased complexity of the geometry inherent to many of initial MHK testing and deployment sites.

ParAcousti is a parallelized, acoustic-wave propagation package developed by SNL to numerically solve as the velocity-pressure equations. This body of work was directed at validating and evaluating the ability of ParAcousti to accommodate the breadth of scenarios possible during the design, regulation, and operation of MHK deployments. ParAcousti represents a novel 3D solution to the problem of underwater acoustic propagation modeling in the time domain and had not been applied or validated previous to this work. Originally, the solution to the velocity-pressure equations presented within ParAcousti was derived from TDAAPS, a Time Domain Acoustic Atmosphere Suite, which was meant to solve acoustic wave propagation in moving media. This program was developed and validated to solve for atmospheric and geophysical models including seismic activity [94]. One of the goals of this work was to confirm that the same equations could represent the solution conditions required to solve for sound waves propagating underwater. The derivation of these equations is presented within this chapter as well as a discussion of the parts of the program that were validated for this work. The assumptions noted were selected to apply the solution to an underwater system. Previously formulated for TDAAPS, the velocity-pressure equations solution had not been confirmed as an appropriate solution for an underwater system until the completion of this work. This system of equations initially traces back to Cauchy's equations of motion and is used to fully describe the propagation of sound through an underwater environment in time for 1D, 2D, and 3D domains.

Non-Attenuative Linearization of Cauchy's Equations of Motion

The derivation starts with Cauchy's equation of motion, which are a series of partial differential equations developed by A. L. de Cauchy in early 1800s to represent non-relativistic momentum transport in any continuum. Assumptions may then be made to tailor the equations to the continuum of interest including any necessary body forces. The basis for the equations are the conservation of linear momentum or more specifically the linear momentum equation, (3.1),

$$\mathbf{F} = \frac{D\mathbf{P}}{Dt} \bigg|_{sys} \quad (3.1)$$

where $\mathbf{F}$ is the resultant force acting on a fluid mass, $\mathbf{P}$ is the linear momentum as defined by 3.2 over some time, t . For all equations within this document, a variable that is bold is a vector.

$$\mathbf{P} = \int_{sys} \mathbf{v} dm \quad (3.2)$$

These equations are designed for a given system of interest, sys , where $\mathbf{v}$ represents the velocity field of a fluid particle. The operator $D()/Dt$ is the material derivative. Equation 3.1 is applied to a differential system consisting of some mass, δm , where that mass is considered constant for the system. Combining this with equations 3.1 and 3.2, this results in equation 3.3.

$$\delta \mathbf{F} = \frac{D(\mathbf{v} \delta m)}{Dt} \quad (3.3)$$

For this equation, $D\mathbf{v}/Dt$ is the acceleration, $\mathbf{a}$, of the differential element being considered within the overall system, and so $\delta \mathbf{F} = \delta m \mathbf{a}$. For our element of interest, we have both body forces and surface forces. Body forces are limited to the weight of the element and may be expressed through gravity. Surface forces are obtained by an interaction of a force acting on a small area at some arbitrary location on the surface of the fluid mass. Forces acting normal and parallel to an area are defined as the normal stress, σ , and the

shearing stresses, τ , respectively. Specifically, the stress is equal to the limit of $\delta\mathbf{F}$ with respect to δA as the area goes to zero. Each of these three components act on all six sides of a representative cube of fluid. Each side of the cube has an orientation and a normal and parallel force acting on it. The resultant change in force on the surface of the cube may be defined as the summation of the change in stress across the fluid element multiplied by the area on which they act. For example, in the x-direction, summing all the forces results in equation 3.4,

$$\delta F_{sx} = \left(\frac{\delta\sigma_{xx}}{\delta x} + \frac{\delta\tau_{yx}}{\delta y} + \frac{\delta\tau_{zx}}{\delta z} \right) \delta x \delta y \delta z \quad (3.4)$$

This is expanded for the y and z directions of the cube as well, where a force acting in the outward or tensile direction is considered positive. The surface forces may be expressed in addition to the body forces which also act in all three directions, x , y , and z . The differential mass is equal to the density of the fluid times the volume, or $\delta m = \rho \delta x \delta y \delta z$, where ρ is density. Combining the force tensors for both the body and surface forces and dividing by the volume, the equation simplifies to 3.5,

$$\rho \mathbf{g} + \nabla \cdot \sigma = \rho \left[\frac{\delta \mathbf{v}}{\delta t} + (\mathbf{v} \cdot \nabla) \mathbf{v} \right] \quad (3.5)$$

where σ is the full 3 X 3 stress tensor for a cube and $\mathbf{g}$ is gravity. The equations required for the further derivation of the velocity pressure equations are a linearization of continuity (3.6a), Cauchy's equations of motion (3.6b), constitutive relationship for stress (3.6c), and a balance of entropy (3.6d) [8, 9],

$$\frac{\partial \rho}{\partial t} + \mathbf{v} \cdot \nabla \rho + \rho \nabla \cdot \mathbf{v} = 0 \quad (3.6a)$$

$$\rho \left[\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right] - \nabla \cdot \sigma = \mathbf{f} \quad (3.6b)$$

$$\sigma = \left[-p + \lambda \nabla \cdot \mathbf{v} \right] \mathbf{I} + \mu \left[\nabla \mathbf{v} + (\nabla \mathbf{v})^T \right] \quad (3.6c)$$

$$\rho \theta \left[\frac{\partial \eta}{\partial t} + \mathbf{v} \cdot \nabla \eta \right] - \rho \theta \xi + \theta \nabla \cdot \mathbf{s} = \frac{\partial e}{\partial t} \quad (3.6d)$$

where total density $\rho(\mathbf{x}, t)$, velocity $\mathbf{v}(\mathbf{x}, t)$, pressure $p(\mathbf{x}, t)$, entropy $\eta(\mathbf{x}, t)$, absolute temperature $\theta(\mathbf{x}, t)$, body force density $\mathbf{f}(\mathbf{x}, t)$, and external energy density $e(\mathbf{x}, t)$ are functions of location $\mathbf{x}$ and time t . Equation 3.6b is a rearrangement of equation 3.5, where the body force density is substituted for $\rho \mathbf{g}$. Variables are the combination of ambient values and any perturbations from acoustic waves. Stress (σ) becomes the representation for a 3×3 tensor of both the normal and shear stresses, μ and λ are the dynamic and bulk viscosity coefficients, respectively, ξ is the entropy production, and $\mathbf{s}$ is the entropy flux. $\mathbf{I}$ is the identity matrix. The linearity of the continuity equation allows for the flow of energy into the system to be proportional to the flow out of the system. This stabilizes the solution and reduces the unknowns such that all energy losses within the domain must be accounted for as part of the equations.

Derivation

Assuming the fluid is inviscid ($\mu = \lambda = 0$) and adiabatic, a linearized system can be reduced from above. For air or water, viscosity is small and this allows us to neglect the shearing stresses which are induced by the viscosity of the system. These systems are considered friction-less. In reality, friction does occur in water and is considered a loss of energy when a sound wave travels through the fluid. Energy is removed as heat and contributes to the reduction in sound energy as the sound wave travels outward. As there are no frictional losses, the system is adiabatic, which indicates that heat does not enter or leave the system. This simplifies the system considerably and losses are considered to be

negligible compared to the reduction of energy through spreading. The linearized equations are simplified with respect to the stated assumptions and rewritten in terms of perturbations caused by acoustic waves (*) and ambient values (°). The adiabatic assumption results in an ambient medium where the material derivative of the specific entropy density and the rate of external energy supply to the medium are both zero. Equations (3.6b) and (3.6c) are combined to produce equation (3.7b) and an equation of state is introduced in (3.7d) relating the perturbation of pressure to those of density and entropy.

$$\frac{\partial \rho^*}{\partial t} + \mathbf{v}^\circ \cdot \nabla \rho^* + \rho^* \nabla \cdot \mathbf{v}^\circ + \rho^\circ \nabla \cdot \mathbf{v}^* + \mathbf{v}^* \cdot \nabla \rho^\circ = 0 \quad (3.7a)$$

$$\rho^\circ \left[\frac{\partial \mathbf{v}^*}{\partial t} + \mathbf{v}^\circ \cdot \nabla \mathbf{v}^* + \mathbf{v}^* \cdot (\nabla \mathbf{v}^\circ)^T \right] + \left[\frac{\partial \mathbf{v}^\circ}{\partial t} + \mathbf{v}^\circ \cdot \nabla \mathbf{v}^\circ \right] \rho^* + \nabla p^* = \mathbf{f}^* \quad (3.7b)$$

$$\frac{\partial \eta^*}{\partial t} + \mathbf{v}^\circ \cdot \nabla \eta^* + \mathbf{v}^* \cdot \nabla \eta^\circ = \frac{1}{\rho^\circ \theta^\circ} \frac{\partial e^*}{\partial t} \quad (3.7c)$$

$$p^* = (c^\circ)^2 \rho^* + h^\circ \eta^* \quad (3.7d)$$

where $c^\circ = \sqrt{\partial p^\circ / \partial \rho^\circ}$ is the ambient sound speed and h° is a measure of the change in the total pressure produced by a change in the specific entropy density. Equation (3.7) specifies a system of equations for the perturbations of velocity, pressure, and density that are dependent upon the ambient conditions of a system and thermodynamic properties of the fluid.

The particle velocity of the ambient medium is further restricted to being divergence free, *i.e.*, $\partial \mathbf{v}^\circ / \partial \mathbf{x} = 0$. This assumption results in only the ambient portion being incompressible. Rearranging slightly and substituting in the spatial derivative of Equation

(3.7d) yields,

$$\frac{\partial \rho^*}{\partial t} + \mathbf{v}^\circ \cdot \nabla \rho^* + \rho^\circ \nabla \cdot \mathbf{v}^* + \mathbf{v}^* \cdot \nabla \rho^\circ = 0 \quad (3.8a)$$

$$\frac{\partial \mathbf{v}^*}{\partial t} + \mathbf{v}^\circ \cdot \nabla \mathbf{v}^* + \mathbf{v}^* \cdot (\nabla \mathbf{v}^\circ)^T + \frac{\rho^*}{\rho^\circ} \left[\frac{\partial \mathbf{v}^\circ}{\partial t} + \mathbf{v}^\circ \cdot \nabla \mathbf{v}^\circ \right] + \frac{1}{\rho^\circ} \nabla p^* = \frac{1}{\rho^\circ} \mathbf{f}^* \quad (3.8b)$$

$$\frac{\partial p^*}{\partial t} + \mathbf{v}^\circ \cdot \nabla p^* + \rho^\circ (c^\circ)^2 \nabla \cdot \mathbf{v}^* + \mathbf{v}^* \cdot \nabla p^\circ = \frac{h^\circ}{\rho^\circ \theta^\circ} \frac{\partial e^*}{\partial t} \quad (3.8c)$$

As the sound speed in underwater acoustics is substantially faster than local velocity fields for these applications, the background medium is assumed to be stationary, $\mathbf{v}^\circ = 0$. This results in a further simplification of the equations, as well as the material derivative of velocity in Equation (3.8b) going to zero. Equation (3.8a) is reduced as the ambient velocity terms are removed and Equation (3.8a) may be decoupled from Equations (3.8b) and (3.8c). Additionally, ∇p° may be approximated as zero as any background velocity is significantly smaller than the local sound speed, where $\nabla p^\circ \approx \mathbf{v}^2/c^2$, and may be ignored to the first order. This assumption allows the equations to be valid for uniform and non-uniform pressure fields. The system of equations then reduces to two coupled, first-order, linear partial differential equations, referred to as the velocity-pressure system and given in Equation (3.9).

$$\frac{\partial \mathbf{v}^*}{\partial t} + \frac{1}{\rho^\circ} \nabla p^* = \frac{1}{\rho^\circ} \mathbf{f}^* \quad (3.9a)$$

$$\frac{\partial p^*}{\partial t} + \rho^\circ (c^\circ)^2 \nabla \cdot \mathbf{v}^* = \frac{h^\circ}{\rho^\circ \theta^\circ} \frac{\partial e^*}{\partial t} \quad (3.9b)$$

These equations have the same general form as the system of equations used in seismic wave propagation modeling. Seismic wave modeling uses a stress tensor instead of a pressure tensor

and two moduli instead of one within the equations [7]. If the acoustic energy source $\partial e^*/\partial t$ is only defined at a point, then the thermodynamic parameters h° and θ° do not need to be known throughout the domain and can be combined into the moment density magnitude. By decoupling Equation (3.8a) from Equations (3.8b) and (3.8c), the perturbation of mass density in Equation (3.8a) can then be determined by integrating the reduced form shown in Equation (3.10) with respect to time. Through Equation (3.10), density perturbations caused by a sound wave are preserved and may be solved for, allowing the sound wave to propagate through a system even though the ambient fluid is incompressible.

$$\frac{\partial \rho^*}{\partial t} = -\rho^\circ \nabla \cdot \mathbf{v}^* \quad (3.10)$$

Contributions to the ambient pressure field from internal gravity waves are considered negligible as the velocity at which they propagate is significantly slower than the pressure waves generated by an MHK sound source [32]. Effects would become noticeable in atmospheric conditions, macro scale models in underwater environments, or underwater environments with large density changes. In comparison, the anticipated domains of interest are relatively small [110].

Further borrowing from seismology literature, [7, 61] the body force terms on the right hand side of Equation (3.9a) can be characterized by the combination of forces and force-dipoles applied to the medium. Forces are represented by the force density vector $\mathbf{F}(\mathbf{x}, t)$ and force-dipoles by the deviatoric portion of the moment density tensor $\mathbf{m}^{dev}(\mathbf{x}, t)$. Consider two unidirectional point forces with the same magnitude A and waveform $w(t)$, but pointed in opposite directions $\mathbf{a}$ and separated by some distance $d\mathbf{n}$. Each point force has a force density function composed of an amplitude scalar, waveform, force direction vector, and a special delta function. The total force density is a summation of the two force density

functions and becomes,

$$\mathbf{F}(\mathbf{x}, t) = -Ad\mathbf{a}w(t) \left[\frac{\delta(\mathbf{x} - \mathbf{x}_s - \frac{d}{2})\mathbf{n} - \delta(\mathbf{x} - \mathbf{x}_s + \frac{d}{2})\mathbf{n}}{d} \right] \quad (3.11)$$

where $\mathbf{x}_s$ is the midpoint between the two sources and $\mathbf{n}$ is a directional unit vector indicating the ‘separation distance’ between the two sources. In the limit as $A \rightarrow +\infty$ and $d \rightarrow 0$, such that the product $Ad = M$ remains finite, the total force density vector becomes

$$\mathbf{F}(\mathbf{x}, t) = -M\mathbf{a}w(t) \frac{d}{dn} \delta(\mathbf{x} - \mathbf{x}_s) \quad (3.12)$$

The directional derivative may be written in a different form to show that $\frac{d}{dn} \delta(\mathbf{x} - \mathbf{x}_s) \equiv \mathbf{n} \cdot \nabla \delta(\mathbf{x} - \mathbf{x}_s)$. The gradient and force direction vectors may be expanded to produce a fully developed form of the total force density vector. A moment density tensor may be used instead of the expanded gradient and force direction vectors to produce a more compact form,

$$\mathbf{m}_{ij}(\mathbf{x}, t) = -Mw(t)\mathbf{a}_i\mathbf{n}_j\delta(\mathbf{x} - \mathbf{x}_s). \quad (3.13)$$

Expressing the total force density vector in terms of the moment density tensor for a double force configuration,

$$\mathbf{F} = \nabla \cdot \mathbf{m} \quad (3.14)$$

The moment density tensor is a 3×3 tensor describing the various combinations of force-dipoles and the isotropic portion of the tensor, which represents a pressure source. The total force becomes a summation of the above expanded force density vector and the deviatoric portion of the moment density tensor. The hydrostatic portion of the moment density tensor is required for the stress-strain constitutive relation appearing in Equation

(3.15). This yields the final, coupled-pair of linear, partial differential equations,

$$\frac{\delta \mathbf{v}^*}{\partial t} + \frac{1}{\rho^\circ} \nabla p^* = \frac{1}{\rho^\circ} \left[\mathbf{F} + \nabla \mathbf{m}^{dev} \right] \quad (3.15a)$$

$$\frac{\delta p^*}{\partial t} + \rho^\circ (c^\circ)^2 \nabla \cdot \mathbf{v}^* = \frac{-1}{3} \frac{\delta \mathbf{m}^{iso}}{\delta t} \quad (3.15b)$$

where $\mathbf{m}^{iso}$ is the trace of the isotropic portion of the moment density tensor. Note that through the linearization the ambient density and sound speed become functions of only 3D space and not of time. However, arbitrarily complex 3D distributions of medium properties in the water and earth domains are allowed, including topography, bathymetry, and acoustic sound speed variations due to temperature, salinity, and pressure in the water, in addition to sub-seabed variations in earth structure [93]. An alternative formulation for sound propagation within a moving medium starting from the Navier-Stokes equations is presented in [81, 82, 116] and results in the same equations shown above. It should also be noted that many of the linearizations used here can be successfully relaxed, but results in increasing the computational costs to solve the equations.

Numerical Implementation: ParAcousti

Equation (3.15) is solved through the finite-difference method and is second-order accurate in time and fourth-order accurate in space [94]. A regular, Cartesian grid defines the numerical modeling domain. For the finite-difference solution, the velocity pressure equations may be rewritten in a discretized form and shown as follows in equations 3.16a and 3.16b.

$$\frac{\delta \mathbf{v}_i(\mathbf{x}, t)}{\delta t} + \frac{1}{\rho(\mathbf{x})} \left[\frac{\delta p(\mathbf{x}, t)}{\delta \mathbf{x}_i} \right] = \frac{1}{\rho(\mathbf{x})} \left[\mathbf{f}_i(\mathbf{x}, t) + \frac{\delta \mathbf{m}_{ij}^a(\mathbf{x}, t)}{\delta x_j} \right] \quad (3.16a)$$

$$\frac{\delta p(\mathbf{x}, t)}{\delta t} + \kappa(\mathbf{x}) \left[\frac{\delta \mathbf{v}_i(\mathbf{x}, t)}{\delta x_i} \right] = -\frac{1}{3} \frac{\delta \mathbf{m}_{ii}^s(\mathbf{x}, t)}{\delta t} \quad (3.16b)$$

For the above equations, $\mathbf{v}(\mathbf{x}, t)$ and $p(\mathbf{x}, t)$ are the dependent variables of the particle velocity and pressure perturbations, respectively, $\rho(\mathbf{x})$ is the material density, and $\kappa(\mathbf{x})$ is the material bulk modulus. Any repeated indices indicate a summation. The right hand side of the equations are the body source terms; $\mathbf{F}_i(\mathbf{x}, t)$ is the force density vector, $m_{ij}^a(\mathbf{x}, t)$ is the anti-symmetric portion of the moment-density tensor, $\mathbf{m}_{ii}^s(\mathbf{x}, t)$ is the trace of the symmetric portion of the moment density tensor. The symmetric and anti-symmetric portions are equivalent to the isometric and deviatoric portions of the moment density tensor, respectively. The moment tensor is a 3 X 3 tensor that describes the actions of various combinations of force couples at a point in space. The isotropic portion of the source is proportional to the trace of the moment tensor and represents a source of pressure. Combining these terms allows for construction of fairly complex sources. Outside the source region, body source terms are zero as the background medium is assumed to be stationary. Both density and bulk modulus are a function of space, but not of time, which means that for a particular simulation, those values are set for the model domain.

Figure 3.1 shows one cell of the domain with a size of $dx \times dy \times dz$ and utilizes a staggered grid for storage of the domain variables. The eight corner nodes of this cell contain medium densities, sound speed, and the pressure-dependent variables. The three components of particle velocities reside on each of the twelve edges of the cell. The time-step is constant and velocity and pressure are updated on the half-integer and integer time steps, respectively. The staggered grid and solution-step removes spurious oscillations within the solution. At locations near large gradients in medium parameters, such as at the water-air and water-earth interfaces, a second-order spatial accuracy is used to preserve numerical stability. Due to the nature of a finite difference grid, the water-sediment layer interface (bathymetry)

of the domain is not continuously smooth but rather steps at grid points. However, with the small grid size dictated by the highest contributing frequency the interactions at this interface are captured well. ParAcousti uses a massively parallel design and can be scaled nearly linearly across hundreds of cores [9, 93].

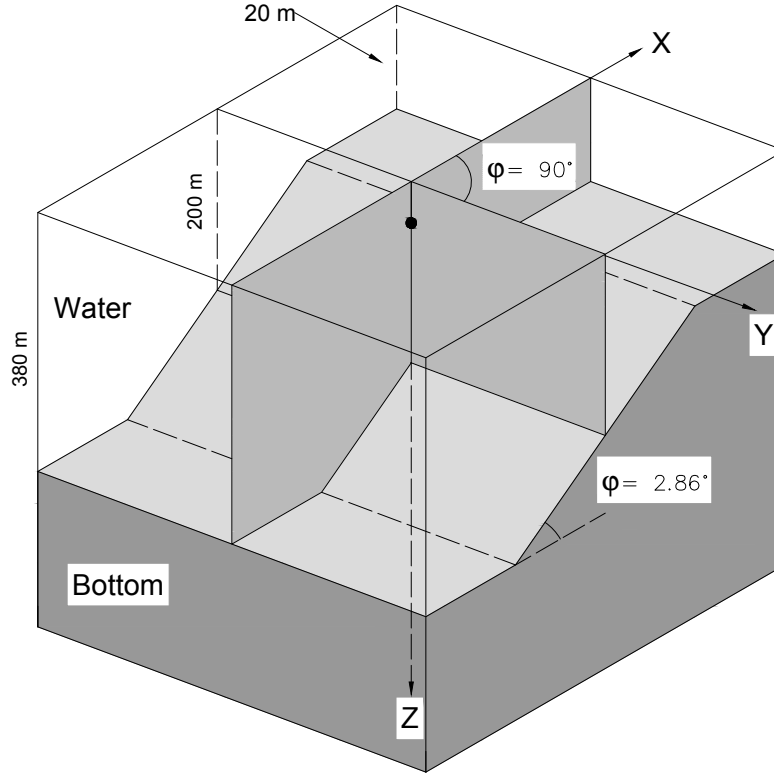


Figure 3.1: The computational domain is represented by a 3D uniformly spaced grid of nodes indicated by the black dots. The arrangement of dependent variables and medium parameters for one cell of the standard staggered grid of nodes is shown and may be extrapolated out to the domain size of interest.

Inputs into ParAcousti are: 1) the domain model with medium properties in all dimensions, 2) the source location(s), source type and strength, and 3) the desired outputs. The model domain consists of a gridded representation of the medium parameters defined on a 3D rectangular grid. The size of the domain depends upon the region(s) of interest

and can encompass water, earth, and air domains, but as shear waves are not included, each domain is treated as a idealized fluid. Within the model domain, the minimum grid point values with respect to each direction is determined as the starting counter. That means that buffer zones may be built into any dimension within the domain to handle any additional instabilities that may occur. Figure 3.2 shows the general progression for building a model to run within ParAcousti. To obtain the desired level of accuracy, a minimum of 10 grid points per desired source-wavelength are required. Appropriate values for grid spacing and time step are calculated as $dx, dy, dz = \frac{\min(c)}{10 \cdot \max(\omega)}$ and $dt = \frac{dx}{\max(c)} \frac{1}{2.04}$ where the 10 accounts for the number of grid points required. The Courant–Friedrichs–Lewy stability condition can be written as a constant times $dx/\max$ velocity. The constant ($1/2.04$ here) is dependent on the precise form of the discretized equations. In this case it is related to the sum of the finite difference coefficients which were selected to maximize the stability of the solution. When creating a model domain of interest, the 2D model is created in the same process as the 3D other than the third dimension is truncated to a minimal size. The data is omitted from recorded results and is maintained as a boundary condition to reduce any additional or false reflections of the sound source off the boundary conditions.

Environmental parameters are part of the earth model as referenced in Figure 3.2 and may be broken into the densities involved to appropriately describe the environment and any changes in medium. For example, a sediment layer has a higher density than that of the water column. Secondly, the sound speed of the medium must also be defined. Sound speeds and densities for various mediums are often tabulated and available for reference. Within the water column, sound speed and density are related to the local static pressure, salinity, and temperature. If this data is available for a location, the sound speed may be calculated using equation 3.17 [55].

$$c = 1449.2 + 4.6T - 0.055T^2 + 0.00029T^3 + (1.34 - 0.01T)(S - 35) + 0.016z \quad (3.17)$$

where sound speed in m/s , T is temperature in $^{\circ}$, S is salinity in parts per thousand, and z is depth in m for the free surface. For ocean systems it is important to remember that temperature and salinity vary greatly throughout the year as well as may occur in layers through the water column. All of these parameters are also a function of geography. Sound speed has the greatest variability near the surface of the water, which will vary daily depending on the weather, time of day, and time of year. In shallow water systems, this effect can change the simulation significantly and should be considered.

Sources may be included at any grid point within the model domain and can be included as a explosive source, a force source, or a delta function. The actual parameters of the source function are generated by the user and included as a function of amplitude (Pa) and time. Another input file contains a description of the output recording geometry, for example the types and positions of acoustic energy receivers, and the location and parameters associated with the sound sources. A receiver is defined as any singular location within the model domain where the requested output data is collected in time. Calculated data are of three types: 1) traces, or time-series of particle velocities or pressure at designated receiver locations in the 3D grid; 2) slices, or 2D pictures of time-evolving acoustic wavefields; and 3) 3D wavefield volumes. Slices must be requested at particular 2D cross sections and location with reference to the 3D domain. Net CDF files are used as the data structure for both input and output files [93], but the software that is used to create them is up to the user. Matlab was used for this project.

Boundary Conditions

In order to simulate an unbounded domain, an absorbing boundary condition is imposed on the extents of the 3D grid in order to suppress reflected energy. The convolutional perfectly matched layer (CPML) is utilized and acts as an energy absorber and reduces the probability of reflected energy that would not normally exist in a real environment where the

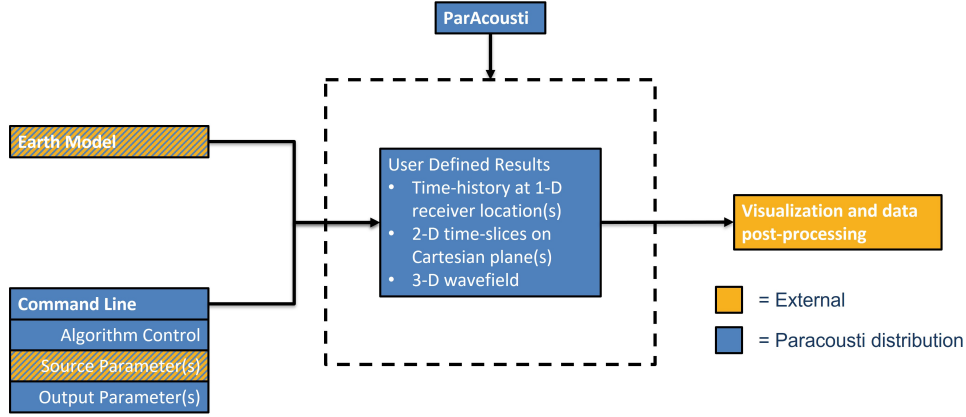


Figure 3.2: The work flow specific to ParAcousti. The earth model is created separately to represent the environmental conditions while a series of command line prompts written in linux describe the boundary conditions, source parameters, and data output. All data output is then post-processed separately in order to fully analyze the created data.

source could continue to propagate outward indefinitely [21, 22, 60]. The formulation results in a negligible amount of energy being reflected backward into the domain. This occurs for waves which enter the boundary of the model domain from the sound source with a large angle of grazing incidence. To combat this problem, a boundary area is created on all sides of the domain area of interest which is equal to a minimum of 10 times the size of the grid cell, which is the length of the shortest wavelength that can be simulated. The CPML dampens the wavefield in the direction perpendicular to the direction of the domain boundary and not any motion occurring parallel. If interference waves develop and propagate in the parallel direction to the domain boundary, instabilities may occur within the boundary condition, which will cause the finite difference solution to collapse. This is heightened for anisotropic media [60]. The boundary area helps to confine any interference waves to the area outside of the model domain of interest until they dissipate. When running problems for 2D systems, it was discovered that the third truncated dimension had to be approximately 100 times the size of the grid cell, at a minimum, to reduce instabilities in the problem.

CPMLs work by utilizing and updating a memory variable that is applied to a value

of interest within the computation. Memory variables are calculated and applied in each of the x , y , and z directions for each spatial derivative within the boundary condition for which the CPML is applied. The standard equations for the updated spatial derivative, $\delta_{\tilde{x}}$, and memory variable, Ψ , are shown below in equations 3.18a and 3.18b for the x direction, respectively. Similar equations would account for the other two directions [60].

$$\delta_{\tilde{x}} = \frac{1}{\kappa_x} \delta_x + \Psi_x \quad (3.18a)$$

$$\Psi_x^n = b_x \Psi^{(n-1)_x} + a_x (\delta_x)^{(n+\frac{1}{2})} \quad (3.18b)$$

For these equations, κ_x , a_x , and b_x are dampening variables dependent on a predetermined dampening profile, n is the step number correlating to the position within the dampening field on the domain grid, δ_x is the original spatial derivative, and $\delta_{\tilde{x}}$ is the updated spatial derivative. Many of the dampening variables are calculated from real, predetermined values that must fit a range in order to increase stability. For ParAcousti, κ is set to 1. Pressure-free surfaces can be imposed at the water-air boundary to act as perfect reflectors of the energy. Second order accuracy is not required at the surface due to the pressure-free condition at that location. Due to the large gradient in properties, a negligible amount of energy is removed from the system. Although not strictly true at these interfaces, it is a very good approximation. An alternative method to addressing these interfaces is to assign air or vacuum properties beyond the water domain. This latter approach must be used when there is a variation in topography or water surface height, e.g. surface waves, as the pressure-free surface presently requires the both the air- earth and air-water interface to be planar.

Delta Source Function

The temporal and spatial discretization allows ParAcousti to simultaneously model multiple, multi-frequency monopole and directional sources. This is advantageous for modeling an array of MHK devices, as multiple simulations are not required for each device. A source within the ParAcousti formulation is defined as a force or force-couple, instead of using the direct pressure values. The force or force-couple is the pressure values of a source integrated over time once for a force and twice for a force-couple. A force-couple source is representative of an explosive, or monopole, that propagates equally well in all directions. A force source propagates along a single or set of orthogonal axes.

An alternative to explicitly defining the source time function is to solve the domain with a delta-source time-function. This adds a single infinite spike of energy at a singular point in time where the energy under the curve is equal to 1 and may be placed at a time of the user's choosing. For most models, a spike at time zero is sufficient. Trace results may be convolved with any source profile after the fact to simulate multiple solution profiles based on one set of data. As noted earlier, grid spacings are defined by the highest frequency of interest for a source profile. For a delta function run, this constraint still applies. The model domain must be created with the grid spacings calculated for the largest value of frequency that may be introduced when the delta is convolved with a particular source function. Due to the limitations of convolutions, if multiple sources are run in a singular model run, they must each have the same profile. 2D slice outputs can not be convolved. However, a model run may be run for a singular source, convolved for a range of source profiles and then summed with the data produced by any number of separate runs with different source locations to simulate an array of sources in one environment.

For an example of the delta function, a 2D simulation was run for a bay off the coast of Washington called Sequim Bay. This particular model was run with a delta function for a source representation and data was collected in time for a location 1 km from the source.

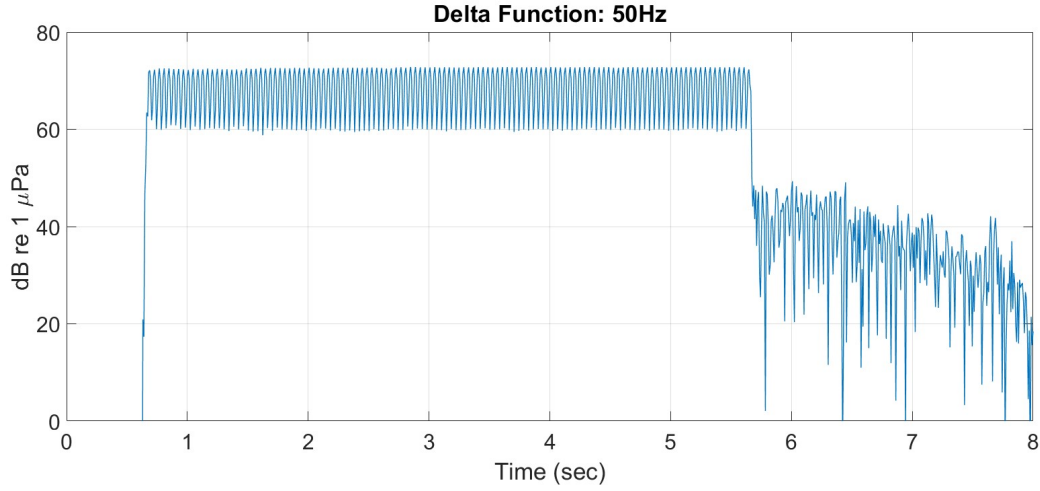


Figure 3.3: The pressure data in time for a location 1 km away from a delta-function sound source with an amplitude of 50 Hz convolved onto the data for a 2D model of Sequim Bay, WA.

To demonstrate the use of the delta function, the output was convolved for both a 50 and 100 Hz signal and compared against one another and to the output from a model run where the signal was built into the inputs from the outset for 50 and 100 Hz, respectively. The signal is for a 5 second pulse which then drops to zero. The sound speed of the model is set to 1499 m/s. The data from the model where the data was convolved matches identically to the data from the model run with the initial conditions for the source parameter built in. Based on the math, this should always be true as long as the cell size for the domain of interest is sized such that it is appropriate for the highest frequency that will be modeled or convolved on the system. If the data is convolved for a frequency larger than the grid cell size is designed for, then the model is not appropriately calculating the travel of the wave as the frequency is higher than the system is designed for. As the frequency increases, the wave length decreases. If not enough grid cells are present over the course of a single wave length, the propagation of that wave will not be accurate. The runs for the convolved 50 and 100 Hz data are shown below in Figures 3.3 and 3.4.

Note that for both of the examples, there is a delay before any sound is recorded.

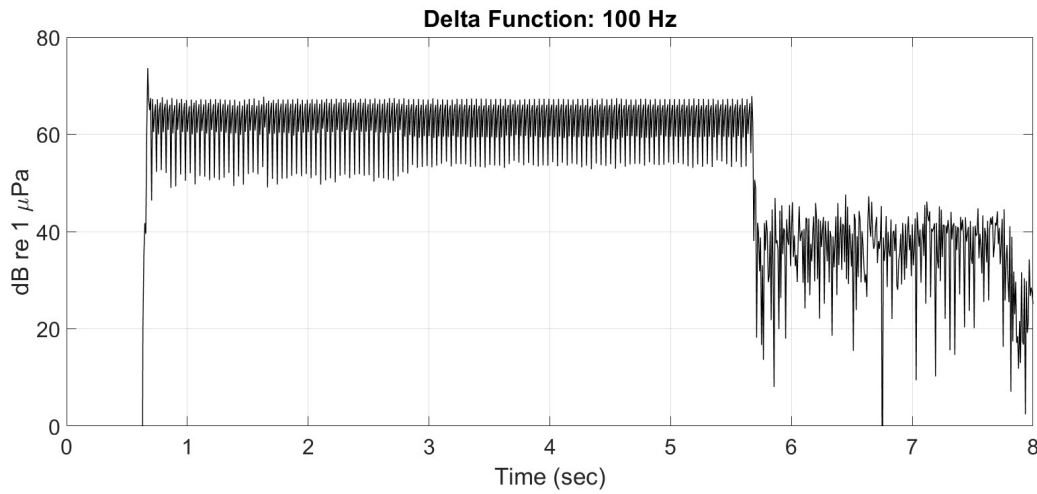


Figure 3.4: The pressure data in time for a location 1 km away from a delta-function sound source with an amplitude of 100 Hz convolved onto the data for a 2D model of Sequim Bay, WA.

That is because the sound is emitted at a source 1 km away and has to travel that distance before the data is received at this location and recorded over time. The delay in time is 0.667 seconds. That is consistent with the set sound speed and considering that the location selected is within the water column at a depth of 3 m, so the sound wave has traveled in a consistent medium. Also consider that that the frequency of Figure 3.3 is half of Figure 3.4, which can be seen in the spacing of the individual waves. The 100 Hz example imparts more energy initially which is why there is a spike in the value at the start of the recording. However, the higher the frequency, the more interactions that the wave form has with the surrounding environment and the faster the wave form loses energy. Every interaction a wave has as it propagates through a set medium translates to a loss in energy. Lower frequency waves travel for longer distances as the wave length is longer and has fewer interactions with the surrounding environment. Note that the examples will differ as Sequim Bay has a set bathymetry and not a flat bottom. A detailed explanation of the model runs conducted for Sequim Bay, WA is the subject of chapter 5.

Model Considerations

ParAcousti allows for many types of adjustments for a particular model to better fit the domain of interest. Some of those considerations are the stability constants and memory constant values associated with the CPML and have suggested values that occasionally are changed via trial and error to increase the stability of a model run. One item that has not been discussed is how data is recorded and then interpolated on to a grid based on the source parameters of interest for a model. ParAcousti permits a finite number of complex sources and spatially varying sound speeds, bathymetry, and bed composition. Many measurements, e.g. bathymetry and soil properties, and temperatures are taken at deployment sites with more than 100 m between data point locations. With the bulk of their sound energy below 1.5 kHz, MHK devices will require grid cells on the order of 0.1-1 *m*, the model domain measurements must be interpolated onto a much smaller grid. The solution to the propagated sound will then be dependent upon how that those properties are interpolated. Input files for ParAcousti were prepared using MATLAB, which has a number of interpolation functions built in, such as linear, nearest-neighbor, and cubic Hermite splines. These interpolation functions were tested on a real world bathymetry to introduce complexities into the model domain to exacerbate any differences in output that may occur from this change in interpolation methods. Uncertainties within the resulting broadband sound pressure levels for a singular source were calculated for the three previously listed interpolation types as applied to a realistic bathymetry off of Newport, OR with a constant sound speed for both the water and soil. The results from this particular project were used to inform the set up of all further interpolations required for problems requiring a real world bathymetry. Newport, OR was chosen for this test as Newport, OR, is set as a testing site for WEC devices monitored by SNL called PacWave.

Bathymetric data for the model was collected for approximately 24.2 miles of coast line and has depth measurements out to sea for approximately 8.19 miles. Bathymetric

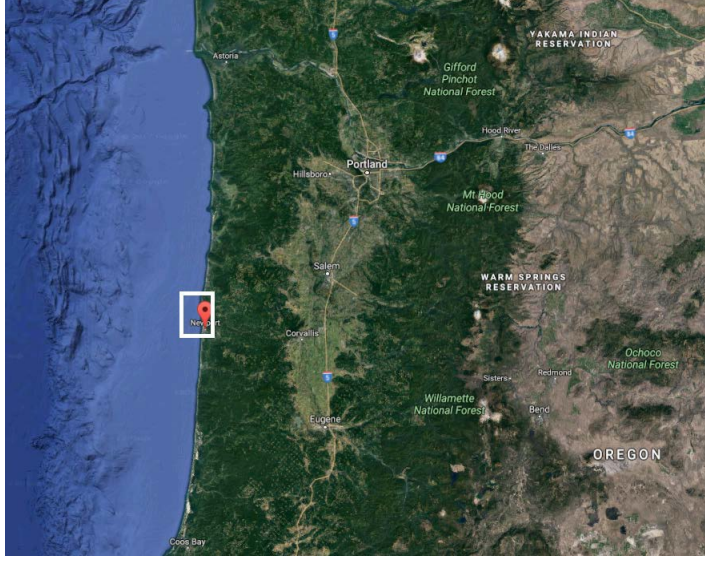


Figure 3.5: Newport, OR is located south west of Portland, OR on the coast. It is near the Pacific Marine Energy Center’s North and the future South Energy Test Sites (NETS and SETS). The size and location of the collected bathymetric data is indicated by the white rectangle on the map.

data was procured from the World Ocean Atlas database from the National Oceanic and Atmospheric Administration [26] and the data required to calculate density and sound speed were simulated in HyCOM by Integral. Figures 3.5 and 3.6 demonstrate the location of both the section of coast that was used for the model and the selected 2D cross section that was selected for the bathymetry of the simulations based on the area. Collected data points were available approximately every 40 m, meaning that for even a low frequency, a large amount of interpolation would be required on the bathymetry to fit the size of grid required for the model. A 2-D cross section of the continental shelf was chosen for increased variability in the topography to potentially highlight differences in results. Each simulation differs by the particular interpolation scheme used. The simulated cross section is shown in Figure 3.7.

A single 100 Hz monopole source with an amplitude of 1 Pa located at a depth of 20 m was modeled out to 3600 m from the shore. Sound speeds were set at 1,500 m/s and 1,800

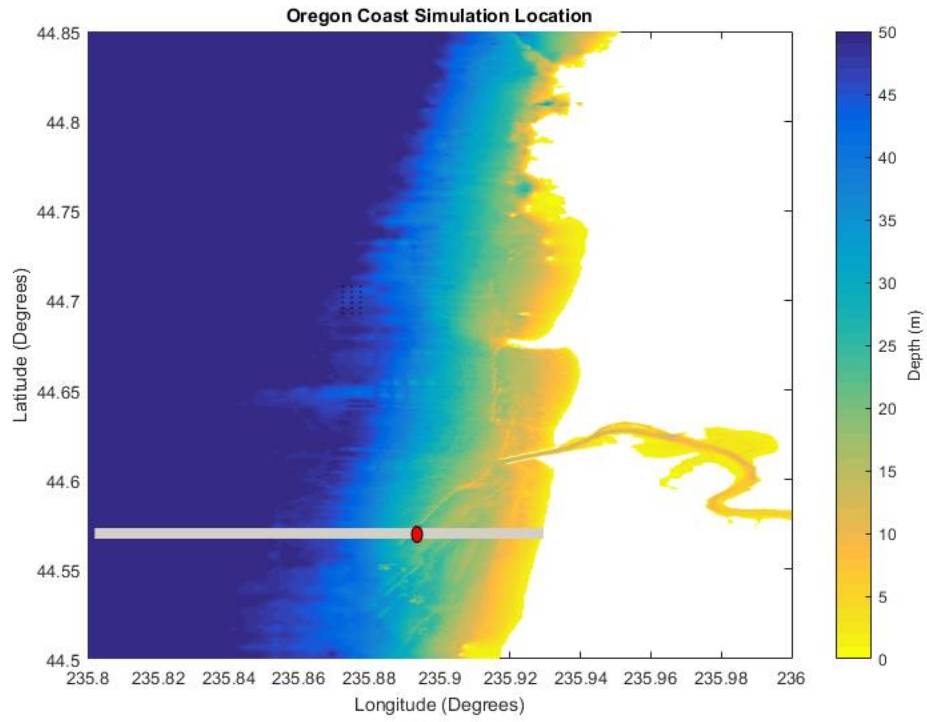


Figure 3.6: Bathymetric data collected for the coastline near Newport, OR. The transect shown by the white line near the 44.57° latitude is used for these models. The source location is marked with a red circle.

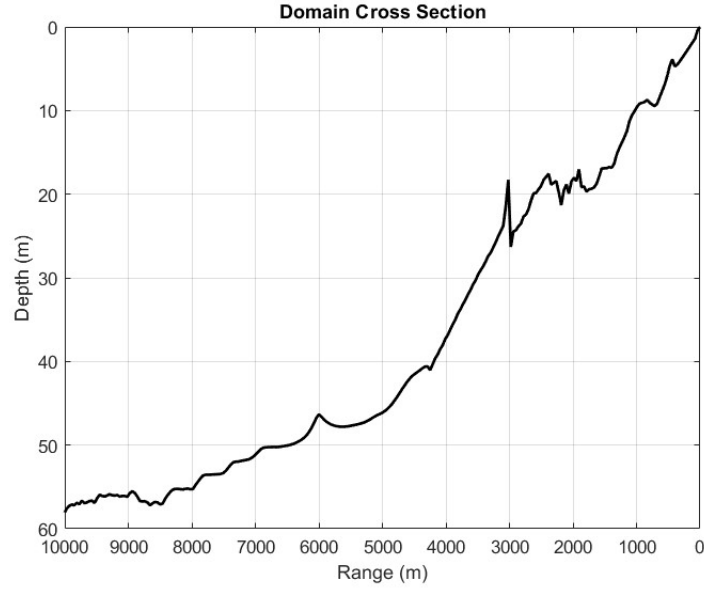


Figure 3.7: The 2D transect of the model domain.

m/s for the upper water layer extending to a maximum of 55 m in depth and the bottom sedimentary layer, respectively. Density was set at $1,000 \text{ kg/m}^3$ and $1,800 \text{ kg/m}^3$ for the two layers, respectively, as well. Bathymetric data was required to be presented at steps of 1.5 m and a time step of 0.0002 s for this source frequency. Bathymetric data was interpolated on to the grid spacing by three interpolation methods: nearest neighbor, linear, and a piecewise cubic Hermite interpolating polynomial (PCHIP). An example of the PCHIP interpolation is shown in Figure 3.8.

Sound pressure levels (SPLs) were calculated for each simulation and compared against one another. Averaged SPL data is shown in Figure 3.9. Results from all three simulations are similar in that absorption can be seen as the sound wave passes into the soil layer of the model. Additionally, all three show the interactions between pressure waves as the sound source propagates away from the source. However, the nearest neighbor data shows fewer, less distinct pressure wave interactions as compared to the other two models. Pressure waves blur into one another. SPL data was averaged over the water depth for each simulation re 1

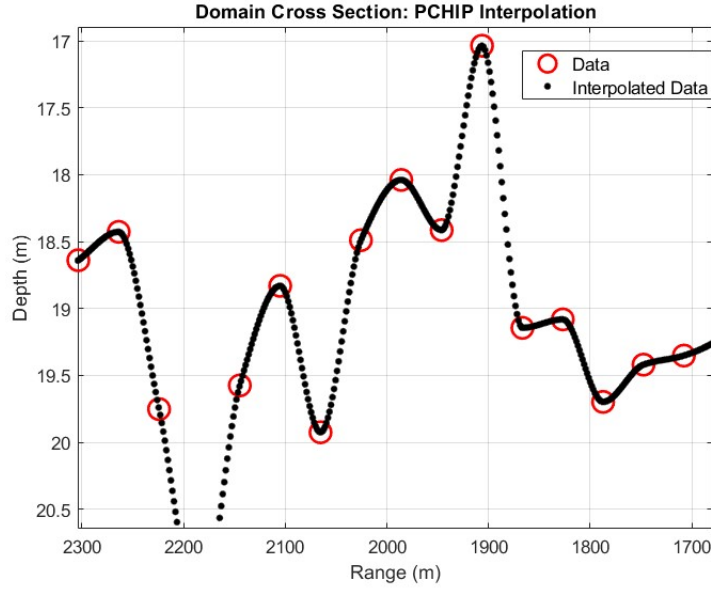


Figure 3.8: A close up of a PCHIP interpolation method applied to the cross section data. Red points are the original data points, black are the interpolated values.

μPa and is shown in Figures 3.10 and 3.11. Depth averaged SPL calculations were completed for the data associated with a time greater than 4 seconds, which is when the sound wave propagated to the edge of the model boundary. The depth averaged SPL plots demonstrate that there is a noticeable difference between runs especially in areas where the topography changes elevation over a short distance. The wavelength of the 100 Hz source is 15 m and therefore approximately 3 wavelengths pass between each collected bathymetric data point. As a source's frequency increases, so does the number of times that frequency has to interact with an interpolated boundary.

A difference was calculated with respect to each SPL value in both data sets. The mean of these values was calculated to find the overall mean difference. The maximums were calculated for both the entire data set of differences and the mean values. SPL data calculated after 4 s when the sound wave have intersected the boundaries of the simulation was used. Results show that the difference between the nearest neighbor and each of the

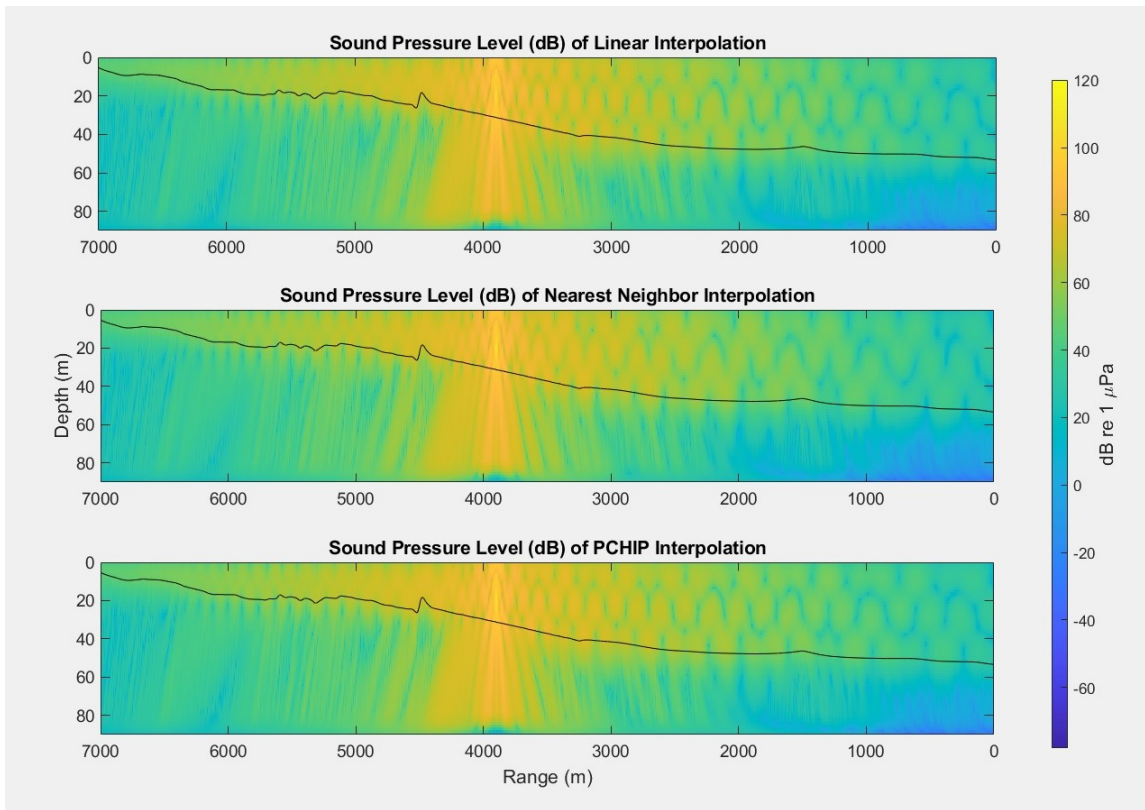


Figure 3.9: SPL data for the linear, nearest neighbor, PCHIP interpolation method in dB.

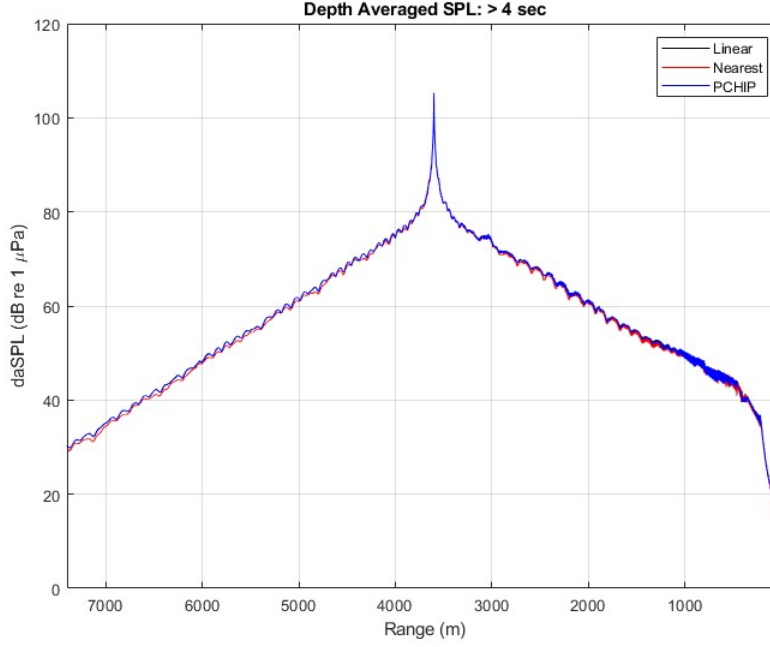


Figure 3.10: Depth averaged SPL for a single source, 100 Hz.

other two methods is the greatest. However, the difference between the linear and the PCHIP methods are fairly similar. This suggests that the linear and PCHIP are the preferred methods for interpolating between data points. The overall maximum differences are high due to being located where there are large spikes in SPL values from rapid changes in topography and the interactions between sound waves. The overall mean, the maximum of the mean, and the overall maximum values are shown below in table 3.1.

Changes in data collection and model setup have a large influence on the overall SPL in a domain. Results indicate that there can be significant differences in model error due to the particular interpolation mechanism used; however, model setup time may also increase in order to interpolate on the appropriate input files. As the frequency of a source increases, the amount of data being interpolated and further calculated based on those interpolated values also increases. Each of the three interpolation methods may provide appropriate trends, but some lack the accuracy required for a particular domain. This effect will become more

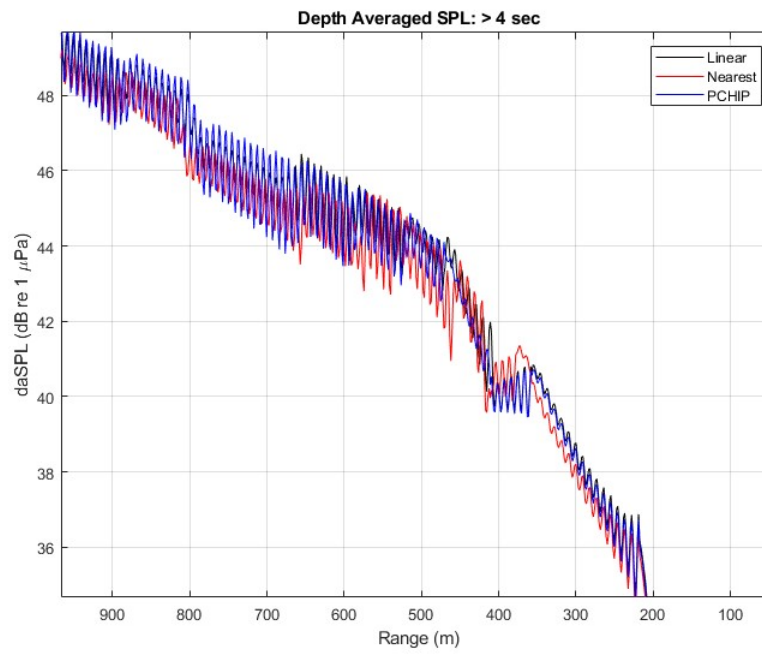


Figure 3.11: A close up view of the depth averaged SPL for a single source. The data is shown as the sound waves propagate toward shore.

Interpolation Method Comparison			
	Overall Mean (dB)	Max Mean Difference (dB)	Overall Max (dB)
Nearest to Linear	2.653	3.9536	35.7305
Nearest to PCHIP	2.4522	3.8222	40.5592
Linear to PCHIP	0.9483	1.5183	38.7914

Table 3.1: Calculated mean, maximum of mean values, and total maximum difference between the resulting SPL for each simulation in dB re 1 μ Pa.

apparent as frequency increases. While the general trends between each of the interpolation methods are the same, results show that there is a significant difference between SPL from the nearest neighbor interpolation and the other two methods. The linear and the PCHIP methods are relatively well matched. This suggests that the linear and PCHIP provide a more consistent means to interpolate data, which becomes important as the source frequency and the distance between measured data increase. The PCHIP compares better to the nearest neighbor than the linear interpolation, but the discrepancy in mean differences is small comparatively. This may be particular to this data set.

Nearest neighbor sets the value of an interpolated point to the value of the nearest data point. Linear fits a different linear polynomial between each pair of data points for curves, or between sets of three points for surfaces. PCHIP preserves monotonicity and the shape of the data and applies a second order polynomial to interpolate between data points. PCHIP is then the only method of the three which allows for a continuous first derivative and a likely continuous second derivative. Real world bathymetry data sets may include data points that represent a variable or dramatic change in slope. An interpolation method which allows for a continuous representation of slope would minimize discontinuities within the bathymetric data set and give a more complete representation of the bottom of an environment of interest. Additionally, PCHIP would be less likely to smooth over any discontinuities on the sea floor.

Nearest neighbor could create discontinuities or artifacts within the bathymetry that are not actually present but are indicated based on one associated data point. PCHIP has been considered the standard for all further work where an interpolation of recorded bathymetry onto a set Cartesian grid was required to build a model.

ParAcousti also allows for attenuation to be added to the system or neglected completely. As sound propagates through a medium such as water, some of the acoustic energy is continuously absorbed by the surrounding environment. Sound is scattered by contact with inhomogeneities which results in decay with range. Absorption and scattering effects are combined into attenuation. For sea water, attenuation can be divided into four parts. The first deals with very low frequencies and is poorly understood and not modeled at this time. The other three parts are contributions due to chemical reactions of boric acid and magnesium sulfate, and the shear and bulk viscosity associated with salt water. The velocity-pressure equations technically only account for geometric spreading, reflection, refraction, and wavefield scattering of sound. So for a full description of the sound field, attenuation must be added into the model.

A standard linear solid from the seismological literature is used in order to simulate attenuation in ParAcousti. A spring and dashpot system is used to represent the standard linear solid or fluid system, where the inviscid fluid (spring) is retained and the compressional components (dashpot) account for attenuation. This is represented by a delta function followed by a one-sided decaying exponential defining a rate of relaxation function. The rate-of-relaxation functions are defined by two parameters, an amplitude scalar and a relaxation frequency for any number of defined rate-of-relaxation functions, set at two. These functions are the adapted version of the velocity-pressure equations with attenuation built in. The parameters are a function of 3D space. Attenuation was validated separately by SNL for frequencies varying from 10 Hz to 10 kHz. It should be noted that attenuation is dependent on frequency. Higher frequency values attenuate at a much faster rate than lower frequency

wave forms. The use of attenuation was considered negligible for the frequencies modeled within this body of work and was not included in any of the simulations.

CHAPTER 4: VALIDATION EFFORTS

In the development of new models and tools, proving that they will yield accurate results requires efforts to validate the system by comparing the output to expected results. These standardized solutions, or accepted results, can be from 1) analytic solutions, 2) other accepted and trusted models, and 3) recorded measurements. This chapter focuses on the validation efforts required to compare the model with the first two, while Chapter 5 compares between recorded data or measurements made in Sequim Bay, WA. As mentioned previously, this work is unique in that the solution for ParAcousti was developed based on TDAAPS. TDAAPS in turn was derived to model seismic waves through a moving medium and not an underwater system. While TDAAPS has been validated for geologic models, the modified solution and subsequent program, ParAcousti, had not been applied to or validated for any underwater acoustic propagation system or wave form.

ParAcousti was compared to four traditional underwater sound propagation problems suggested by [55]. The problems are 1) a single Gaussian pulse within a unbounded domain, 2) a single continuous source within an ideal waveguide, 3) a single continuous source within a Pekeris waveguide, and 4) a single continuous source within a specified 3D sloping bed. All four of these problems are defined within literature as a standard, and details from each problem were extracted directly from [55, 84, 109]. To further demonstrate the capabilities of ParAcousti, a fifth example is presented for a group of three sources placed off the coast of Newport, OR. This location is a new WEC testing site and was ideal for a first case study of a real world environment. The idea for this example was to demonstrate how ParAcousti handled multiple sources in order to determine if a study to understand variability within an array of sources was viable. Chapter 6 further discusses an uncertainty study applied to several case different environments as case studies.

Model Setup

ParAcousti is used to calculate the propagated sound of four traditional problems and then extended to investigate the effect of an array of three MHK sources in a simple Pekeris wave-guide. All sources for these examples are based on a monopole source time function, with a general profile of:

$$S(t) = \sum \frac{A}{4\pi^2\omega^2} (1 - \cos(2\pi\omega t)) \quad (4.1)$$

where ω is the frequency of the source (Hz), t is the present simulation time (s), and A is the desired pressure amplitude (Pa). The division by $4\pi^2\omega^2$ accounts for the conversion of the source time function into a pressure through a double derivative. The unity offset for the cosine ensures smooth derivatives of the source time function at $t = 0$ s. The profile is summed over all relevant frequencies. Monopole source profiles emit in all directions equally and simultaneously, meaning that the sound energy being emitted by the source travels out in every direction through the wave field. Source functions may also be created to model dipole and quadrupole sources as well. Dipole sources emit in two distinct hemispheres in a 3D space while quadrupole sources emit in four distinct quadrants. Most sound sources are not identical front to back. This would be the case for most MHK devices which are developed to allow the flow of water or movement of a wave to generate power. Horizontal axis turbines in particular are set to turn a turbine blade as water flows through the turbine. This creates a sound profile that is distinctly different for the front of the turbine as compared to the back. This would be an example of a dipole source. All the examples from literature were modeled for a monopole source, so these models were developed to match those conditions. Monopole sources are also the least complex to model of the three and generally provide an accurate view of the sound field. Figure 4.1 demonstrates the layout of each of the described

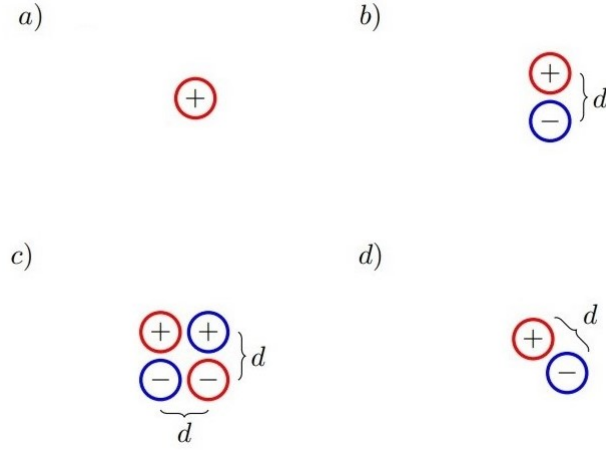


Figure 4.1: Schematic of the sources available in underwater acoustic propagation modeling: a) monopole; b) dipole; c) quadrupole; d) 45° inclined dipole [85].

source types including a dipole that is emitting at a 45° angle from the x-axis. The individual fields are indicated with a positive or negative to differentiate that each part of the source is unique.

In addition, there are two simple analytic, range dependent solutions to approximate how sound levels decrease as sound propagates away from a source. The first is spherical spreading, which describes the decrease in sound level as a sound wave propagates away from a source uniformly in all directions, as a sphere. This occurs for a sound source at mid-depth in a water column, where the sound wave does not contact any boundaries or change in medium. The distance of 1 m is assumed to be that of the acoustic source level where energy losses are negligible and provides an excellent reference distance. Intensity is the average amount of sound energy transmitted per unit time through a unit area in a specified direction. The intensity decreases as the inverse square of the range for spherical spreading. The amount by which the intensity decreases relative to its level at the source is

called the transmission loss. Transmission loss (TL) described in decibels (dB) is expressed in equation 4.2.

$$TL = 20 \log_{10}(r_s) \quad (4.2)$$

where r_s is the radius distance in m from the sound source. The further down range from the source, the more energy is dissipated and the larger the value of TL grows. The sound pressure at any distance may be calculated by taking the SPL of the sound source and subtracting the value of TL at any distance. However, sound does not propagate uniformly in all directions from a source in a water column perpetually. At some range, the sound wave will interact with some change in medium or boundary condition, like the sea floor or water surface. The second approximation for spreading loss in a medium with upper and lower boundaries can be obtained by assuming that the sound is distributed uniformly over the surface of a cylinder having a radius equal to the range r and a height H equal to the depth of the water column. For a background medium with no sound absorption, cylindrical TL, is calculated by equation 4.3;

$$TL = 10 \log_{10}(r) \quad (4.3)$$

Both spherical and cylindrical spreading are only rough approximations to actual spreading losses occurring in a body of water such as the ocean. Typically in application, spherical spreading is used as an approximation to represent the TL loss that occurs until the radius distance is equal to a distance which interacts with a boundary condition. At that point, the equation transitions to cylindrical spreading. Neither type of spreading loss accounts for refraction, reflection, attenuation, or any changes in interactions due to the dependence in sound speed on depth or density. Even though they are strictly approximations, spherical and cylindrical spreading are often used to obtain an estimate of sound levels around a source without doing complex computer calculations and can provide a

conservative value for which to compare model simulation data to make sure that the sound data makes sense for a given problem.

Validation from Literature

The time required for the initial wave to propagate through the entire domain is calculated based on the slowest sound speed and the longest dimension of the domain. The solution time is generally doubled to ensure that any reflected sounds are able to appropriately propagate, and pressure recordings are collected for the total simulation time. Results are presented for the steady state portion of the model run, which occurs after 3 s for the first three validation cases. However, data may be collected or presented at any point specified by the modeler.

Both a local machine with a 3.0 GHz Intel Xeon E5-1620 processor and 32 GB of installed RAM and a high performance computing cluster with a total of 1080 2.0 GHz Intel Xeon E5-2650 CPUs (65 total nodes) and 64 GB of RAM per node were utilized for the following simulations. Run times for the array simulation at the end of this section were observed on the order of 6 hours and 1 hour, for the local machine with 4 cores and the cluster using 16 cores, respectively. The simulations had 91 million cells and 40 thousand preset time steps; each time step was set to 0.0002 s. Additionally, the time step input into the model does not indicate the time required to solve for each step. Anecdotal evidence on the cluster suggests a near-to linear scaling with the number of cores used. This suggests the workstation was not efficiently resourced for this model, but the time is provided as a reference and to demonstrate the ability to perform time-domain simulations without high-performance computing. The computational time and required resources for ParAcousti can be further improved by utilizing optimized finite difference coefficients. It has been demonstrated that, depending on the optimization scheme used and source profile, simulation time can be further reduced by up to a factor of 10. These performance gains, however, are

tied to the class of problem being solved and may result in inefficiencies and instabilities if applied generally. A two-dimensional, 100 m deep water column was used to simulate three well understood problems. The fourth problem had a linear, sloping bottom and so water depths differed based on location. The water column is defined as having a density of 1000 kg/m³ and sound speed of 1500 m/s.

Gaussian Pulse

The first problem modeled the force-couple as a Gaussian pulse in an unbounded domain; CPML boundary conditions were applied to all of the boundaries to allow for an infinite propagation of the source and no sediment layers were included. The energy from this source decays inversely to the square of the distance from the source and independent of the source frequency. The pressure becomes,

$$P(r, z, t) = \frac{\frac{\partial^2}{\partial t^2} S(t + \frac{r_s}{c})}{4\pi c^2 r_s}, \quad (4.4)$$

where S is the force-couple profile of the source, evaluated at a distance r_s from the source location, P is the pressure evaluated at a particular location and time, and c is the sound speed. Figure 4.2 shows the comparison between the analytic solution in Equation 4.4 and the calculated pressure as a function of time, 500 m from the source. The two solutions compare well and have a maximum root mean square deviation of 5.4E-07 Pa. As this is exceedingly close to zero, the solutions are similar. Solutions will deviate as the model domain increases in complexity as the Gaussian pulse is developed for only open bounded conditions without a sediment layer. This demonstrates strong evidence that ParAcousti can correctly model standard analytical and well defined solutions.

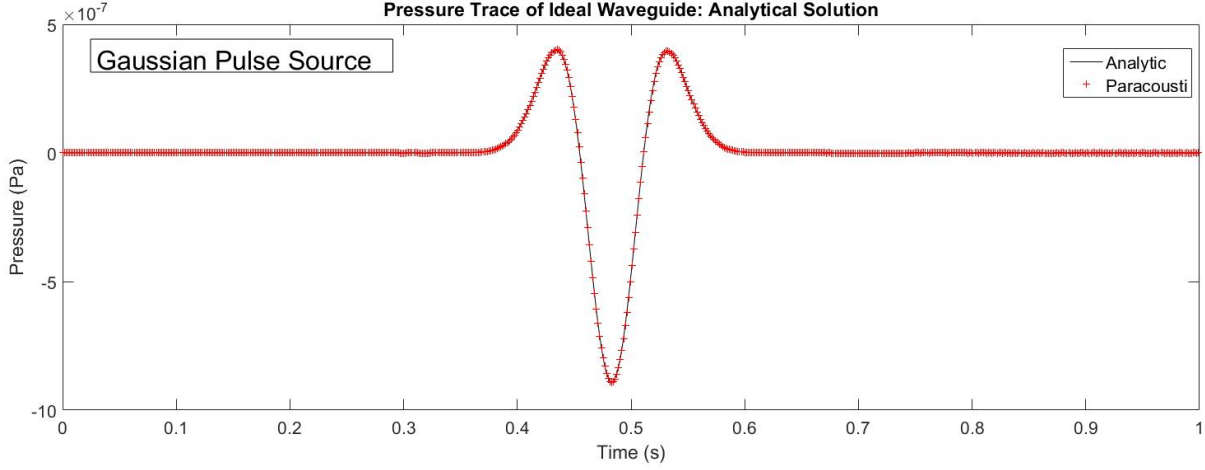


Figure 4.2: Comparison of ParAcousti solution of an unbounded field with spherical spreading and the analytical solution.

Ideal Wave-Guide

The second problem simulated is an ideal wave-guide by maintaining CPML conditions on the left and right extents of a 3 km domain, but constraining the top and bottom surfaces to a pressure-free condition. This reflects all of the energy from a continuous 20 Hz, 1 Pa re $1 \mu Pa$ source back into the domain at the top and bottom, but absorbs the energy leaving through the sides. The source was located at a depth of 36 m from the surface of the domain, which continues on to a depth of 100 m. Figure 4.3 shows a sound pressure level profile of the solution from 3 to 5 seconds. The 3 s mark is the conservative approximate point at which the wave reaches the end of the domain and the solution becomes steady. The pressure waves moving through the medium reflect off of the top and bottom surfaces without loss of energy. The pressure waves retain their structure as they travel away from the source, decaying as the waves are spread radially away from the source. Symmetry is lost because the source is not centered in the depth. The modal interference length is defined as $r^{-1/2}$ with the defined bounding condition [55]. An analytical, normal modes solution is available for an ideal case and the envelope function is defined as:

$$\psi(r, z, t) = -\frac{iS_\omega}{2D} \sum_{m=1}^{\infty} \sin(k_{zm}z_s) H_0^{(1)}(k_{rm}r), \quad (4.5)$$

where in the above equation, k_{zm} is defined as the vertical wave number, k_{rm} is the horizontal wavenumber, z_s is the depth to the source, and $H_0^{(1)}$ is the Hankel function with respect to the vertical wave number and the range.

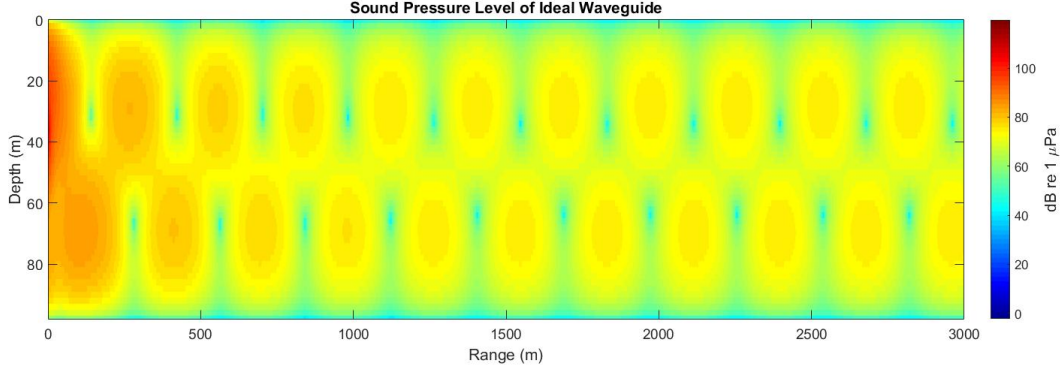


Figure 4.3: A sound pressure level profile of the ideal wave-guide with a single monopole source.

Additionally, the analytic solution for the ideal case is presented for depths of 36 and 46 m. The average root mean square (RMS) pressure deviation is 4.06E-04 Pa and 6.39E-04 Pa for 36 and 46 m depths, respectively, with a maximum value of 120 dB re 1 μPa re 1 m. Values are defined at a distance of one meter as the source function goes to infinity at a distance of 0 m from the source. The 1 m reference value is standard to acoustic propagation research. The deviation was calculated for all points along the entire range of the model domain. As pressure decreases as you move downrange from the sound source, this artificially reduce the average value of (RMS) pressure deviation. Deviations are provided in

Pa as SPLs, in dB, are calculated by referencing the pressure at any given location to that of a reference sound pressure, which varies given the medium you are working in. This reference scales the data as opposed to giving a direct comparison for the RMS that is presented when using pressure values.

Pekeris Wave-Guide

The third problem modifies the ideal wave-guide by introducing a sediment layer at the bottom of the water column [84, 91]. The sediment layer adds an additional 100 m depth to the domain and has a constant density and sound speed of 1800 kg/m³ and 1800 m/s, respectively. These are typical values for a sand. This water-earth interface permits energy to be removed from the water column as the sound wave propagates through the sediment and is clearly demonstrated in Figure 4.4. The sound pressure level is calculated from 3 to 6 seconds of the solution data, with the source still at a depth of 36 m and a frequency of 20 Hz. An approximate normal mode

$$\psi(r, z) \approx -\frac{iS_\omega}{2D} \sum_{m=1}^M a_m(k_{rm}) \sin(k_{zm}z) \sin(k_{zm}z_s) H_0^{(1)}(k_{rm}r), \quad (4.6)$$

where a_m is an added attenuation not present in Equation (4.5).

A comparison of the ParAcousti SPL data from the ideal and Pekeris wave-guides at depths of 36 and 46 m, respectively, is shown in Figure 4.5. These results match the analytic solutions, with the Pekeris data showing a longer modal interference length due to the second mode losing energy to the sediment layer at a higher rate than the first mode. As one mode continues to attenuate energy with range, modal interference is reduced and the other mode will control how the energy propagates [55]. Both the ideal and Pekeris cases show an initial loss of energy with the Pekeris decaying at an initially faster rate. The Pekeris case includes interactions caused by the sound propagating in different densities, with the density increasing at a depth of 100 m instead of forming a boundary as in the case of the

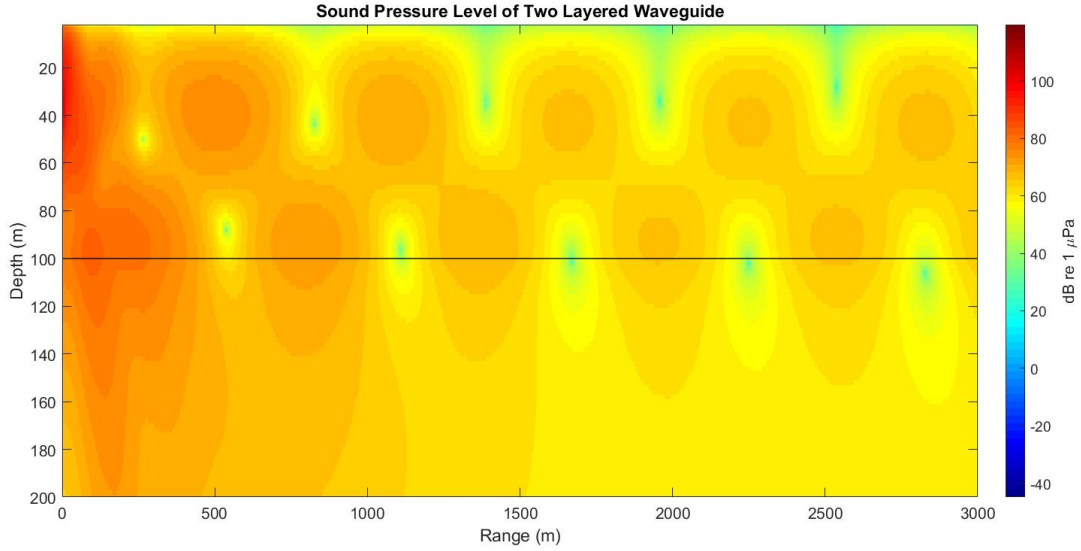


Figure 4.4: A sound pressure level profile of the Pekeris wave-guide with a single monopole source.

ideal waveguide. The density changes present in the Pekeris waveguide cause the sound waves to refract and have a larger wave spacing as compared to the ideal case. The lack of interactions and perfectly reflecting boundaries cause the ideal case to have a much lower energy loss associated with the length of the domain. This holds true for both depth profiles shown, with lower values in SPL and increased spacing of the sound waves for the Pekeris model as compared to the ideal case. Note that the 36 m line is consistent with the depth of the source. For all comparisons with respect to acoustic signals, peak values with the signal are considered. Often times noise within the data set presents in the low pressure values of the signal.

Values for both the Pekeris and Ideal cases were compared to the spherical analytic solution and a spherical transitioning to a cylindrical analytic solution at a radius of 36 m, which is the depth of the source. At 36 m, the outward propagating sphere would interact with the top boundary of the Pekeris model domain, causing the system to transition to a cylindrical spreading case. Values are defined in Figure 4.6. The both cases follow the

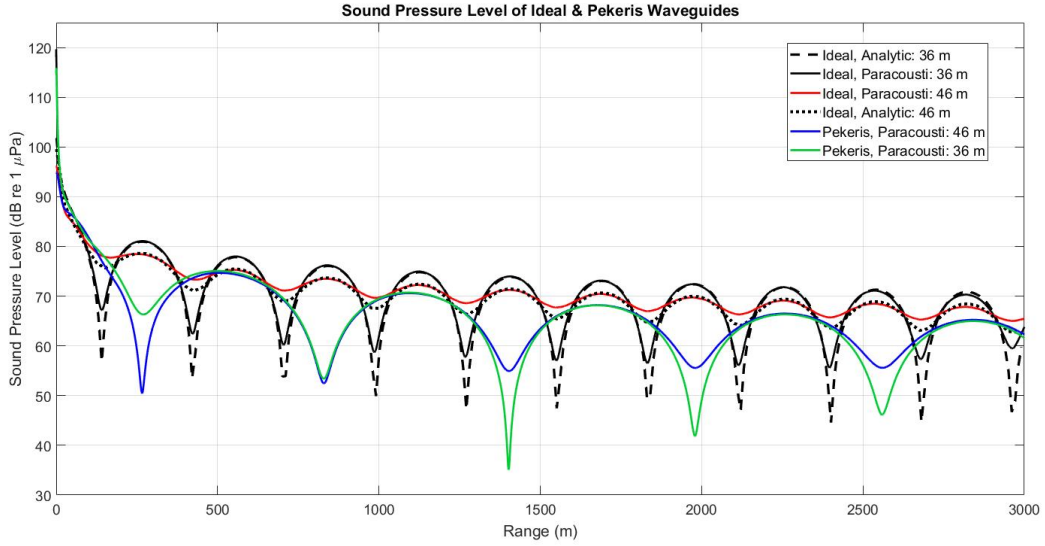


Figure 4.5: Comparison of a ParAcousti solution for a single monopole source propagating in both Pekeris and Ideal wave-guides, as well as the analytic solution for the ideal wave-guide, at 36 m and 46 m depth contours.

initial decrease in SPL with a better fit for the Ideal case; however, as the sound continues to propagate outward, the spherical/cylindrical spreading line follows the top of the Ideal values. The spherical case continues to drop energy at the previously defined logarithmic rate, with all peak values falling above the spherical spreading case. Spherical spreading typically is a conservative, lower value as it does not represent any energy being reflected back into an environment from changes in density. Both the spherical and cylindrical spreading equations or a combination of those equations do not include any density values at all. Both the Pekeris and Ideal model domains include particle interactions, changes in density, and boundary conditions, even if they are minimal. The Pekeris values remain lower than the spherical, cylindrical spreading case as the inclusion of a sediment layer further removes sound energy as sound waves move into the sediment layer, increasing the number of interactions between the propagating sound wave and the environment.

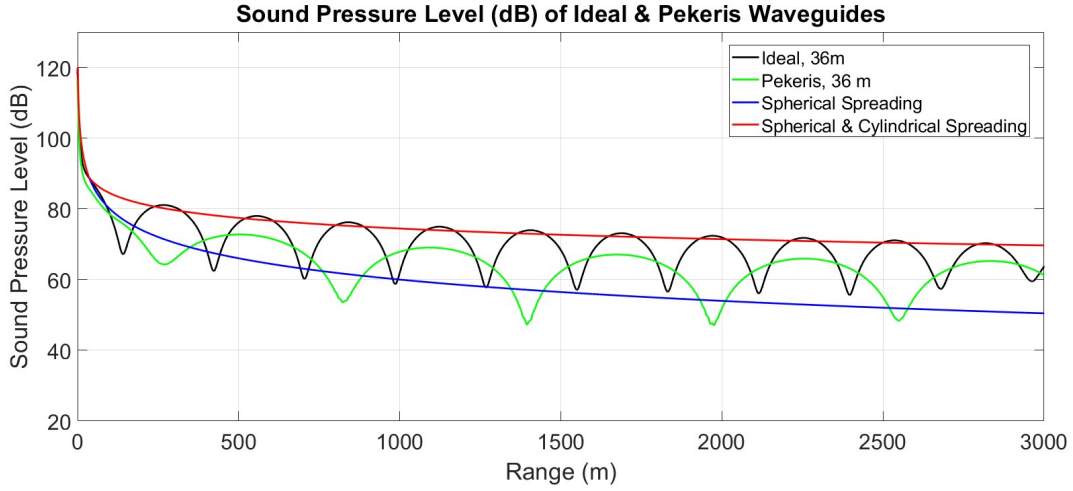


Figure 4.6: Comparison of a ParAcousti solution for a single monopole source propagating in both Pekeris and Ideal wave-guides, as well as the standard solution for a spherical spreading case and a spherical spreading case transitioning to cylindrical spreading at a distance of 36 m. Both the Pekeris and Ideal data are from a depth of 36 m.

3D Sloping Bottom

The fourth problem is a single, continuous 25 Hz monopole source located at a depth of 40 m below the surface in a 3D environment. The source is a Hanning- weighted, four-period sine wave with a RMS pressure of 0.4329 Pa. Below the source is a sloping bottom that varies between 20-380 m in depth at 2.86° , and shown in Figure 4.7 [109]. The source is placed so that it falls near the midpoint of the slope, where the depth of water is 200 m above the sediment layer. The domain boundary below the sediment bed is kept at a constant 400 m depth, and the domain stretches 8 km in the x-direction and 25 km in y-direction. The water column has a constant density and sound speed of 1000 kg/m^3 and 1500 m/s , respectively, while the sediment bed is set to 1500 kg/m^3 and 1700 m/s , respectively. With a constant $dx = dy = dz = 1 \text{ m}$ this results in approximately 1 billion cells and a run time on a cluster of nearly 13 hours on 13 cores for 6 seconds of simulated time. Attenuative parameters were not included as ParAcousti explicitly models the sediment bed and absorbs energy at the boundaries via the CPML.

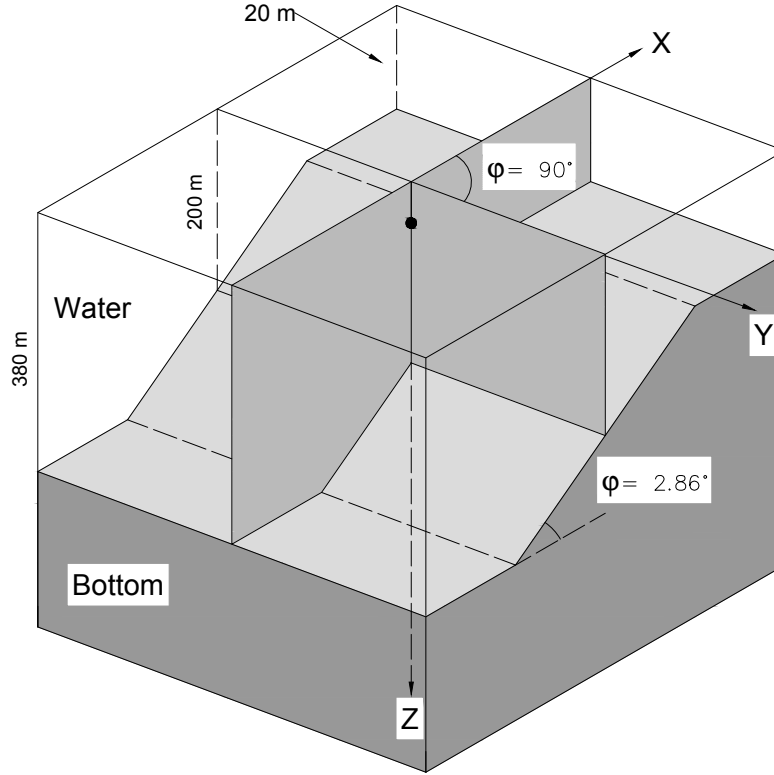


Figure 4.7: Depiction of the geometry for the truncated 3D sloping bottom domain. Domain lengths as specified are not shown. Modified from [109].

The resulting sound pressure level on a plane at a constant depth of 30 m (10 m above the source) is given in Figure 4.8 and compares well to the 3D parabolic equation solutions found in [109]. The plane intersects the sediment layer at approximately $x = 3,400$ km from the source, showing reflection off the sloping interface results in the same interference patterns and banding and where significantly less energy is transferred as the azimuthal arc is increased. Meaning, as the angular distance from the sloping sediment layer is increased, there is a decrease in energy transfer as interactions are being reduced between the waveform and the sloping bed. Beyond 10 km in the y-direction it can be seen that energy reflected away from the slope apex significantly interacts with the energy moving across the slope. As each sound wave is reflected, it results in a slight deflection off the apex of the slope. This

results in any energy path, which starts propagating up the main slope of the model toward the shallower depth of the model, being turned around to eventually propagate down the slope where the water column depth is increased. Individual sound waves trace paths which begin to cross one another for modes one and two, resulting in intra-modal interference at ranges over 15 km [109]. Figure 4.8 demonstrates the change in energy propagation as well as modal interference after 10 km. In comparison, the SPL at $x = 0$ and a depth of 40 m, shown in Figure 4.9, demonstrates the sound energy dissipation at a depth above that of the sediment layer.

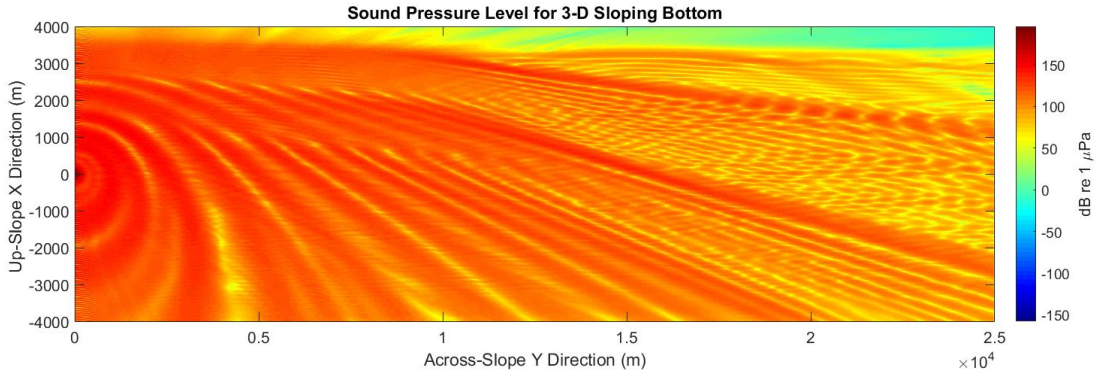


Figure 4.8: SPL slice of 3D sloping bottom domain. A 25 Hz source is located at a depth of 40 m below the surface. Sound propagates down range across the slope.

Furthermore, Figure 4.10 compares the $N \times 2D$ and 3D SPL solutions provided by Sturm to the 3D solution from the ParAcousti model, taken from the location of $x = 40$ m and a depth of 30 m. The ParAcousti solution shows a similar response to the fully 3D solution of Sturm, up to about 16 km. Beyond 16 km, SPLs calculated by a ParAcousti drop below those in the $N \times 2D$ solution due to intra-modal interference. However, the response is less pronounced than the 3D model and results in a different propagating structure than

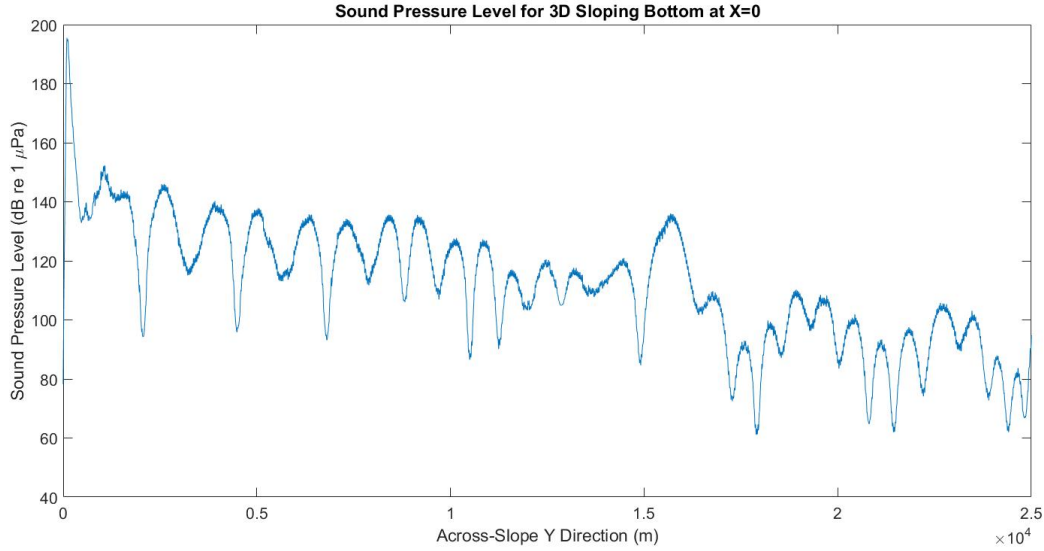


Figure 4.9: SPL across the slope (y-direction) at the location of $x = 0$ and a depth of 40 m. At the location of $x = 0$, the sound wave path is always above that of the sediment layer and shows a gradual overall decrease in SPL as the sound wave propagates down range.

either of the parabolic equation solutions.

Applications of Arrays

To demonstrate the influence multiple sources will have on the sound scope, an array of three sources, spaced 40 m apart in an equilateral triangle and centered at 50 m in depth was modeled in a Pekeris wave-guide. Each source is a monopole of 150 Hz, 120 dB re $1 \mu Pa$ re 1 m and they are in-phase with each other. Figure 4.11 shows the SPL field that results from their interactions, with the sources indicated by three black dots. As expected, a much more complex sound field develops compared to Figures 4.3 and 4.4 as the continuous profile from each source interacts with the others. The sound energy dissipates quickly as it is allowed to propagate through the sediment layer and higher-order modes are attenuated in the water column as the range increases and the overall amplitude is reduced as energy is lost to the surrounding environment.

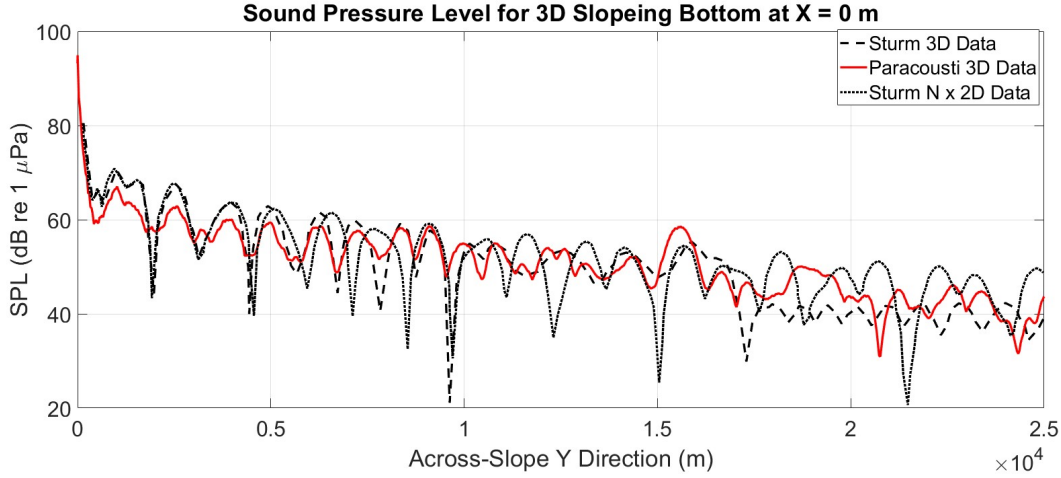


Figure 4.10: Comparison of SPLs for the Sturm parabolic equation solutions (3D and N x 2D) and 3D ParAcousti solution across the slope (y-direction) at the location of $x = 40$ m and a depth of 30 m. The Sturm data were recreated from a digitization of results found [109].

The simulation time required does not increase as the number of sources increases, which is not true for other modeling approaches discussed. However, it is predicated upon the maximum source frequency and domain size. ParAcousti can accommodate multiple sources in a single simulation, each represented by a unique sound profile. Sound profiles are created through a source function such as Equation (4.1). A single source with multiple frequencies may be formed by summing several source functions together, each with a particular frequency and amplitude. A source may be predetermined or derived via an imported recording. This lends ParAcousti the ability to model an array of MHK devices and provide a comparison as *in-situ* measurements become available.

ParAcousti has the capability to calculate the propagated sound field from multiple sound sources with unique profiles and these sources can have monopole, dipole, or a combination of these source types as contributions. As each finite-difference grid point allows for separate density and sound speed values, real world domains can be easily represented and evaluated. Through comparison to analytical solutions and literature, strong evidence

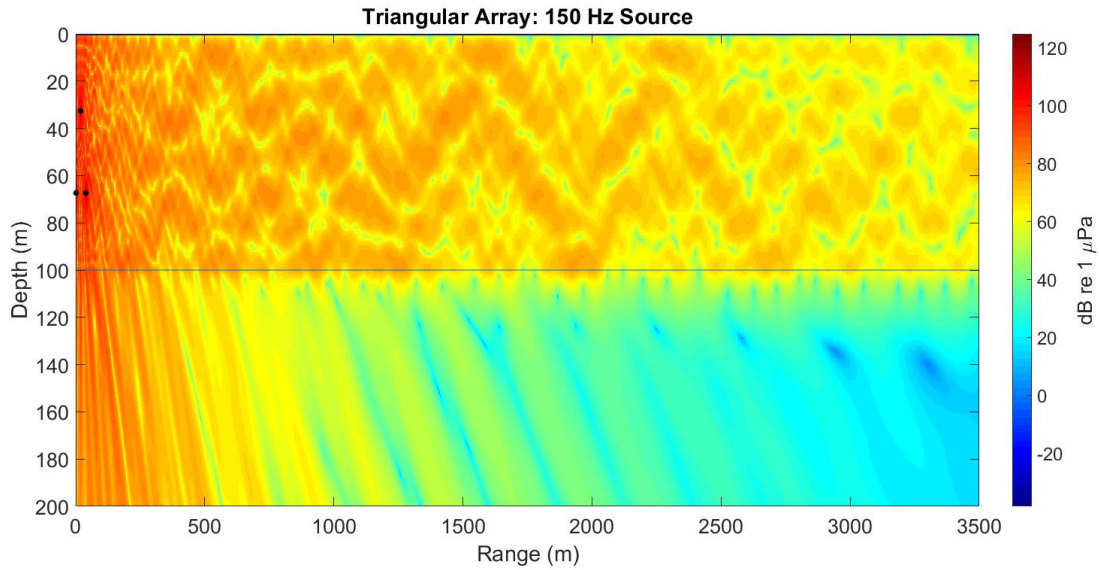


Figure 4.11: (Color online.) Sound pressure levels for a triangular array of MHK sources in a two-layer wave-guide.

was provided that ParAcousti is able to reproduce standard analytical solutions and produce data which the peak values nearly match published values for accepted solutions in literature. Solutions are not identical as the models are not identical. However, ParAcousti data matches the slope in SPL peak values indicating that energy is being removed from the system at a similar rate although ParAcousti is accounting for additional boundary conditions and interactions within the model domain. This was completed for both 2D and 3D systems indicating that the velocity pressure equations are providing accepted data for simplified, standard model domains and pre-defined simulations. Although ParAcousti was developed for modeling MHK deployments, it may be used to understand any underwater sound-source and its propagation. Additional modeling information provided by ParAcousti will allow for an increased understanding of how an MHK device, or array of devices, will affect an environment. This understanding may reduce or eliminate negative impacts to any fish or marine mammals in an area of interest and permit continued deployment of MHK installations.

CHAPTER 5: SEQUIM BAY RECORDED DATA COMPARISON

The inclusion of MHK sources in the United States over the last decade has provided an additional source of renewable energy to meet the energy goals outlined by the Department of Energy. Each MHK device, or array of devices, produces a unique sound signature that may be traced to the individual morphology of the device, orientation, operating conditions, and environmental properties associated with the device location. Additionally, few MHK devices have been developed and thus are being tested to understand how any contributed sound will impact the environment. All introduced sound sources will interact with any anthropogenic or natural noise sources already present in an inundated environment [15, 16, 17, 35, 36], and simulating the sound environment through various underwater acoustic propagation models would allow for an understanding of the potential impacts of any MHK devices prior to construction. Validation of any chosen acoustic model is necessary to determine if it may be appropriately applied to a particular real world environment. This work details the comparison and validation of ParAcousti as compared to acoustic data recorded at Sequim Bay, WA in January 2018. A picture of the bay is provided in Figure 5.1.

This chapter presents a comparison of ParAcousti to experimental data collected at Sequim Bay, WA in July, 2017 and January, 2018 by Integral Consulting, Inc. Validation efforts for ParAcousti are required to provide an accurate tool for any potential users of the program. Three validation activities were completed. The results of the first effort were a comparison between ParAcousti and several analytic solutions to prescribed model setups for underwater acoustic propagation modeling were described in Chapter 4. In-situ experimental data sets provide challenges and complexities not apparent in artificial simulations. Recorded data was compared to the ParAcousti model to determine the effectiveness of ParAcousti as a sound propagation modeling tool and confirm that the program is capable of modeling real marine environments successfully. This effort also begins to elucidate the level of fidelity



Figure 5.1: Sequim Bay, WA in September 2020. The bay connects to Puget Sound to the north and is just East of Sequim, WA.

required for the driving environmental and source data to achieve an accurate solution.

The data from Sequim Bay was selected from six potential data sets due to the spatial and temporal fidelity of the measured data and because the bay itself is fairly isolated from any connecting bodies of water with consistent environmental parameters and a shallow bottom. Additionally the data set provided ambient sound characterization, recording methodology, and source characterization. Sequim Bay's data set was concise and from a contrived source, which would allow the source function to easily be broken down and input to ParAcousti directly instead of having to analyze sound recordings to determine an appropriate source function. Additionally, the source was emitted from a speaker, which is a monopole sound source, where the orientation would not be a variable. Other data sets considered were: ○ 1995/2006 SWARM: New Jersey coast, Woods Hole Oceanographic Institution ○ Azura wave energy collector (WEC): Oahu, HI, University of Washington ○

SeaRay WEC: Puget Sound, WA, University of Washington ○ NPAL Philippine: coast off the Philippine Islands, North Pacific Acoustic Laboratory (NPAL) ○ Sequim Bay: Sequim Bay, WA, Integral Consulting, Inc.

This chapter first documents the Sequim Bay data set and the environmental parameters selected to construct model domains used within ParAcousti. The purpose of this project is to fully understand, demonstrate, and document ParAcousti's ability to model complex environments and data sets while validating against an experimental data set. Reduced fidelity and variability in environmental parameters manifests as the difference between model and measured results. Validation against a recorded data helped to determine the measured environmental parameters that primarily influence the model output and those that may require a higher fidelity model calibration. The end result is to determine those parameters that are necessary for an accurate representation of acoustic propagation in an underwater system. The increased flexibility of ParAcousti to model multiple types of domains and sound sources is particularly advantageous for MHK acoustic propagation modeling as deployment sites are often within shallow-water systems. Shallow water systems allow for an increased probability that any noise source will interact with a boundary or change in density causing the sound field to either be focused or dispersed. This focus or dispersion effect is observed within deep-water systems as well, but with a reduced impact to the energy source, as the energy within the pressure wave must travel longer distances prior to any interactions. The primary purpose of modeling MHK devices in an environment is to discern any potential impacts. Interactions between relevant domains and a signal source determine the rate at which energy dissipates as the sound propagates outward. Given that typical MHK deployments will occur as arrays within shallow water systems and the noise they produce is complex, ParAcousti is able to predict the impact and effected radius any introduced noise may have on an environment.

Sequim Bay Data Set

To determine an accurate prediction of the acoustical landscape produced by MHK operations, ParAcousti was validated against a specifically chosen recorded data set in a controlled, shallow bay in the USA. The project area and corresponding data set was located at Sequim Bay, WA, north of Olympic National Park, WA, USA. All experimental data was collected by Integral Consulting, Inc. during two separate monitoring efforts comprised of monitoring ambient and induced acoustic levels from a provided sound source. The first data set was collected during the week of July 10, 2017 and the second was collected during the week of January 15, 2018. Sequim Bay is nearly separated from Puget Sound by a spit of land, effectively causing the bay to be a relatively well controlled noise environment. The bay is approximately 3.2 km in length by 1.6 km in width at the north end. Bottom depths are on average 28 m, with a maximum of 39 m, and the bottom is comprised of soft clay or silt. A layer of suspended solids, or “fluff,” overlays the bottom with a depth ranging from 0 to 3 cm, dependent on the location within the bay. Sediment data was provided in a Benthic Habitat Report conducted in December of 2016 by Integral wherein over 30 sites were sampled, cataloged, and photographed to assess the soil types and overall habitat of the bay bottom [53, 54].

Other environmental properties included a bathymetric survey. Bathymetric data was surveyed on an approximate 0.5 m grid on the interior of the bay with spacings increasing to 6 m along the shore-line, where the existing topography and water depths made surveying increasingly difficult from within a boat. All bathymetric data was provided in Washington State Plane North coordinates in meters and is referenced to the water surface when measurements were taken, automatically providing water depths associated with the data. Temperature, salinity, and conductivity measurements (CTD data) were recorded in July, 2017. During this collection effort, sound speed data was calculated from the CTD data.

For both data collection efforts, scientists from Integral measured typical ambient noise sources over the course of one week. Integral then introduced singular pulses varying in frequency, over time out in the bay after ambient levels had been documented. Data logs were provided, which detailed all collection efforts and locations of deployments that were time sensitive to the actual project and not recorded in the test plan. Depths of the sound source were placed between 2 and 3 m below the surface for the July data set and at 2 m in January. All sources, receivers, and CTD data were deployed from a Pacific Northwest National Laboratories (PNNL) research vessel, the R/V Strait Silence. The controlled source, which was moved to various locations around the bay, emitted 5 second long pulsed sinusoidal sound waves over a period of 15 minutes ranging in stepped-frequencies between 100 to 5,000 Hz. Pulses were separated by a gap of 0.1 seconds and the range of frequencies repeated a total of 8 times. Initially, higher frequencies up to 25 kHz were tested during the July effort; however, these were above the recommended collection limit for the chosen receivers. Only one singular frequency was broadcast at any given time on a broadband signal. The sound sources were produced by a high and low frequency icTalk acoustic source produced by OceanSonics Ltd and provided by PNNL. The low frequency and high frequency sources have recommended ranges of 10 Hz to 2.2 kHz and 10 kHz to 200 kHz, respectively. Investigation of the source determined a variable power output at different frequencies, which is to be incorporated into the validation efforts. The single source was deployed at specified locations ranging 50, 100, 200, 500, and 1,000 m from the sensor array and emitted the described signal. The locations moved out radially from the stationary sensor array, but were not in line with one another and were unique with respect to each collection effort [54, 58, 95, 96].

Acoustic receivers were deployed using two different structures that had unique constructions for each of the two data collection efforts. The receivers were mounted on a singular array, which was to remain in a stationary location consistent between the July and January data sets. Both data sets recorded ambient and propagated sound

data with a stationary, three-element vector sensor system composed of three M20 particle velocity sensors manufactured by Geospectrum Technologies and a MicroMARS acoustic sensor produced by Desert Star Systems. Analog measurements were converted to a digital format and recorded using an off-the-shelf 16-channel data logger manufactured by Omega Engineering Inc. (OM-LGR-5320). For the July collection effort, the sensor array was mounted to a suspended structure and buoy system, which was secured at the north end of the bay by a series of weights. The bottom of the array was located 15 m below the surface of the water. Unanticipated movement of the sensor array as well as additional flow noise, and low frequency sound emitted from the data logger itself resulted in data with a high amount of uncertainty. The system was redesigned for the January effort and the sensor array framework was mounted to the bottom of the bay, at a depth of approximately 25 m, and secured by weights. For both systems, each of the three M20 particle velocity sensors were spaced 0.5 m perpendicularly with the bottom sensor resting on the sediment layer, with the M20-100 residing in the center of the array. Both arrays were initially placed at the same specified latitude and longitude within the bay; however, the July array drifted from its starting location. As such, all data for this work has been pulled from the January data set as well as any latitude and longitude locations as the sensor array location was not altered during the course of testing and the data overall was clearer at lower frequencies. The sensor array structure is shown in Figure 5.2, and Figure 5.3 illustrates the bay and water depths therein. For the January 16, 2018 data set, the sensor array was located at $N48^{\circ}0.5096'$ $W123^{\circ}1.4571'$. For the January data set, source locations are shown within Table 5.1.

The three particle motion sensors manufactured by Geospectrum Technologies were used to determine the location of the sound sources and included two model M20-40s and one M20-100. The M20-40s measure 3D acoustic pressure and particle velocity in the X , Y , and Z planes. The M20-100 measures the particle velocity and acoustic pressure in addition to the pitch, roll, and heading. The raw collected data was relayed using current signaling to

January Data Point Collection Locations	
Location (Washington State Plane Coordinates)	Distance From Sound Source (m)
N48° 3.5174' W123° 1.4148'	50
N48° 3.5245' W123° 1.5326'	100
N48° 3.5797' W123° 1.5786'	200
N48° 3.7746' W123° 1.5223'	500
N48° 4.0397' W123° 1.5514'	1,000

Table 5.1: Locations of the five source locations, which were lowered off the side of a ship to move further and further from the receiving device in the bay. Location values are provided in the Washington State Plane coordinate system and distances are in (m).

an ADC converter and stored on a solid-state hard drive for post-processing. A MicroMARS BAR recorder developed by Desert Star Systems was used to record the ambient noise in the surrounding area. The particle motion sensors have a recommended recording range of up to 3 kHz. All data used for this project was recorded by the M20-100.

Sequim Bay allowed for several variables, such as the source signal and locations, to be controlled. An actual MHK deployment would have introduced additional uncertainty due to sound produced by the actual machinery and flow noise. These project parameters and the constraints of the bay itself were one of the main factors for selecting the data set for validation of ParAcousti. The deployed monopole, manufactured source emitted a documented range of stepped frequencies that were centered about a single frequency at any given time during testing. Frequency leakage occurred when the sound was emitted causing an approximately 2 Hz frequency shift in the recorded data dependent on the actual emitted frequency level. Consistent with the majority of MHK devices, some of the recorded frequencies fall within 50 to 1,500 Hz, which provide frequencies relevant to the research goals [18, 39, 58, 64, 68, 79, 89]. Additionally, ambient noise was occasionally recorded in

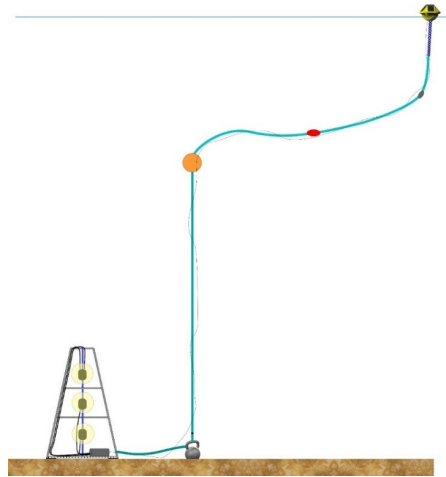


Figure 5.2: Depiction of the structure fashioned to hold the sensor array on the bottom of Sequim Bay for the January data collection effort [53].

between efforts to set up a new source location, as well as the environmental parameters for the site. Pre-processing of the data was completed by Integral during the spring of 2018 where raw voltage data was converted to calibrated pressure values. The associated Python files and data files containing acoustic particle velocities in 3D were provided by Integral.

Model and Experimental Data Set Comparison

For the validation process, Integral Consulting, Inc. provided all pressure data files, which had been converted from the original raw data files from both the July and January collection efforts. Experimental data was further processed to compare the pressure values to the output calculated by ParAcousti. For model setup, ParAcousti required the following physical data, that had been provided by Integral: 1) bathymetric data, 2) source parameters, 3) sound speeds, and 4) densities. Source parameters were provided by the test plans published by Integral detailing the source used during the January data collection, the icTalk acoustic source from PNNL. Sound speeds were calculated via the CTD data and sediment descriptions provided by the benthic habitat study allowed for density values to be estimated

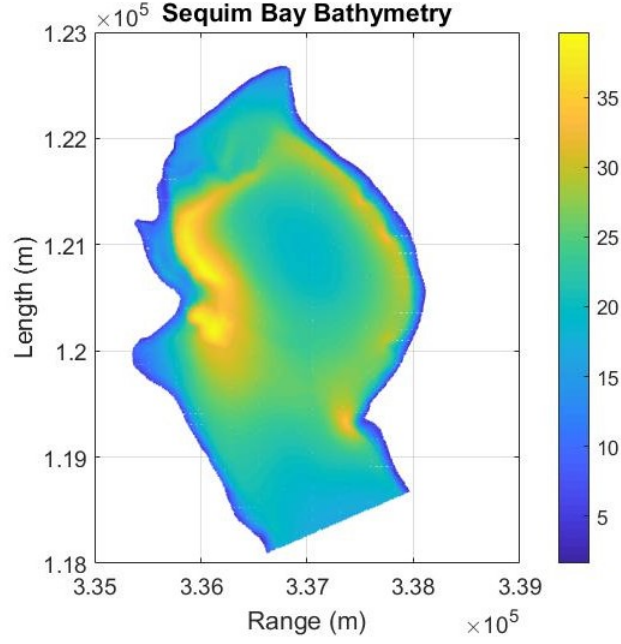


Figure 5.3: Bathymetry of Sequim Bay with associated depths in meters.

for the sediment layer. Validation efforts were separated into two groups; constructing both a 2D and 3D model within ParAcousti and processing the recorded data set in which to compare with the recorded (measured) data.

ParAcousti Model

For any experimental validation, the simulation model is first constructed within ParAcousti using the physical data provided. Models, once constructed, may be tested and calibrated to fit an experimental data set to determine model sensitivity to measurement resolution. For this comparison a 3D model was created as well as a series of 2D models that were constructed along the topographic linear path between the source and sensor array. In short, a range of frequencies were modeled through time as they propagated across the bay and were examined in both 3D and 2D models.

The typically required inputs for ParAcousti are: 1) domain area and medium properties, 2) source locations and parameters, and 3) desired outputs from the model. The

surveyed bathymetric data for Sequim Bay provides the locations of the interface between the water column and sediment layer on the bottom of the bay. Values assigned to each node differentiate the material type within the model. All bathymetric data was referenced to the minimum x and y coordinates within the recorded data setting that point as (0,0) for the initial construction of the model domain grid.

Bathymetric data was stored and interpolated onto a fully 3D Cartesian grid surrounding the bay or interpolated onto a 2D slice in the x, z dimensions, linearly connecting a predefined location for a source and sensor array. In 2D, the x-dimension may be thought of as the range, r , to orient the observer. A PCHIP interpolation was chosen to smooth uncertainty associated with an interpolation of the data as the 0.5 m and larger was greater than the spacing of 0.2 m to capture up to 750 Hz. Temporal and spatial resolutions defined by the source parameters will impact the error between the model and measurements. If the difference between the initial bathymetric data and the finite difference grid is large enough the data extrapolation required for interpolation may increase uncertainty significantly. The boundary was squared off by the rectangular Cartesian grid, which was large enough to encapsulate the entire area of the bay that was provided with the bathymetric data with a buffer edge for boundary conditions. The very northern tip of the bay was omitted as it is the end of a jetty where the bay connects to the rest of the Salish Sea. The convolutional perfectly matched layer (CPML) was utilized and acts as an energy absorber [21, 22, 60]. Typically, 100 additional grid cells are recommended in the dropped dimension for 2D models to increase the reflected angle of sound energy. All values outside of the bathymetric data set were assigned a depth value of zero and treated as a sediment layer. Pressure-free boundary conditions were also imposed at the water-air boundary at the top of the model to act as perfect reflectors of the energy. The surface of water was assumed to be smooth. Additionally, due to the Cartesian grid being applied to a complex bathymetry, the water-sediment layer interface of the domain is not continuously smooth as in reality, but steps at defined grid

points. For Sequim Bay, the model was constructed with a water column and single sediment layer. For all models created for the Sequim model domain, the time step was set such that it was either identical or divisible into one another for lower frequency models. This ensured that compared data sets had values which always fell on the same time step count and did not require a second set of interpolations. Models were set to have a grid size step minimum of 0.2 m and a time step of 0.00005 seconds. A 2D model had approximately 4.5 billion cells and 3D models had upwards of 82 billion cells. 2D models had a solution time of 7-14 days run over 128 cores. Simulation time was dependent on cores, type of cores, and memory available on the computation cluster.

Initial modeling efforts used the July data set to start the process of learning to design the Sequim models as the January data set was not available at that time [54]. For those initial models, typical sound speed of 1,500 m/s , 1,700 m/s and density values of 1,000 kg/m^3 , and 1,500 kg/m^3 for both water and soil, respectively were used. These initial environmental values were chosen based on models completed by Sturm and Jensen and were used to verify that the models created using ParAcousti were creating reasonable results before increasing model complexity [55, 109]. The final models were then created with sound speed values averaged across a range of depths from the collected CTD data at six separate locations within Sequim Bay in July 2017. These values were then averaged with respect to all six locations to produce a single sound speed in depth. Sound speed values were not averaged in range for the 2D model as the January source locations were not identical to that of the locations for the collected CTD data. Depth averaged sound speed values from each location that the CTD data was collected were equal to 1,498.8, 1,498.3, 1,498.4, 1,498.7, 1,499.3, and 1,500.3 m/s for the 10, 50, 100, 200, 500, and 1,000 m locations, respectively. This results in an average overall sound speed of 1,499.0 m/s for the water column, and a standard value of 1,000 kg/m^3 was applied for the density. While sea water density values are closer to 1,030 kg/m^3 , the CPT data collected for Sequim Bay show salinity values of

approximately 30 PCU, which are lower than that of a standard ocean body, which typically ranges from 35 - 40 PCU. Additionally, this was recorded for summer temperatures. If adjustments are made for decreased temperatures, the predicted density may be close to $1,010 \text{ kg/m}^3$. Increased density values increase sound speed, which would cause a shift in time to receiver, but would have a minimal impact on overall SPL value. Future work could further determine the potential impact changes in sound speed would have on the Sequim Bay model simulations.

Density values represent the soil type on the bottom of the bay. While no core samples were provided to clarify the soil type, the benthic report determined that the soil type varies from a fine sand to a sandy silt as the water depth in the bay increases. The soil was also described as a "soft mud". Geotechnical soil parameters were approximated as ranging from 1,730 to 1,840 for density of soft mud [98]. Variation in soil parameters is likely as soil is rarely homogeneous in nature. Additionally, the soil type may change near the shore of the bay. Model complexity can be reduced through the soil density approximation imposed; however, uncertainty increases. Typically, a soft mud is comprised of small particles such as clay and silt. Sound speed parameters for either of these types have been recorded as ranging from 1,550 to 1,600 m/s [123]. The bottom of the bed is also covered with "fluff" comprised of suspended sediment and detritus from the water column ranging from one to five cm in thickness. This thickness is significantly smaller than the grid resolution required for the ParAcousti simulations and the layer of "fluff" was not included in any model represented within this report. The "fluff" layer is suspected to have attenuative properties. However, the small thickness of the layer reduces the likelihood that attenuation will be significant and so was subsequently not included in the models.

Based on the soil parameter information, two separate categories of models were created with the following properties. Average values of $1,785 \text{ kg/m}^3$ for the density values and $1,575 \text{ m/s}$ for sound speed based on recommendations by Richardson were used initially for the

sediment layer. The values are referenced as the first set of physical parameters. The second set of models used density and sound speed values of $1,595 \text{ kg/m}^3$ and $1,625 \text{ m/s}$ based off the information presented by the benthic habitat report [25, 53, 98, 125]. Soil parameters could be adjusted further to calibrate the model to the recorded data. The type of soil will change the amount of energy being reflected back into the water column. Attenuation was not included within the soil parameters for this model as it is anticipated to have a negligible effect for any reflected sound energy back into the water column.

An initial calibration model was created at the lowest tested frequency in order to efficiently investigate parameter sensitivity prior to running more computationally-expensive, higher-frequencies and scenarios as well as to reduce the risk of any associated errors. The source was defined as single, monopole sinusoidal function. The amplitude was set to 1 Pa. The frequency was set to 100 Hz, which was the starting frequency for the Sequim data set. Lower frequency values allow for a larger grid spacing as each individual wavelength was larger than that of a high frequency sound. Larger grid spacing values associated with a low frequency source results in a reduced number of grid points, a smaller model domain, and a reduced model solution time so that the time required for any additional runs required to debug the initial model and calibrate the system is dramatically decreased. High frequency sound sources have a higher number of interactions, including reflections, and dissipate faster than a low frequency source. After testing, all final model setups were calibrated to the January data set as the sensor array was stationary and the sensor locations well defined within the bay. Additionally, the July data set had a large amount of low frequency noise emitted by the data logger, which obscured much of the low frequency data. While advantageous for modeling, stationary systems are subject to additional flow noise around the sensor array itself and should be considered during any data comparison.

The source function was run as both a continuous function out to 8 seconds or as a pulse, which ended after 5 seconds to mimic the recorded data set and the source was based

on a time function, with a general profile of 5.1:

$$S(t) = \frac{A}{4\pi^2\omega^2}(\cos 2\pi\omega t) \quad (5.1)$$

where ω is the frequency of the source (Hz), t is the present simulation time (s), and A is the desired pressure amplitude (Pa). The division by $4\pi^2\omega^2$ accounts for the conversion the source time function into a pressure through a double derivative. The unity offset for the cosine ensures smooth derivatives of the source time function at $t = 0$ s. The profile is summed over all relevant frequencies and presents a source with a frequency of 100 Hz and an amplitude of 1 Pa located 2 m in depth below the surface for the initial models.

Aside from the domain parameters, another input file contains a description of the output recording geometry, for example the types and positions of acoustic energy sources and receivers. Calculated data are of three types: 1) traces, or time-series of particle velocities or pressure at designated receiver locations in the 3D grid; 2) slices, or 2D pictures of time-evolving acoustic wave fields; and 3) 3D wave field volumes. The Sequim data set are pressure data files collected at a singular location, at the sensor array, over a period of time. In order to make a comparison, traces were collected within the ParAcousti models at locations corresponding to that of the sensor array as well as various other grid locations in order to make sure the model was working properly. Furthermore, slices were collected for the entire grid to visualize the propagation of the sound waves outward from the source. ParAcousti has the ability to calculate particle velocities as well, however, these values have not been investigated. Simulation runs were completed on the Hyalite computing cluster at Montana State University.

Experimental Data

Integral Consulting, Inc. has provided assistance with Python script files which convert the collected raw sound data files into pressure trace files which may be used to compare

against the ParAcousti models. The January data set was selected to compare against the calculated ParAcousti data as the sensor array remained in a singular location during any particular day of testing. The locations do change day to day as the systems, including the sources, were deployed daily from January 15, 2018 through January 18, 2018. Data was selected from January 16, 2018 and allows for data collected at sources placed distances of 50, 100, 200, 500, and 1,000 m from the sensor array. Data collection was variable and dependent on the day; January 16 provided the most complete set of data for every distance while maintaining fairly consistent environmental conditions as opposed to taking various data measurements from several days to make a complete data set.

All collected data was converted with respect to $1 \mu Pa$ and was then processed using MATLAB to sort the data. The received file contains all frequency levels overlaid for the entire 15 min time interval in which all 20 frequencies, ranging 100 to 5,000 Hz, are cycled through. Singular frequencies were separated out using the spectrogram function into 4096 frequency bins, from which data may be selected from the desired frequency to compare against ParAcousti's models. The original data was sampled at 10,000 Hz and has 9 million data points. Using the spectrogram function reduces the data set to 4096 data points for each frequency over the 15 min span of time. This reduces the fidelity of the data but is appropriate for comparison purposes as otherwise the visualization of each frequency pulse would not be possible. Data start times vary depending on the location and the human error associated with starting the recorder and sound source at the same time. Clear pulses are visible for frequencies above 500 Hz, up to 3 kHz; however, run time for this work prohibited those outputs. Unfortunately, below the 500 Hz mark, the data is fairly noisy and nearly at or below ambient recordings. Ambient levels were discerned by the pressures recorded for frequencies where a signal was not emitted; meaning all the frequencies in between those listed as the emitted 20 values. Signals are limited to 5 second pulses recurring eight times over the 15 minutes. From the binned frequency data, each of the eight pulses was identified.

Acoustic data is inherently noisy. Pressure values vary widely and as a singular frequency pulse propagates outward, it interacts with the energy present in the sound environment, causing sound energy to blur into the other frequency ranges. When the data was separated into frequency bins, the surrounding frequencies were analyzed to determine if the sound energy which should overlay with the pure tone was in that frequency bin. Most were shifted either direction by approximately 5 Hz. By collecting data from the bins surrounding the pure tone frequency selected, the energy that was lost to the immediately surrounding frequencies was preserved within the measured and processed signals. An FFT and spectrogram analysis was used to determine the location of the frequency pulses and the frequency range that the signal was present in surrounding the selected pure tone.

Results & Discussion

Results for the models and experimental data are principally visualized as sound pressure levels (SPLs) referenced to $1 \mu Pa$. All recorded and converted pressure data was already referenced to $1 \mu Pa$ and values were squared to represent power levels instead of energy. Power levels were converted to SPLs or sound energy levels (SEL) as necessary. SPL data converted to sound energy level data, SEL, was integrated over a length of time of 24 hours.

ParAcousti models were split into 2D and 3D simulations as the 2D model runs are 12 times faster. On 16 cores, a 2D model will run in approximately 6 hours while a 3D model will take upwards of 72 hours to process for a 100 Hz simulation constructed for Sequim Bay for a simulated time of 8 seconds. 2D model runs constructed for a 750 Hz frequency band run for approximately five days on 192 cores due to the scaling of the model domain. Models were constructed initially for a 100 Hz sinusoidal source operating at 1 Pa and then later for a maximum of 750 Hz in order to handle a signal with frequencies ranging from 100 – 750 Hz. The modeled source had a RMS pressure of 1.0622 Pa and is located at 2 m below the

water surface. Source levels were calibrated to the following decibel levels for each specified frequency and are listed in Table 5.2.

Calibrated Source Levels	
Frequency (Hz)	dB Level re 1 μ Pa at 1 m
100	87.69
200	94.36
500	110.24
750	113.82
1000	113.29
1200	105.62

Table 5.2: Calibrated source levels that may be applied to the ParAcousti data provided by Integral Consulting, Inc.

The source calibration levels were provided for the 200 - 1200 Hz frequency band. Data points were plotted and interpolated to a curve to calculate the appropriate value for the 100 Hz frequency. The equation used is shown in Equation 5.2, where y is the calibration value in (dB) and x is the source distance in (m).

$$y = -3E-10x^3 - 6E-5x^2 + 0.0901x + 78.682 \quad (5.2)$$

All model domains were run to a maximum depth of 60 m, while the actual bottom of the water column was dependent on the bathymetry itself and the location of the sources. The bed depth was different for all 2D models as the slices taken from the 3D system were unique to each location. Depths range from 10 to 34 m in depth. The max depth for the 3D model was 39 m. The 2D cross-sections do not cross over or intersect the deepest portion of the bay, which is included in the 3D model run. 2D model cross-sections were calculated

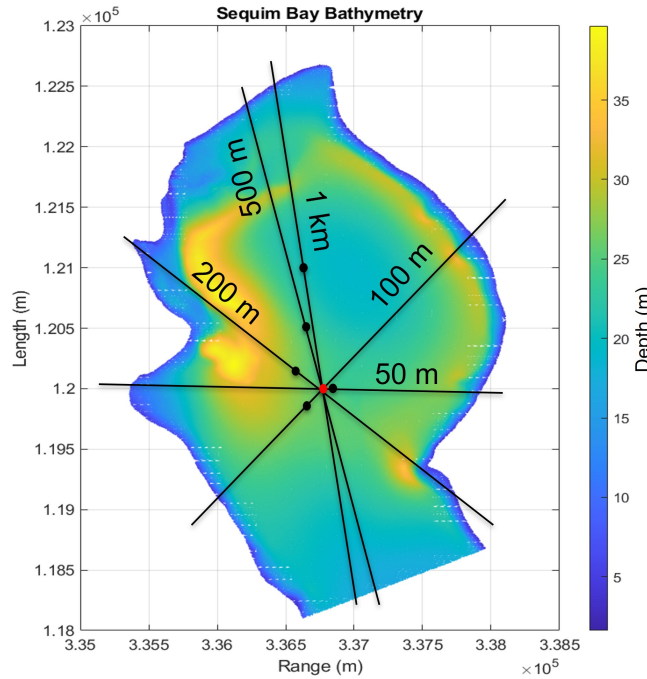


Figure 5.4: The location of each 2D cross-section profile and the intersecting points of the sound sources and receiver array location in black and red dots, respectively. All cross-sections are unique.

by interpolating a straight line from the reported source and receiver array locations within the bay. Locations for each source were not in a straight line and varied depending on the location throughout the bay causing each 2D cross-section to provide a unique simulation domain. Boundary conditions were enforced on either end of the cross-section so that the cross-section ended by terminating itself into either the jetty on the north end of the bay or the bank on the south end. Figures 5.4 - 5.9 show the location of where each 2D cross-section intersects the bay as well as each cross-section profile. The 200 m profile is the most dynamic with the most severe bathymetry, while the 50 m location has the most consistent bottom with a shallow depression. The location of the source is shown as a black dot and the receiver array is a red dot. Any change in bathymetry will increase reflections of sound waves off the sediment layer back into the water column.

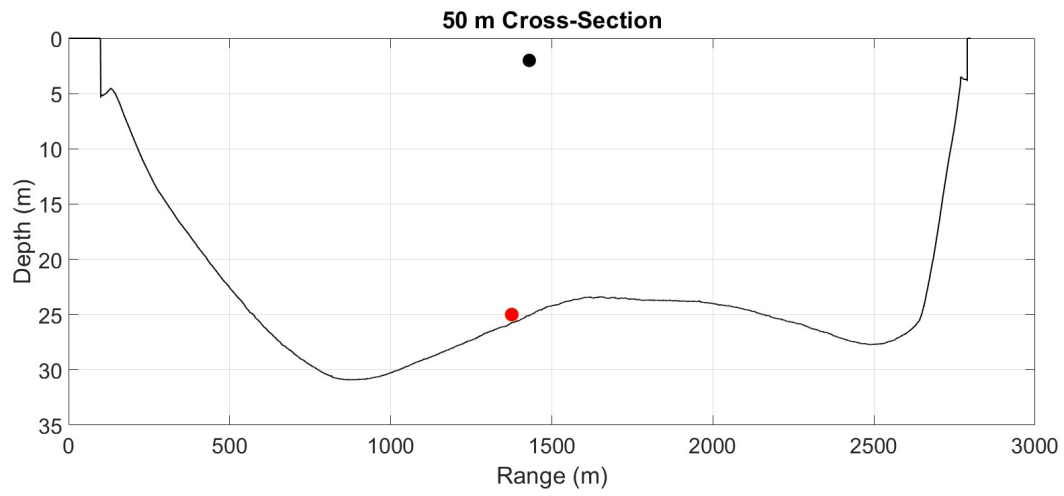


Figure 5.5: The 2D model cross-section profile for the 50 m source location. The source is shown as a black dot while the receiver array is a red dot.

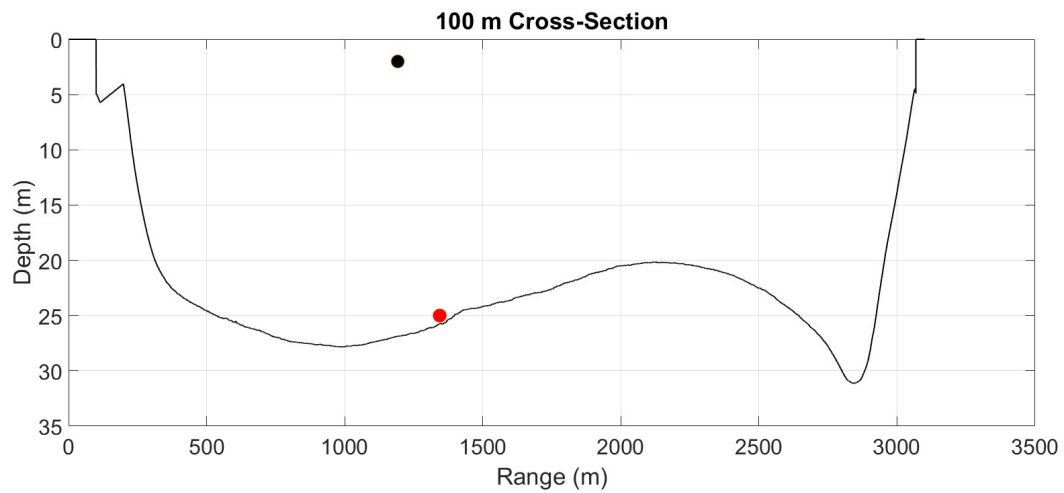


Figure 5.6: The 2D model cross-section profile for the 100 m source location. The source is shown as a black dot while the receiver array is a red dot.

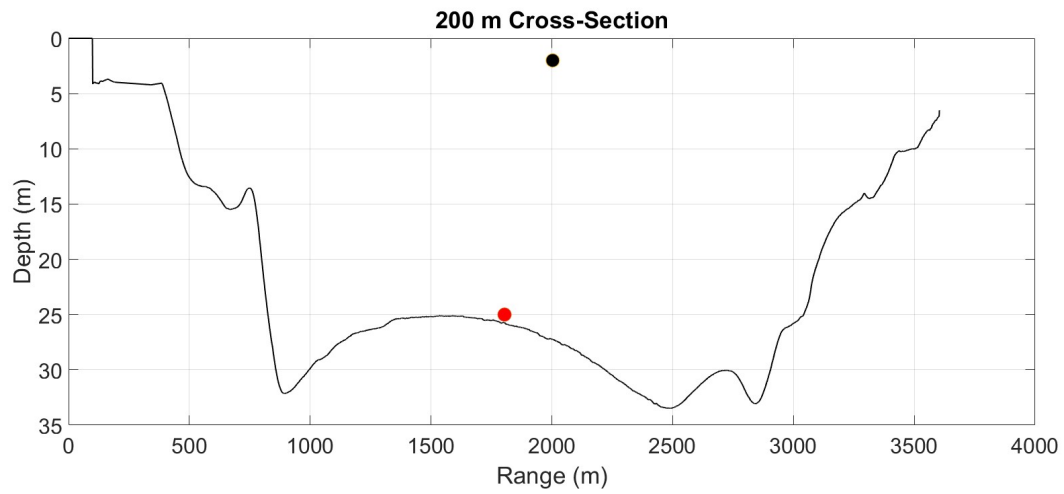


Figure 5.7: The 2D model cross-section profile for the 200 m source location. The source is shown as a black dot while the receiver array is a red dot.

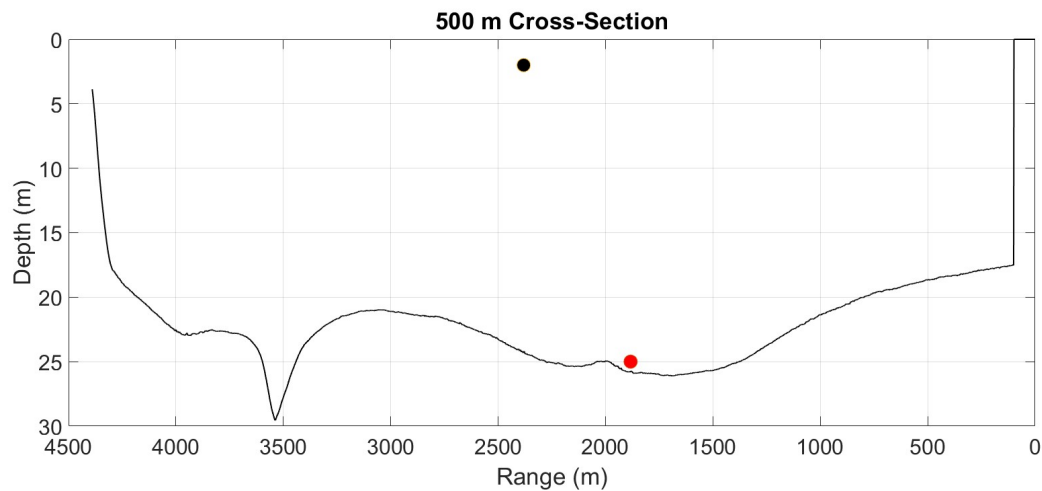


Figure 5.8: The 2D model cross-section profile for the 500 m source location. The source is shown as a black dot while the receiver array is a red dot.

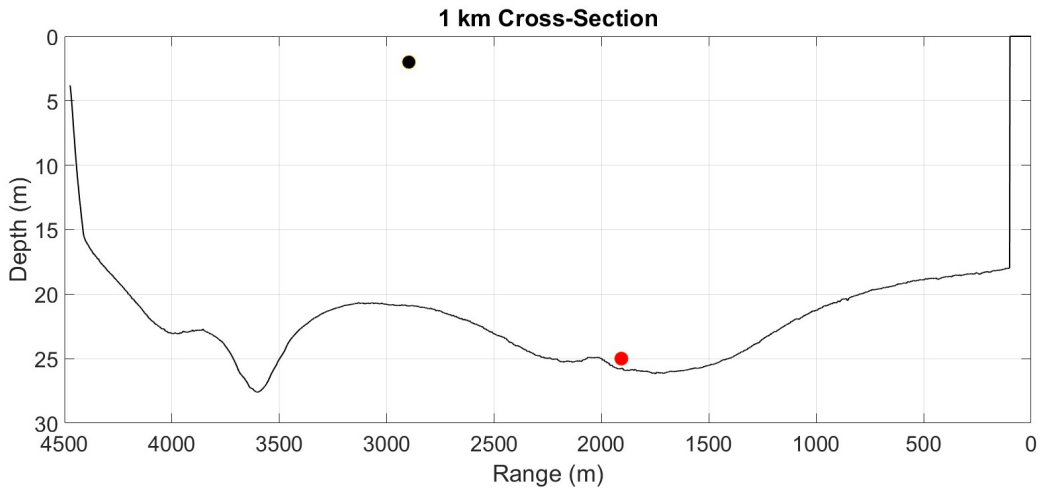


Figure 5.9: The 2D model cross-section profile for the 1,000 m source location. The source is shown as a black dot while the receiver array is a red dot.

2D Model Results

For all distances, 2D models were constructed and run with an artificial model width of -160 to 160 m to prevent any sound reflecting back into the system. The CMPL boundary conditions were applied to these buffer boundaries. The x-dimension, or range, was dependent on the length of 2D slice through the 3D domain required to connect the location of the sound source and the sensor array. The extent of the domain was extended past the edge of the bay with a 100 m buffer zone applied to each end that extended into soil. If the slice ended within the open end of the bay, that was left as the boundary condition for the model domain. The ranges for each 2D model were 2,800, 3,100, 3,700, 4,300, and 4,400 m in length for the 50, 100, 200, 500, and 1,000 m distances from the sensor array, respectively. Single frequency models were run with a continuous source function operating for 8 seconds and separately with a pulse function operating for 5 seconds with a total run time of 8 seconds. The time step was set to 8×10^{-5} seconds for model stability. Both continuous and pulse models were run with the first set of sound speed and density parameters. The models were then updated to the second set of sound speed and density parameters set for a

sandy silt, and the models were re-run using the pulse configuration for the source. The grid size was set to 0.2 m. Approximately 3 seconds is required, varying slightly for each run, for energy to propagate to the furthest reaches of the model boundary. Thus, an 8 second model run is ample to allow for any reflected energy to travel back across the bay to interact with the signal or dissipate after the end of a pulse to discern the remaining amount of energy in the system.

Figure 5.10 shows the comparison of the SPLs generated from the 50 m location for the 2D, 100 Hz model for each of the three operating conditions, meaning a continuous source and two pulse sources, each with first and second set of density and sound speeds. Data comparisons located for the 100, 200, 500, and 1,000 m locations are located within Appendix A as the data output is similar to that of the 50 m location. SPLs are represented for the location of the sensor array in time and demonstrate that as distances increase between the source and sensor array, so does the time required for the sound energy to reach the array. All three conditions have the same delay in time required for the array to start recording propagated noise. Additionally, while the pulse source is emitting, the SPLs are the same for continuous and pulse sources. SPLs drop off to below ambient within 0.5 seconds of the end of the pulse, which is approximately 57 to 65 dB re 1 μPa for Sequim Bay, depending on the location within the bay. The second density and sound speed (physical parameters) result in an increase in the amount of energy reflected back into the bay and a reduction in dampening. This is indicated by a higher SPL value for each of the distances when comparing the pulse source data after 5 seconds. The difference between the two physical parameter pulse runs increases as the distance from the source increases due to an increased amount of time where sound may be attenuated or reflected back into the system given the particular sound speed and density of the soil. Differences in the SPLs during the pulse are under 1 dB re 1 μPa for the 50, 100, and 200 m distances; however, they are approximately 5 dB re 1 μPa for 500 m and 8 dB re 1 μPa for the 1 km data set. SPLs decrease after the pulse

has stopped and energy is no longer being introduced at a constant rate. Note that ambient noise levels will not need to be added on top of the results produced by ParAcousti as any ambient sound is masked by external sources with a greater energy signature in the real environment, which is what would be compared to the output from ParAcousti. Ambient levels are still required to know if simulated or recorded data falls above or below ambient, or regulated, levels.

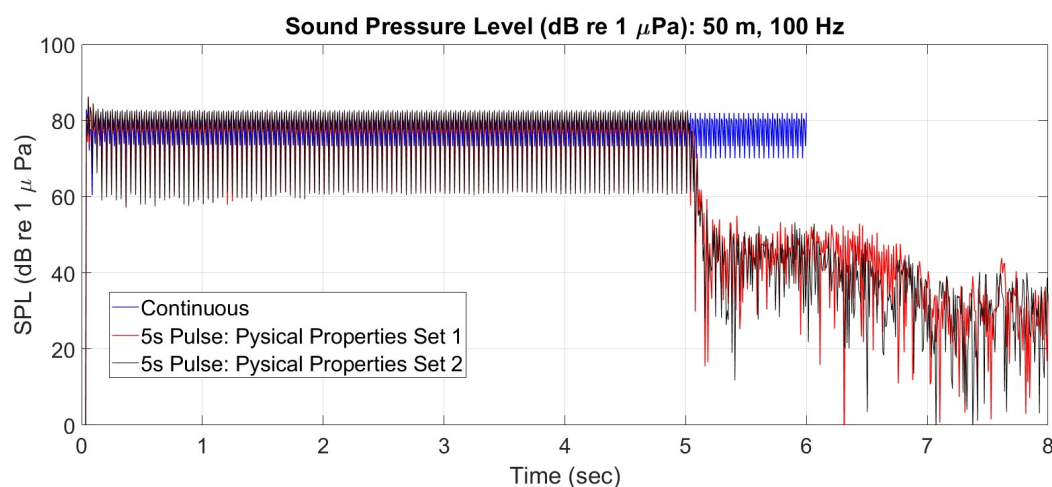


Figure 5.10: SPLs in time located at the sensor array, 50 m from the source produced by all 2D, 100 Hz ParAcousti models at that distance.

SPLs increase in general slightly for the 100 m distance over the 50 m distance by approximately 4 dB re 1 μPa . This is related to the bathymetry represented by the cross-section for 2D models. The 100 m cross-section has a sharp increase in the sea floor on the right hand side of the model not present in the 50 m cross-section. This change in bathymetry would increase reflections back to the sensor array as opposed to a shallower, rounder bottom section observed in the 50 m data.

As the experimental data was recorded as a series of pulses, the pulsed data was selected to be further compared with the experimental data set. One concern with the experimental data was that energy from the previous frequency level would still be present

in the environment once the following pulse in the series was initiated. The pulse data from ParAcousti indicates that values fall below 65 dB re 1 μPa ambient within the 0.1 seconds of pause between pulses and so the amount of energy remaining in the system is likely to be obscured by ambient noise. SPLs peak for the 100 m data set at 86 dB re 1 μPa and are lowest for the 1 km data set at 65 and 75 dB re 1 μPa for the continuous, initial pulse data and the secondary pulse data, respectively. This indicates that sound is nearly at or below ambient values when it has propagated 1 km away from the source. A comparison of the secondary pulse 2D data is shown in Figure 5.11. The overlay of the SPLs in time indicates the noise in the reflected data once the pulse has stopped increases and the levels remain fairly constant but slowly dissipating after the initial drop. A secondary drop is observed after 6 seconds, which approximately coincides with the time when the signal would have encountered the boundary of the bay a second time, given the sound speeds in the model.

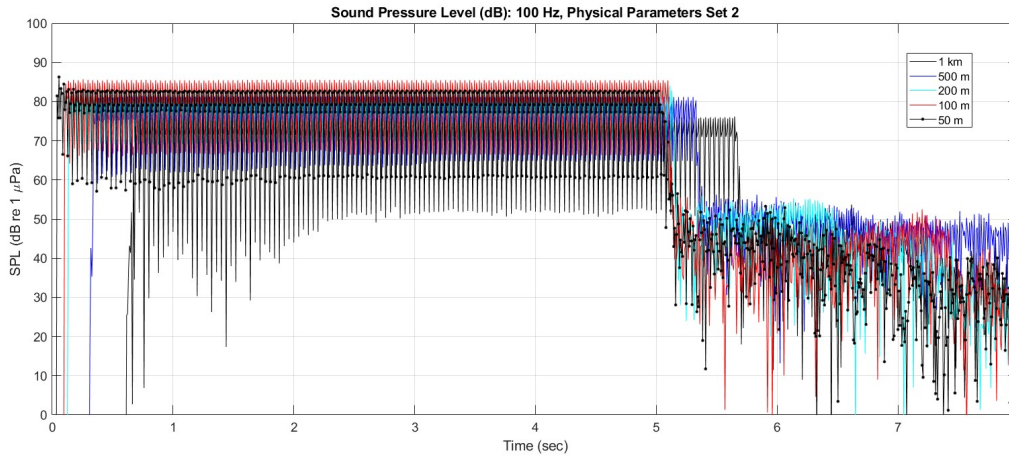


Figure 5.11: Comparison of all 2D, 100 Hz pulse ParAcousti SPLs in time calculated at the sensor array for distances 50, 100, 200, 500, and 1,000 m from the source with Set-2 physical parameters.

ParAcousti allows for data to be output as a snapshot in time within a cross-section of the model domain. For the 2D models, data was output every 8×10^{-2} seconds along the y-axis for all values of x and z. Pressure values were converted to SPLs in dB re 1 μPa at the times

of 0.5, 1.0, 3.0, 5.0, 6.0, and 8.0 seconds for the 1 km distance output and 5.0 seconds for each of the other distances. The time of 5.0 seconds was chosen as that time is immediately prior to the point in time that the pulse is terminated and is the most comparable to a continuous signal. Root mean square values were calculated over three wavelengths, or 10 time steps, to smooth the data slightly as sound pressure spikes may occur instantaneously and distract from the overall trend of the data. Any MHK device operating at a site would be operating continuously. It also provides a point in the data where the solution is comparable between all five distances and is the closest to a steady state solution. Figures 5.12 - 5.18 depict the output from each of these instances in time; the black line denotes the bottom of the bay. Note that the 2D model runs shown are for the first set of physical parameters, not the second. The images produced from the second show similar trends. By displaying this model output, it is more easily compared at 5 seconds to the continuous data from the 3D models.

Figures 5.12 - 5.17 display the progressing sound wave as it is emitted for a total of 5 seconds, requiring approximately 1.8 seconds to propagate from the source location to the furthest boundary. Once, the sound wave reaches the boundary of the bay, the interaction with the sediment layer results in a substantial amount of the energy from the sound wave being reflected back into the water column. Sound that does pass into the sediment layer dissipates and continues to propagate out of the domain. Directly under the source, sound pressure levels are maintained as the angle of incidence is low resulting in a decreased amount of reflected and dissipated energy. The density changes present in the sediment layer additionally cause the sound waves to refract and have a larger wave spacing as compared to sound waves in the water column. This interaction is most evident in the outer corners of the domain where the water level is minimal. At the completion of the pulse, sound energy dissipates rapidly and the last of the pulse can be seen at 6 seconds for the 1 km data reaching the boundary of the bay. After which it is reflected back into the

water column off of the sediment layer, represented at 8 seconds. Reflected sound waves will combine constructively or destructively depending on the interaction resulting in regions of higher and lower SPLs. SPLs reach a maximum of approximately 120 dB re 1 μPa at 1 m from the source.

A comparison of all distances at 5 seconds, provided in Figures 5.18 - 5.21 indicates a compression of the propagated wave spacing in time as the wave is recorded further from the initial source. This could partially be due to the difference in bathymetry as well as the fact the cross-sections associated with the larger distances increase in size resulting in a larger model domain. The 200 m cross-section is particularly rough and indicates more of the initial pulse energy is reflected back at the sound source. The 50 m and 100 m models have the fastest dissipation rates for energy, but also exhibit the model domains with the smoothest bottoms, which would reduce reflections back into the model and enhance the attenuative properties of the sediment layer.

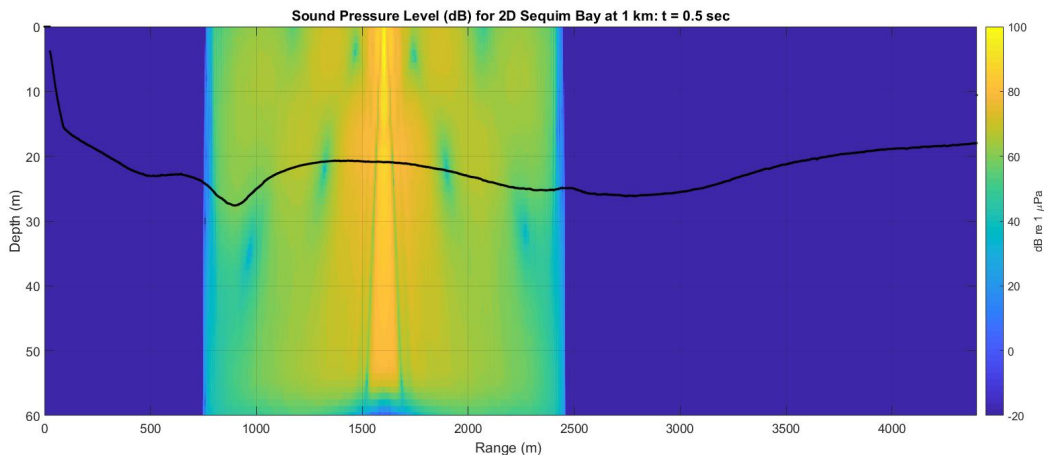


Figure 5.12: SPLs at 0.5 seconds output from the 2D, 100 Hz ParAcousti model; sensor array is located 1 km away from the source.

Spectrograms of the 2D pulse data at the sensor array with the second set of density and sound speed parameters were calculated to validate that the only frequency levels detected

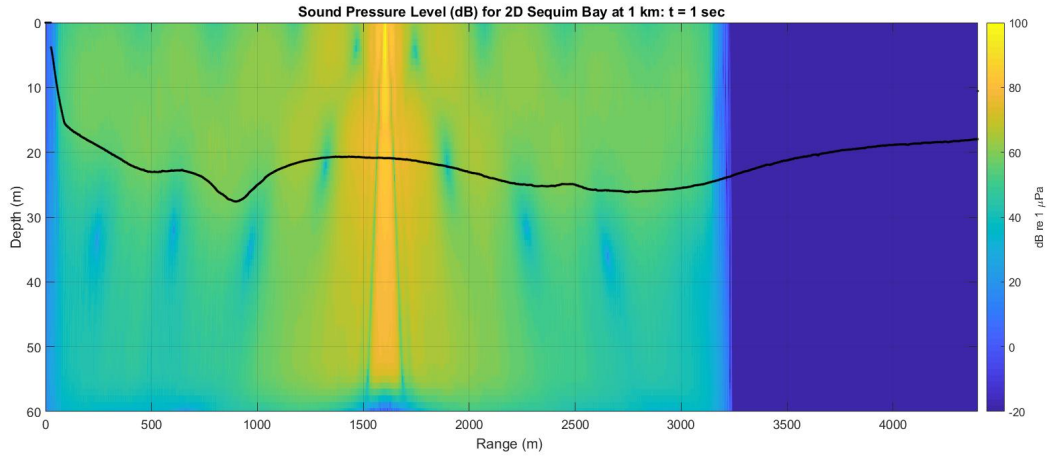


Figure 5.13: SPLs at 1 seconds output from the 2D, 100 Hz ParAcousti model; sensor array is located 1 km away from the source.

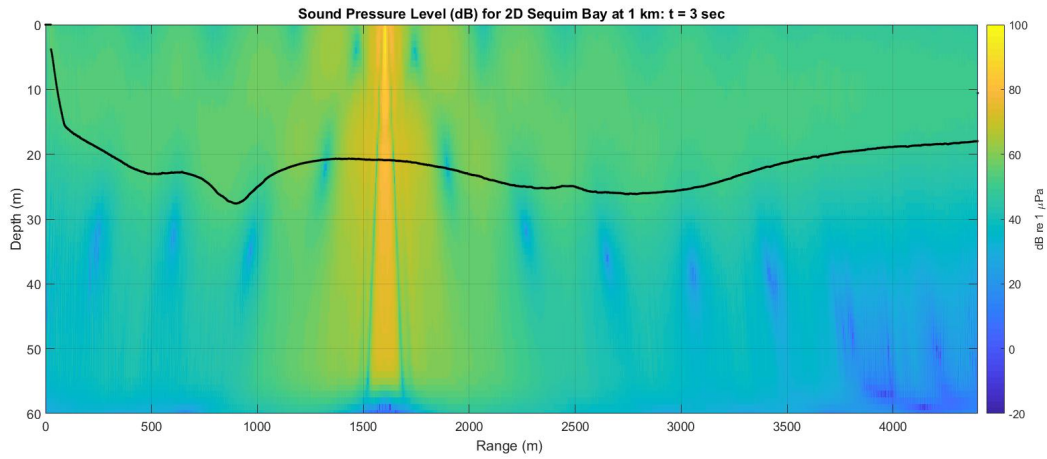


Figure 5.14: SPLs at 3 seconds output from the 2D, 100 Hz ParAcousti model; sensor array is located 1 km away from the source.

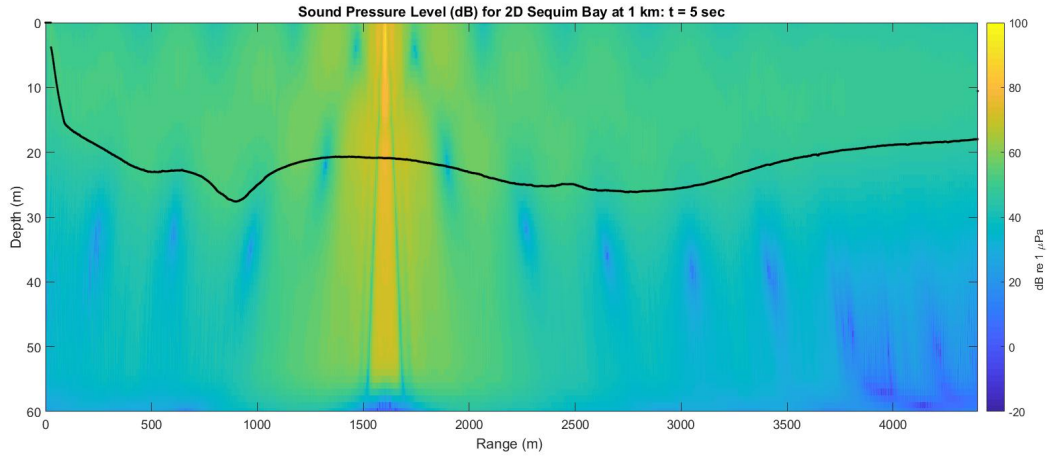


Figure 5.15: SPLs at 5 seconds output from the 2D, 100 Hz ParAcousti model; sensor array is located 1 km away from the source.

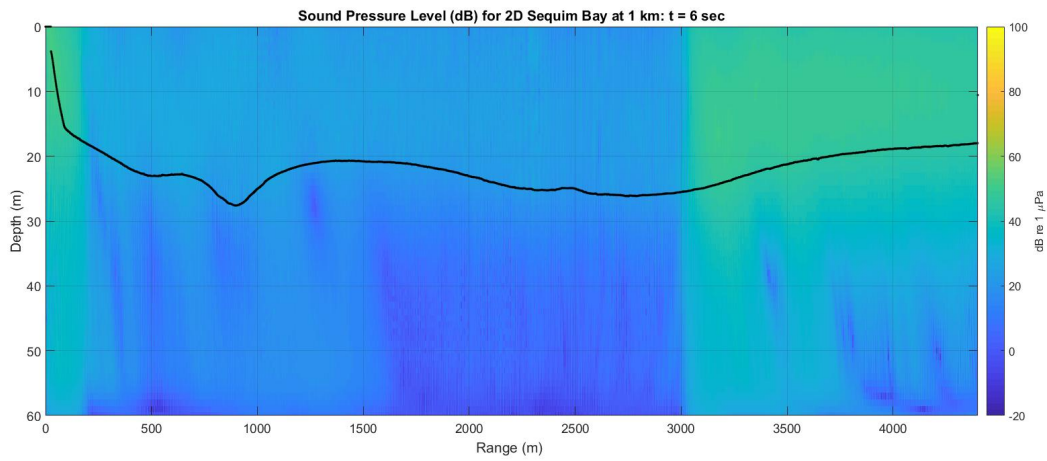


Figure 5.16: SPLs at 6 seconds output from the 2D, 100 Hz ParAcousti model; sensor array is located 1 km away from the source.

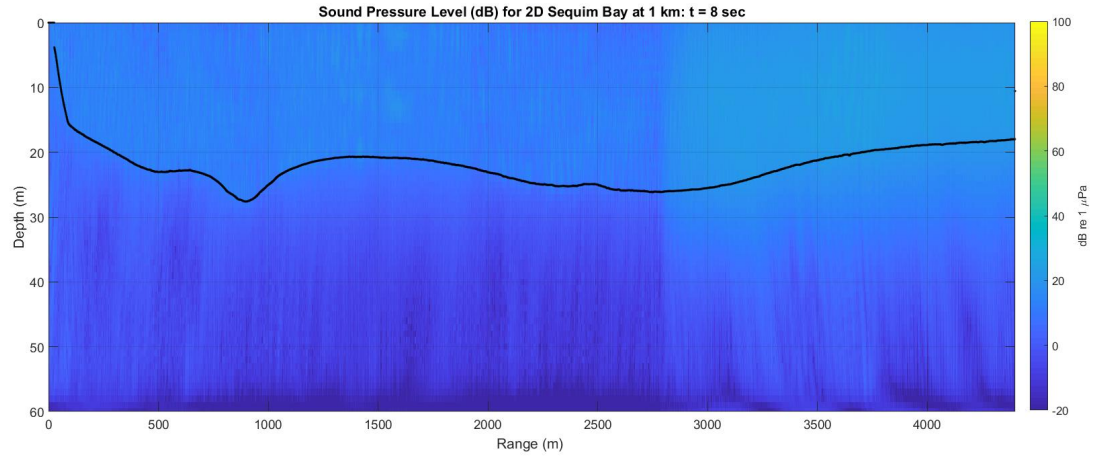


Figure 5.17: SPLs at 8 seconds output from the 2D, 100 Hz ParAcousti model; sensor array is located 1 km away from the source.

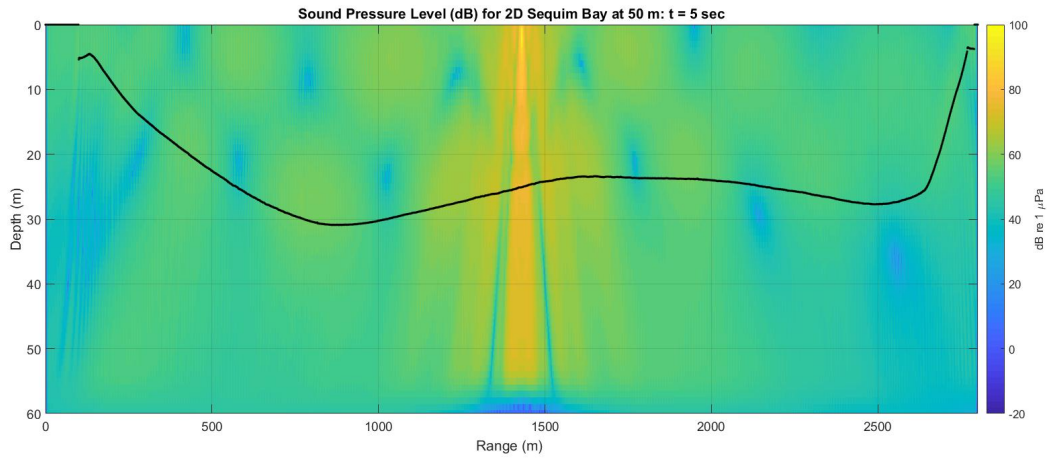


Figure 5.18: SPLs at 5 seconds output from the 2D, 100 Hz ParAcousti model; sensor array is located 50 m away from the source.

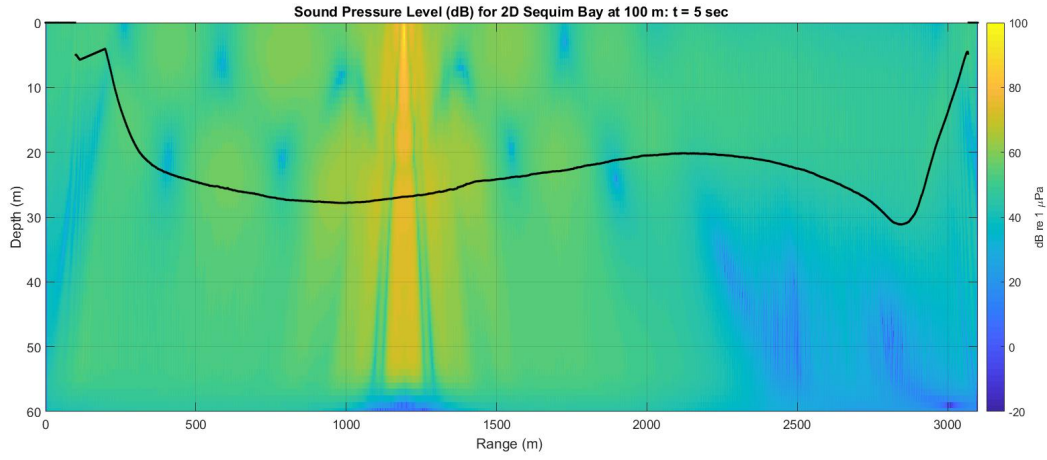


Figure 5.19: SPLs at 5 seconds output from the 2D, 100 Hz ParAcousti model; sensor array is located 100 m away from the source.

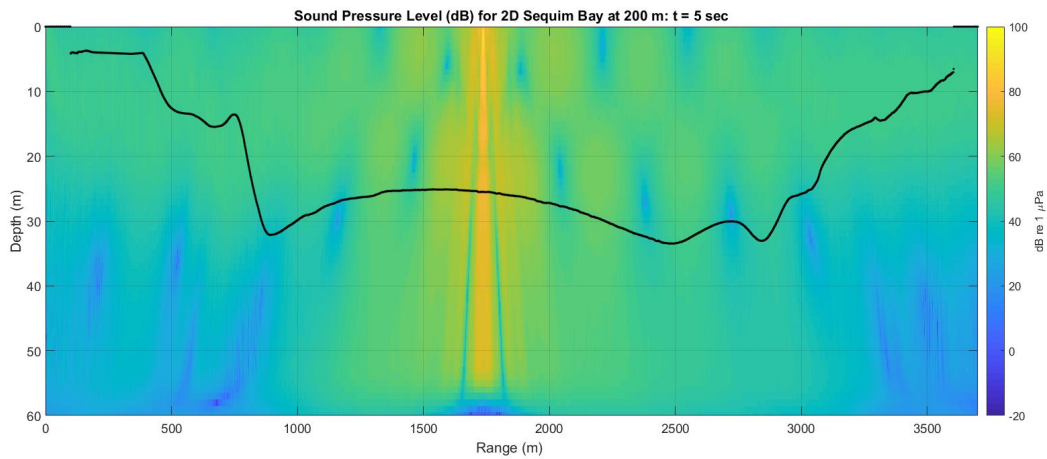


Figure 5.20: SPLs at 5 seconds output from the 2D, 100 Hz ParAcousti model; sensor array is located 200 m away from the source.

were 100 Hz. Data was calculated for all five source locations and distances from the sensor array. The spectrogram shown in Figures 5.22, indicates a primary frequency of 100 Hz for the first 5 seconds which dissipates in energy after the pulse is ended. The start of the main pulse is also indicated by a large jump in power levels associated with when the energy from the source reached the sensor array. All five spectrograms show frequency levels other than the 100 Hz of approximately 600 and 850 Hz. Energy in both of these bands dissipate after the initial emission of the source. Spectrograms were calculated for each distance and reflect and decrease in power levels as the distance from the source increases. The plots are expressed in SPLs (dB). After 850 Hz, there is a very low level of energy present in all frequency bands up until the end of the pulse. This indicates that the interaction of the signal and the environment cause a slight bleeding of energy levels into all frequencies, almost similar to a broadband signal. Recorded power levels are consistent with the SPLs recorded in time for the same locations. Additional spectrograms are available within Appendix A.

3D Model Results

As a comparison to the 2D models, 3D models were also calculated for the bay. For this case, the entire bathymetry was interpolated onto a grid 2800 x 4626 x 60 m in the x, y, and z dimensions, respectively. The time step was set to 8e-5 seconds for all 3D models that were set to run to 8 seconds for a continuous, 100 Hz source. The model domain was set with the first set of physical properties. Two source distances from the sensor array were calculated: 500 and 1,000 m. The 1,000 m run timed out resulting in a shortening of the data out to 5.5 seconds. However, a steady state condition in the model is reached by approximately 3 seconds. Data at the location of the sensor array in time was output for the 500 m location and compared to that of the 2D output with the same source and physical parameters for the model domain. Figure 5.23 illustrates the two data sets superimposed on one another. Both values show similar SPL levels at approximately 80 and 76 dB re 1 μPa

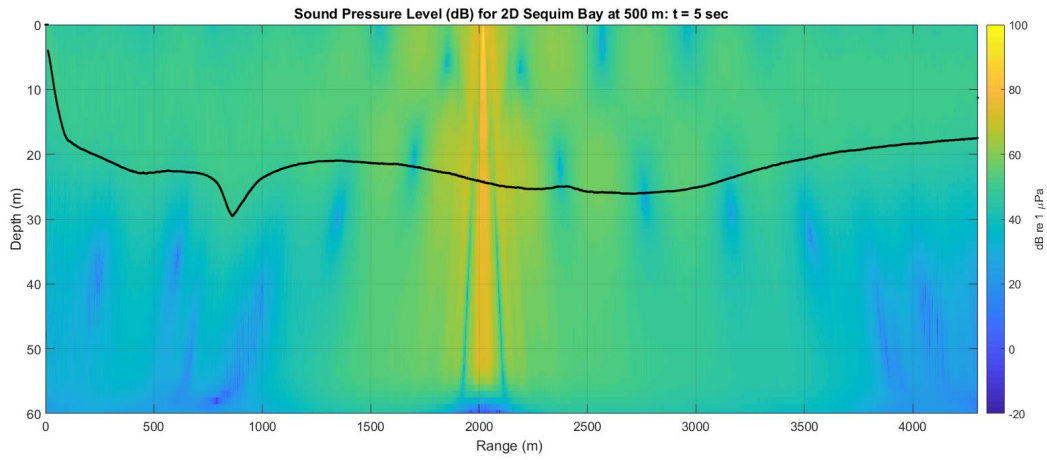


Figure 5.21: SPLs at 5 seconds output from the 2D, 100 Hz ParAcousti model; sensor array is located 500 m away from the source.

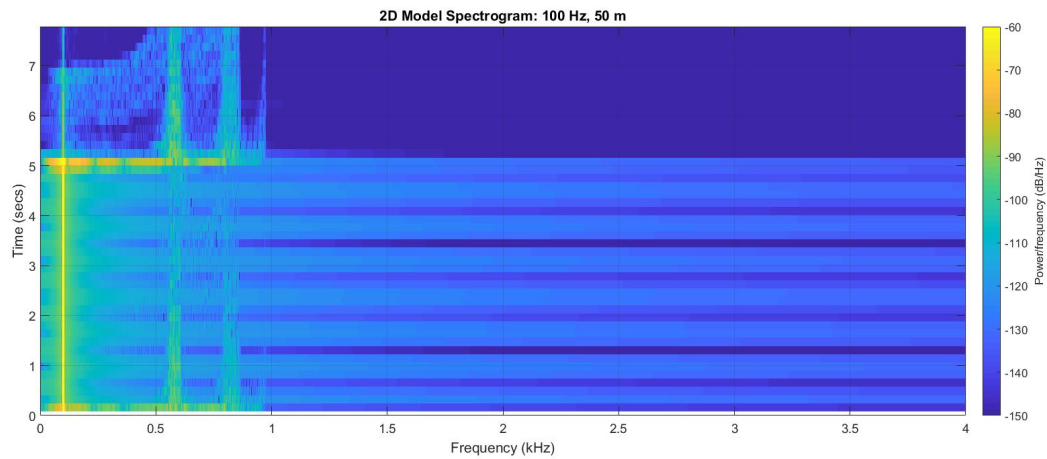


Figure 5.22: Spectrogram analysis of the 2D ParAcousti pressure output in time modeling a 100 Hz source located 50 m from the sensor array. Data is located at the sensor array.

for the 3D and 2D data sets, respectively, at that 500 m distance. An increase in 3D values over that of the 2D was not expected; however, a 3D system will include every surface along the bottom of the bay from which energy may be directed inward creating a more complex sound environment. This is additionally demonstrated by the variability of the data itself. The 3D data is considerably more noisy and has a greater range of values associated with the top and bottom values of the propagating pressure waves. The 2D model domain is reduced and would not incorporate those additional interactions within the domain.

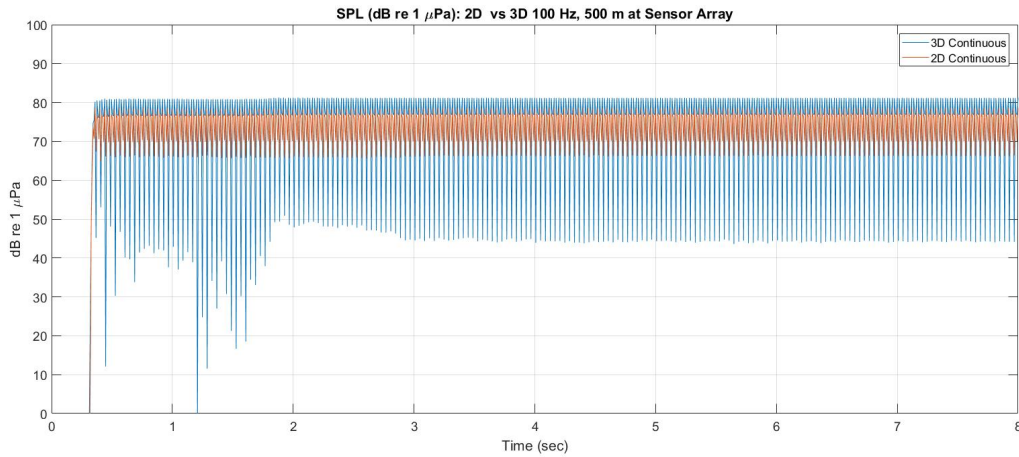


Figure 5.23: Comparison of the SPLs in time from the 2D and 3D ParAcousti model outputs for a 100 Hz continuous source operating 500 m from the sensor array.

As the 3D model run sources were continuous, 500 of the calculated 1,000 snapshots in time of the domain were overlaid to calculate the SPL of the domain for the last 4 seconds when a steady solution had been reached. The SPL cross-section in the domain was taken at a depth of 3 m so all data would be with respect to 1 m from the source. The slice provided is in plan view, or with respect to the x and y dimensions of the domain. Output is shown for the 1,000 m source distance in Figure 5.24. The plan view aspect allows for the entire bay outline to be resolved. Sound waves propagate outward from the source until the boundary of the bay is reached, at which point the energy is either reflected back or

refracted within the sediment layer. The depth of 3 m allows for the pressure waves to be relatively undisturbed by the bottom of the bay but also indicates that SPLs at this depth maintain a level of over 80 dB re 1 μPa until the edge of the bay. Near the bottom of the Figure 5.3, there is a dramatic increase in the rise on the bottom of the bed creating a type of reflective wall. Both the right and left ends of the bay are relatively shallow in comparison and serve to quickly attenuate sound as it is not reflected back into the bay. SPLs have a greater amount of dissipation for the 1 km source. Indications of greater attenuation and dissipation are present near the boundaries of the bay itself. As the slice is placed at only 3 m from the surface of the water, few changes in environmental parameters are present to effect a reduction in energy until the edges of the bay and model domain are reached.

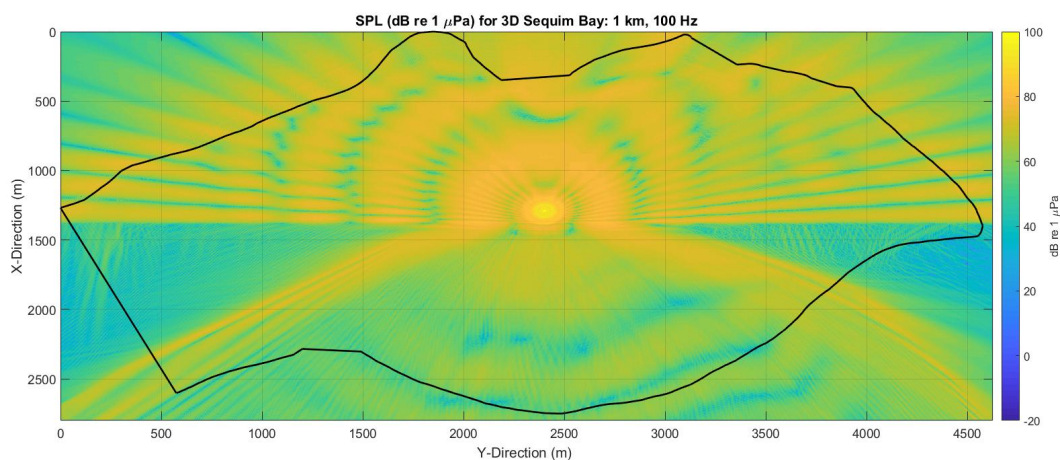


Figure 5.24: 3D ParAcousti SPL output for 100 Hz model with the source located 1 km from the sensor array for a continuous source function.

While Figure 5.24 displays the steady state sound pressure level throughout the bay at the 3 m water depth, 1 km source location, at 50 Hz, a 1.5 second pulse for 50 Hz was also simulated within the bay to determine how quickly sound energy levels leave the bay or are reflected back into the water column from the sediment layer. Data was collected at various points in time at a depth of 3 m within the bay. Figures 5.25 - 5.30 demonstrate how the

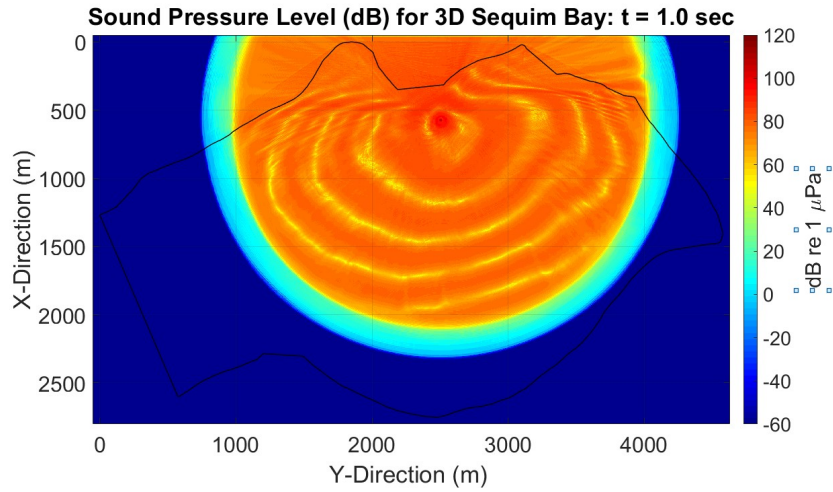


Figure 5.25: 3D ParAcousti SPL output at time equal to 1.0 seconds as a 1.5 second pulse propagates outward from the 1 km source location at 50 Hz, 3 m below the surface of the water.

sound energy moves outward through the 3D bay. Sound reaches the outer limits of the bay by 1.5 seconds and by 2.0 seconds the ring indicating that the pulse has stopped producing sound can be seen propagating outward from the sound source location. All of the main pulse energy has left the bay by 3.0 seconds. The maximum SPL value of the source was set to 120 dB re 1 μPa re 1 m. As ParAcousti does not model any additional ambient sound, all positive SPL values are produced by the sound source itself. Energy is still present after 3.0 seconds indicating that the sound waves are being reflected off the sediment layer and back into the water column. The reflection angles within the wave paths are visible at 4.0 seconds. At a time of 5.0 seconds, the secondary energy waves that were reflected back into the bay and bounced around are not leaving the system. The additional complexity of a 3D system is evident in how energy remains contained within the bay itself far after the sound source has stopped emitting a frequency value. SPLs eventually fall to below 40 dB re 1 μPa after a period of 4.0 seconds and that values is maintained until the end of the simulation at 6.0 seconds.

Pressure data may also be expressed as sound energy levels (SELs), where the SPLs

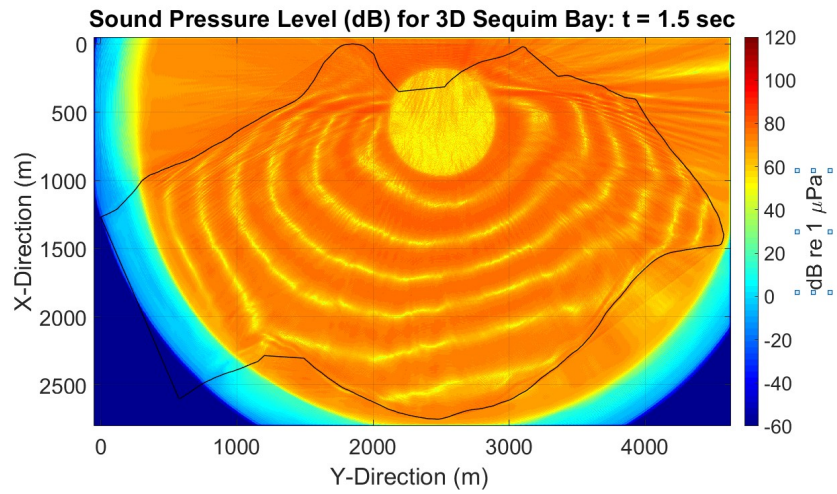


Figure 5.26: 3D ParAcousti SPL output at time equal to 1.5 seconds as a 1.5 second pulse propagates outward from the 1 km source location at 50 Hz, 3 m below the surface of the water.

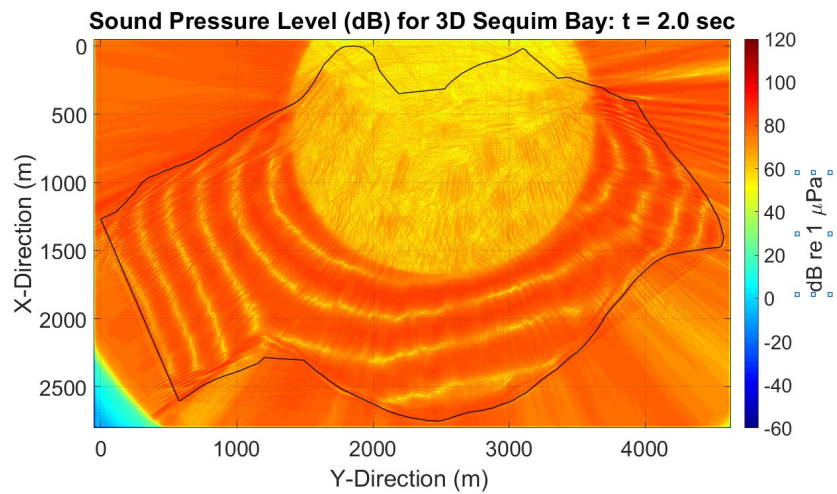


Figure 5.27: 3D ParAcousti SPL output at time equal to 2.0 seconds as a 1.5 second pulse propagates outward from the 1 km source location at 50 Hz, 3 m below the surface of the water.

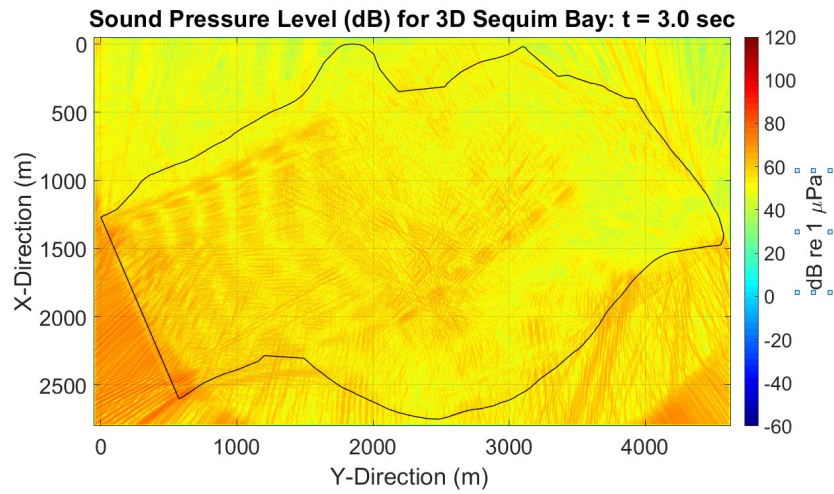


Figure 5.28: 3D ParAcousti SPL output at time equal to 3.0 seconds as a 1.5 second pulse propagates outward from the 1 km source location at 50 Hz, 3 m below the surface of the water.

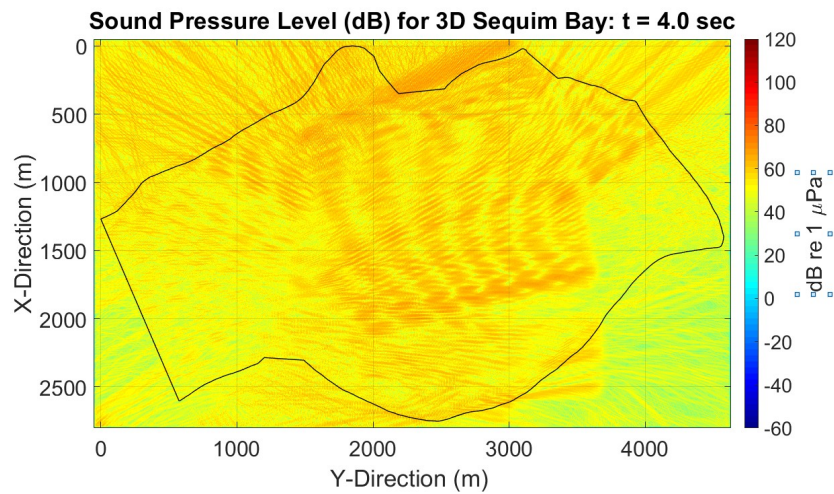


Figure 5.29: 3D ParAcousti SPL output at time equal to 4.0 seconds as a 1.5 second pulse propagates outward from the 1 km source location at 50 Hz, 3 m below the surface of the water.

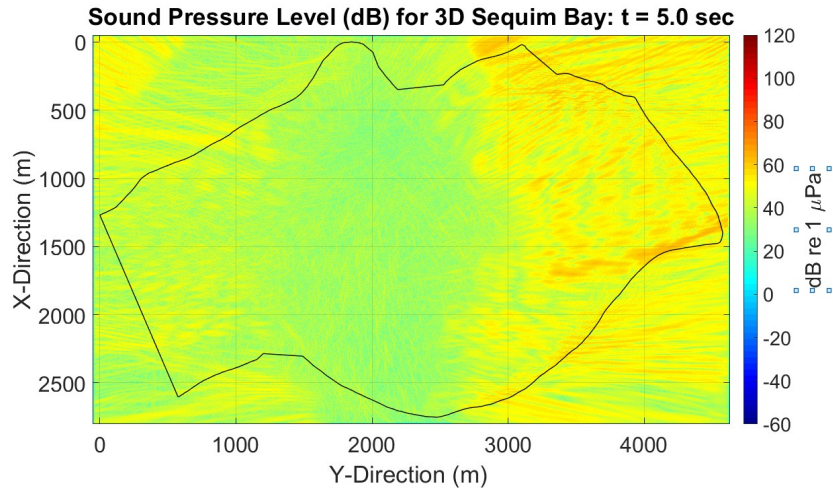


Figure 5.30: 3D ParAcousti SPL output at time equal to 5.0 seconds as a 1.5 second pulse propagates outward from the 1 km source location at 50 Hz, 3 m below the surface of the water.

of a point in time or a slice through a model domain are then integrated over a period of time to discern the cumulative effects of a generated sound in an underwater environment. As the sound continues to be emitted and propagated through an environment for days or weeks at a time, that sound will build and produce a level greater than that recorded by the SPLs. SELs were calculated for the 3D pressure results for the 1 km distance over a period of 24 hours (assuming the continuous solution is constant) and are demonstrated in Figure 5.31. Regulatory considerations typically list the allowed SEL with respect to a period of 24 hours under which the particular MHK device must fall below. For example, NOAA requires that the SEL cumulative level fall below 155 dB re 1 μPa for high frequency cetaceans [115]. For the 1 km SELs, the maximum recorded is approximately 150 dB re 1 μPa at the source location. SELs were then grouped into the maximum and average value occurring in 250 m wide bands radiating out from the source. This provides a metric from which to assess the radius away from the source that will fall below thresholds of temporary and permanent damage to a marine animal within that calculated radius. However, bands give an idea of the zones of influence within the bay as the source propagates outward. The maximums show

the pressure waves demonstrated earlier by the SPL output. Marine mammals could find areas of lower SELs surrounded by higher SELs surrounding the sound source. The radii for the permanent threshold shift (PTS) and temporary threshold shift (TTS) were calculated as 45 m at 137 dB re $1 \mu Pa^2$ and 1338 m at 112 dB re $1 \mu Pa^2$ for the energy levels. Note, these values were arbitrarily chosen to demonstrate how the results from ParAcousti can be used and do not correspond to limits for any individual species. As the bands are analyzed over a particular width, the values and distances do not perfectly agree with the PTS and TTS radii calculated based on the entire data set, were not averaged across a 250 m wide band.

Experimental Data Analysis

Data was taken from the January 16, 2018 day of the Sequim Bay project data set for comparison. The data associated with sources placed 50, 100, 200, 500, and 1,000 m from the sensor arrays were collected over a period of five hours. However, all data sets at each location (a total of five), were recorded for a maximum of 15 minutes. A spectrogram analysis of the five distances was completed. The spectrogram analysis for the 50 m distance is shown in Figure 5.32, and demonstrates that the sound source may clearly be broken down into its frequency components. Spectrogram analysis allows the user to break a broadband data set into each of its respective frequency bins. The data was separated into 4096 frequencies using a fast Fourier transform, or FFT. The sound emitted from the source was not a pure tone causing energy levels to cascade into the frequencies surrounding the intended frequency. Additionally, higher frequencies had a small energy shift causing the majority of the energy to be in a frequency approximately 2 Hz below the intended or emitted value. Spectrograms were calculated for data recorded at the sensor array and are presented in terms of dB re $1 \mu Pa$, not SPLs. Energy levels within the frequency bands are staggered by approximately 0.1 seconds and are emitted in 5 second burst consistent with the reported methodology.

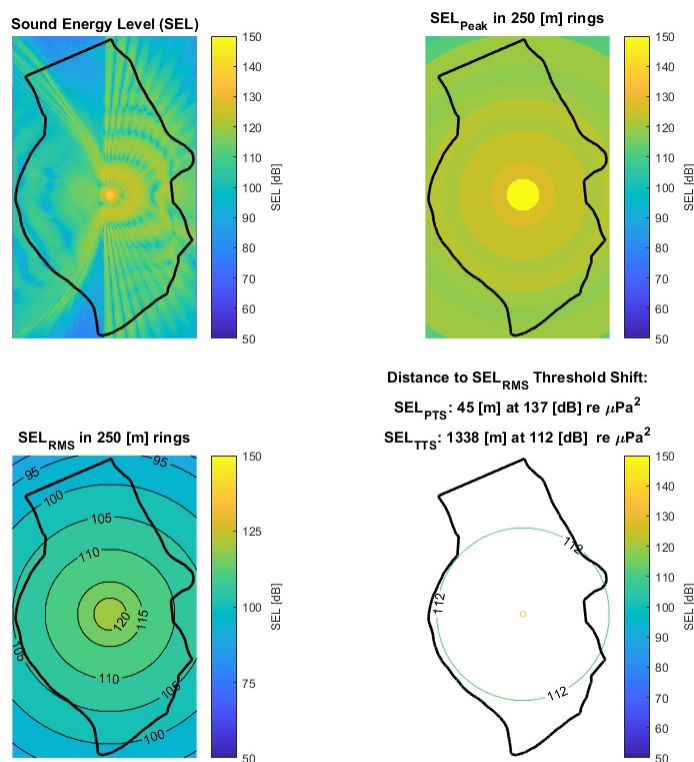


Figure 5.31: SELs for the 3D, 100 Hz data set. The source was positioned 1 km from the sensor array. Top left is the SELs for the entire bay at 3 m in depth. Top right is the maximum SEL every 300 m radiating outward from the source. Bottom left is the average SEL value every 300 m radiating outward from the source. Bottom right is the radius within which PTS and TTS standards for continuously operating MHK devices are violated.

The analysis involved in forming spectrograms causes a 1000 fold loss in data fidelity as the data is placed into the designated number of frequency bands. This loss in data causes pressure transitions between the emitted pulse and ambient data to be slightly blurred. This is further indicated in a lack of consistency in the length of pulses and gaps in the data, which are approximately 5 and 0.1 seconds, respectively, but vary up to plus or minus 0.5 seconds. Sections of the data for a singular frequency where a pulse is not present are approximately 92 seconds or 1.53 minutes when all other frequency data sets are removed. Additional

spectrograms for the 100, 200, 500, and 1,000 m distances are available within Appendix A.

Within the spectrogram, each small dot is a pulse from the source output. Data collected beyond 200 m becomes very difficult to discern the increases in energy from the frequencies produced by the pressure source. Data recorded below 500 Hz overlaps with a considerable amount of ambient noise that exists at the same frequencies and serves to obscure the emitted data. Ambient values range between 57 and 65 dB re 1 μPa and pulse values from 65 to 75 dB re 1 μPa . Note that for each location, unique frequency signatures are recorded with and over top of the emitted pulse source causing some amount of additional noise at particular frequencies.

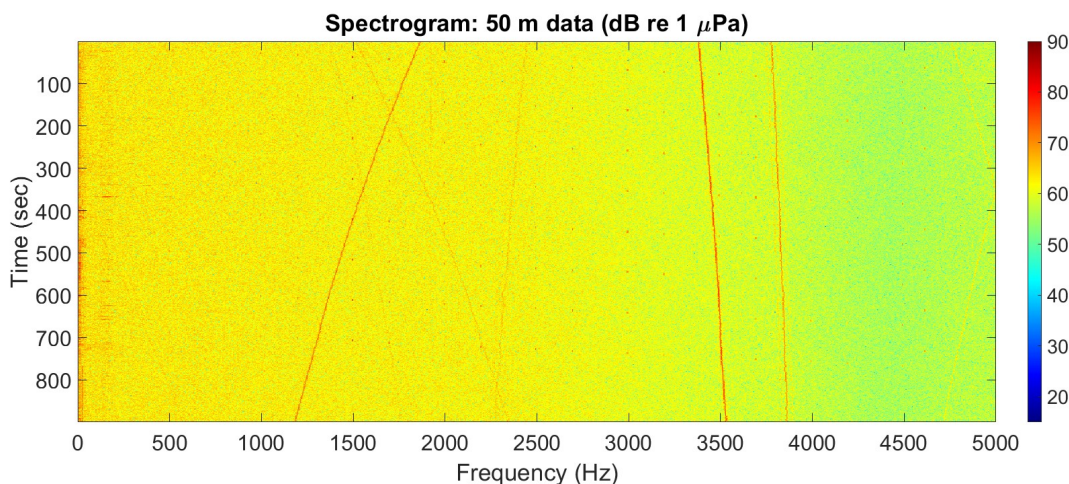


Figure 5.32: Spectrogram of all recorded Sequim Bay data in time at the source array location, 50 m from the source.

Based on the spectrogram analysis, the SPLs for the entire 15 minute block were plotted for the 50, 100, 200, 500, and 1,000 sources distances for both the 100 Hz and 500 Hz bands. Figures 5.33 - 5.34 show the SPL data through time for 100 Hz for the 50 m and 500 m. No increase in dB level is recorded due to a pulse and values are typically consistent falling near 65 dB re 1 μPa for the entire recording. This trend in data indicates that all energy emitted from the icTalk source in this frequency band is either below ambient values, obscured by

the ambient data, or concealed by the additional noise generated by other sources producing energy in the same frequency band not related to this study. The SPL values for the 500 m and 1,000 m profiles indicate it is that later, as both show values increasing in an erratic pattern correlating with the locations of added noise on the spectrogram shown in Figures A.11 and A.12. The 500 m data is particularly interesting in that it displays a discontinuity at approximately 450 seconds resulting in a maximum reading of 77 dB re 1 μPa . The 1 km data set is similar and has a maximum value of 73 dB re 1 μPa . The data profiles for the 100, 200, and 1,000 m locations are located within Appendix A as the structure is similar to the provided figures. Past model runs, acoustic propagation physics, and data sets alike clearly show that energy levels dissipate with distance. Therefore, either increased ambient noise levels or external sound sources in the 100 Hz frequency band are the likely contributing factor to the elevated SPL values.

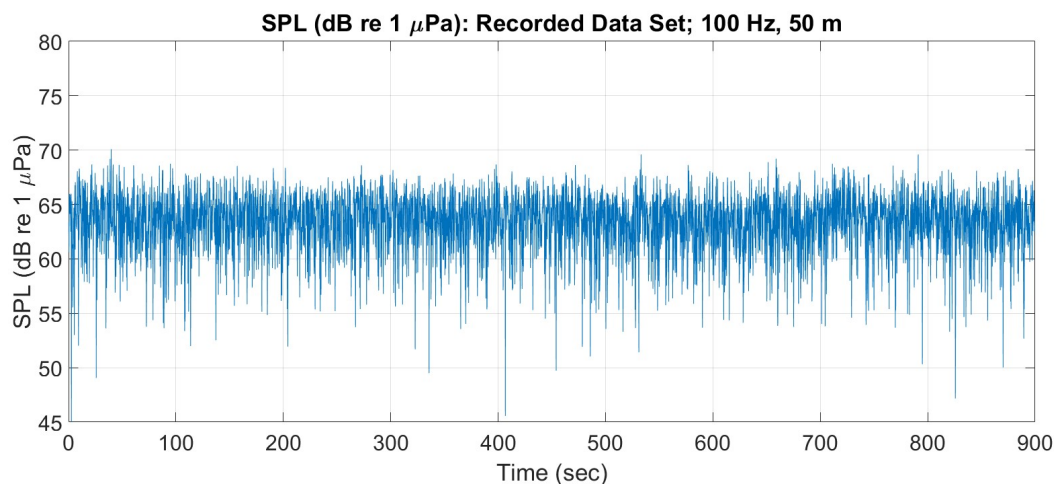


Figure 5.33: The 100 Hz recorded Sequim Bay data files converted to SPLs in time for the 15 minute emission period; located at the sensor array, 50 m from the source.

Recorded data for the 200 Hz profiles is similar to that of the 100 Hz data, where individual pulses are indistinguishable from the surrounding ambient noise. Alternatively, the 500 Hz data clearly shows spikes in the SPL data from the emitted source pulse over

the course of the 15 minute time span for the 50, 100, and 200 m distances after which the values fall to or below ambient levels. Values associated with the 500 and 1,000 m locations show similar patterns to the noise present in the 100 Hz data set; however, the effect is less pronounced, and the data remains to be noisier than the closer distances. Maximum SPLs are recorded as approximately 72.5, 70, and 68 dB re 1 μPa for the 50, 100, and 200 m distances respectively. SPL values between the pulses are consistently around 65 dB re 1 μPa , consistent with the sound emitted quickly falling to ambient levels. Pulses do exhibit a slight change in SPL value though time and are shown in Figures 5.35 - 5.36 for the 500 Hz frequency band at 50 and 500 m. This could be due to, again, interactions with extraneous outside sources or changes in environmental parameters throughout the day. Recordings for the 750 Hz band show distinct pulse structures much like the 500 Hz band, with 8 pulses occurring in total, each 5 seconds in length. Both the recorded experimental data for the 200 Hz and 750 Hz profiles, as well as the 100, 200, and 1,000 m locations for the 500 Hz data set are available in Appendix A. Recorded values for upper frequencies ranging from 1 - 5 kHz are not presented, as those frequencies were found to be prohibitively high to run in a 3D simulation for Sequim Bay due to the size of cell size required. The small cell size required memory values exceeding 200 G. Additionally, 100 - 750 Hz demonstrates a distinct overlap with the sound frequencies associated with MHK devices.

Experimental Data Comparison: 100 Hz for 2D Model Initially, the data submitted from Integral had not been calibrated to account for the change in energy profiles between the different frequencies emitted by the speakers in the bay. The first 100 Hz pulse model runs that were compared to a single pulse from the recorded data set for each of the distances available was not adjusted for that calibration. When compared to the recorded data, all of the simulation data calculated through ParAcousti was a higher decibel level than that of the recorded data. All recorded 100 Hz data falls below ambient levels and so is difficult

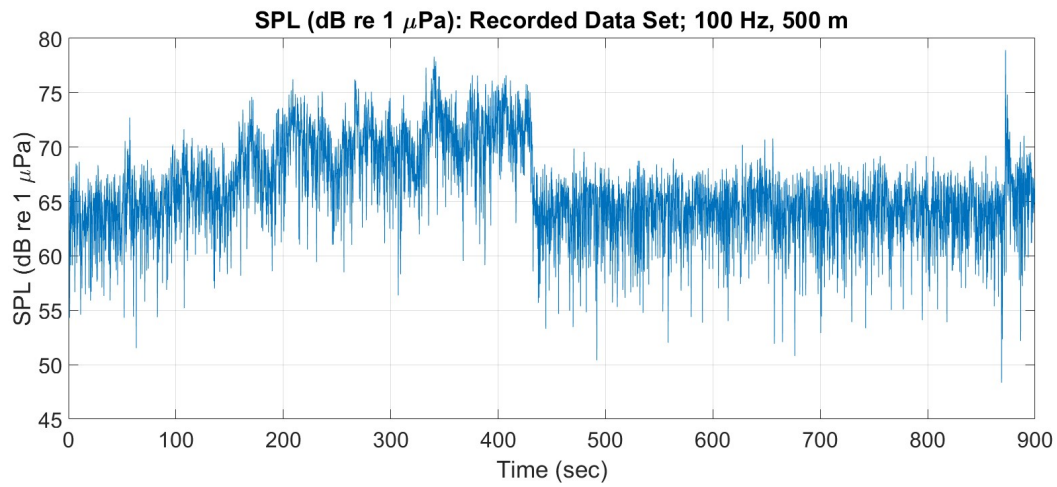


Figure 5.34: The 100 Hz recorded Sequim Bay data files converted to SPLs in time for the 15 minute emission period; located at the sensor array, 500 m from the source.

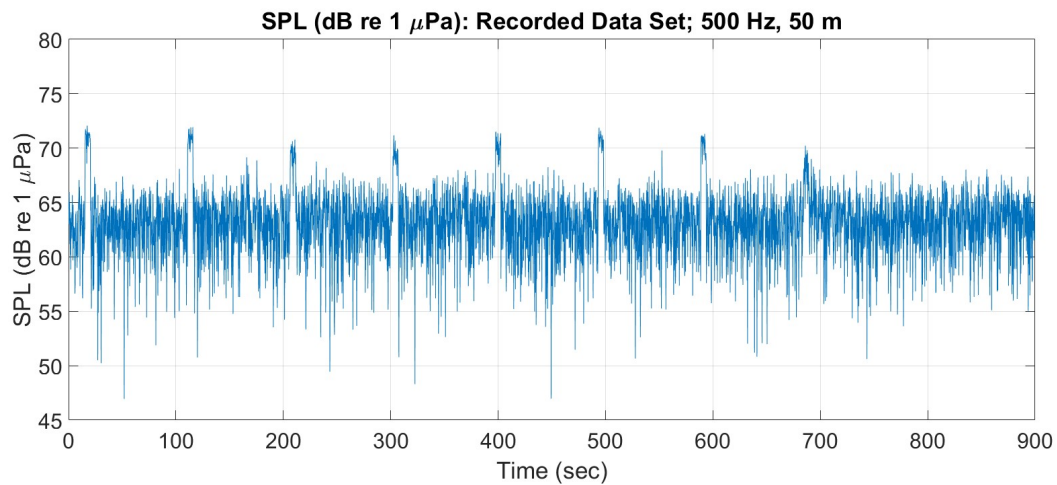


Figure 5.35: The 500 Hz recorded Sequim Bay data files converted to SPLs in time for the 15 minute emission period; located at the sensor array, 50 m from the source.

to compare to the ParAcousti models, which are modeling a sound source which does not interact with the surrounding environment. However, the results indicate that any further investigations should be considered with frequencies at or above 500 Hz where pulses are easily identified and sound decibel levels are above ambient. The results of the comparison between the 100 Hz signal and the recorded data are shown in Figures 5.37 - 5.41. Recorded values approach the ParAcousti data as distances increase.

Experimental Data Comparison: 20.3 Second Signal

All additional models have had changes in power levels factored into the model runs compared to the experimental data. The calibration is applied to each source amplitude individually. Previous models were also completed for either a continuous source or a single 5 s pulse. The experiment conducted by Integral emitted a single frequency pulse for 5 seconds with a space of 0.1 seconds between each pulse. As a pulse would require longer than 0.1 seconds to exit the full dimension of the bay before the next pulse frequency was emitted, some energy from the previous pulse would still be present in the bay before the next pulse energy propagated outward from the selected source location. 2D ParAcousti models were created to simulate the 100 - 750 Hz pulses, one propagating after the other. A total run time of 20.3 seconds was set to account for the time set between pulses as well as each 5 second burst. The model sources were set as delta functions so that each 5 second section of the 20.3 second data set could be convolved for each associated frequency. This also allows for a greater degree of freedom to change the source parameters. The domain and environmental parameters remain fixed. The density values were set to 1000 kg/m^3 and 1595 kg/m^3 for the water column and sediment layers, respectively. The sound speed was set to 1499 m/s and 1625 m/s for the water column and sediment layer, respectively. Both the 50 m and 100 m source location 2D profiles were used for these models to better compare the visible recorded pulse data, as the pulses in the experimental data are best

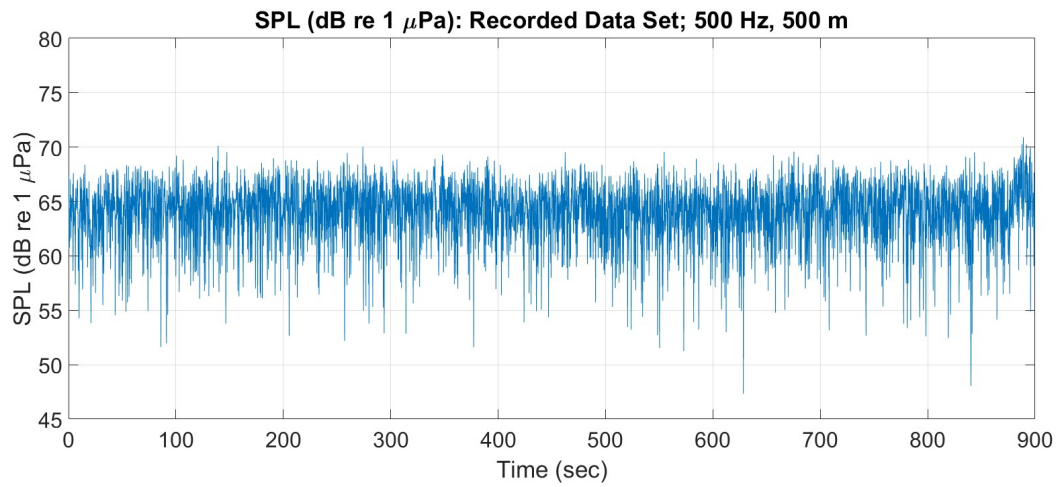


Figure 5.36: The 500 Hz recorded Sequim Bay data files converted to SPLs in time for the 15 minute emission period; located at the sensor array, 500 m from the source.

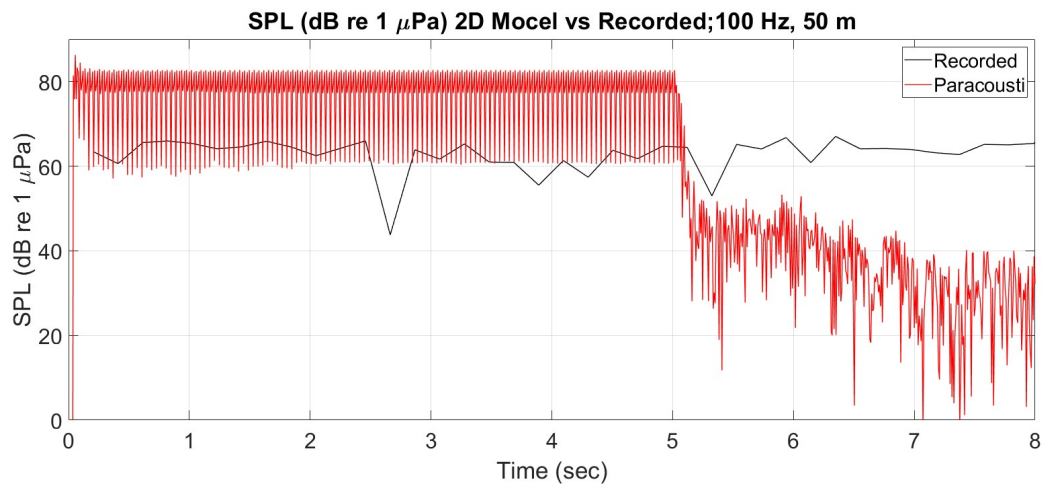


Figure 5.37: SPLs for the calculated 100 Hz pulse data as compared to the recorded data at 50 m.

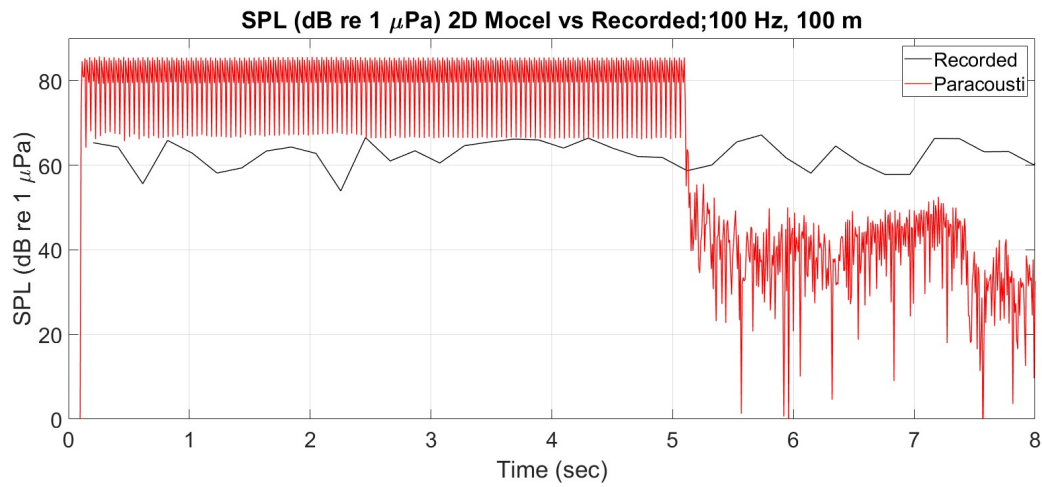


Figure 5.38: SPLs for the calculated 100 Hz pulse data as compared to the recorded data at 100 m.

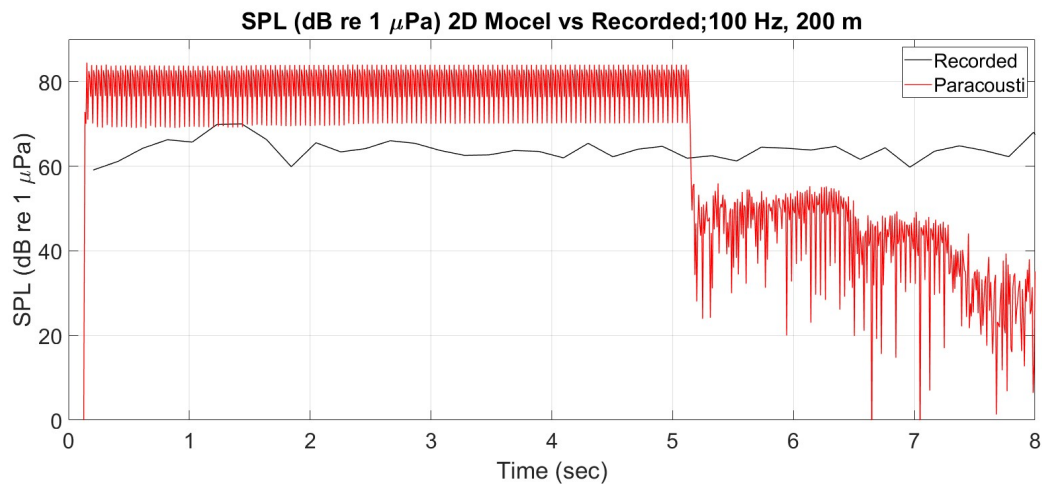


Figure 5.39: SPLs for the calculated 100 Hz pulse data as compared to the recorded data at 200 m.

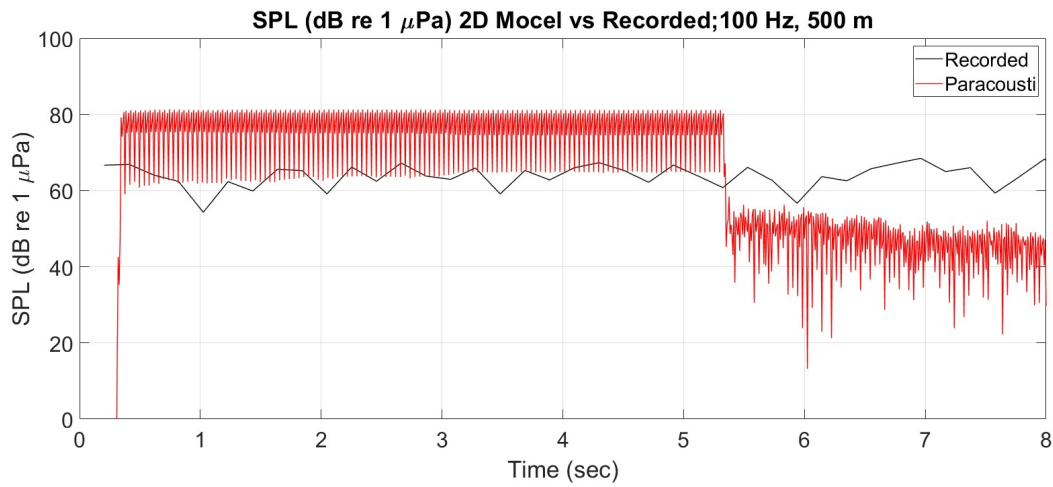


Figure 5.40: SPLs for the calculated 100 Hz pulse data as compared to the recorded data at 500 m.

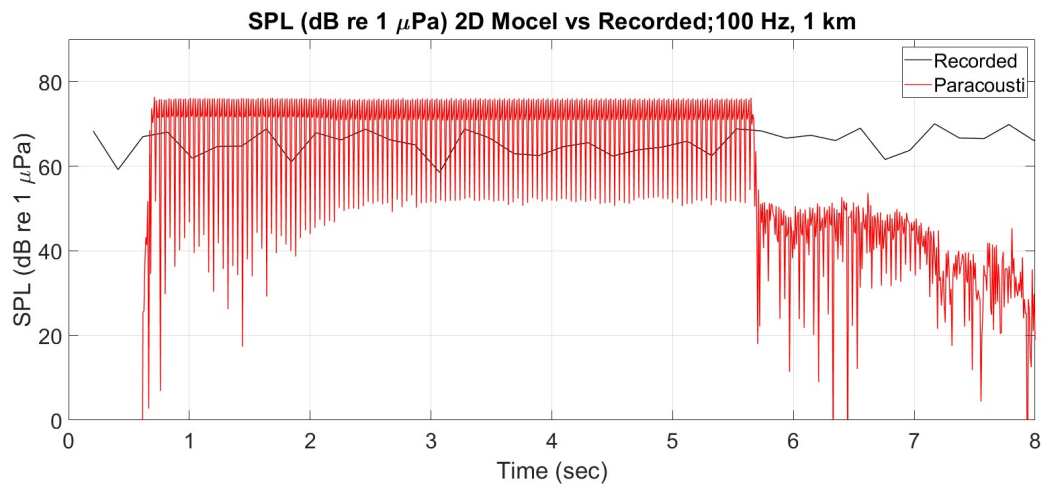


Figure 5.41: SPLs for the calculated 100 Hz pulse data as compared to the recorded data at 1 km.

identified at the 50 and 100 m locations. The 50 m source location run completed while the 100 m source location was terminated at 12 seconds due to stability problems within the computational cluster at Montana State University. Again, the receiver array structure was located at a depth of 25.2 m. Available computed data is shown in Figures 5.42 and 5.43. SPL values are consistently below 70 dB for both the 100 Hz and 200 Hz data, which is below ambient and expected. A strange occurrence appears in the 50 m data for the 500 Hz profile as compared to that of the 100 m, 500 Hz profile. The 50 m data starts at a value of 74 dB and immediately drops to a value of 62 dB, both with reference to $1 \mu Pa$. The 100 m data for 500 Hz is at a value of 77.6 dB overall. This indicates that there is a dramatic change in bathymetry between the 50 and 100 m source locations. The receiver is situated on the edge of the deepest section of the bay. The spike is not continuous if you move away from the receiver location indicating that the dramatic change in the bathymetry changes the reflections of the sound signal at specifically 500 Hz as it propagates out from the source and reflects off the bottom of the bay. The receiver is also located near the sediment layer. As the sound wave interacts with the sediment layer, sound is reflected back to the receiver adding to the noise and variability of the data set. The 100 m data is more stable due to the fact the source is further away and does not interact as much with the change in bathymetry. The 100 and 200 Hz data is lower for the 100 m location as opposed to the 50 m location as there is twice the distance to allow for energy dissipation through the system.

Experimental Data Comparison: Calibrated ParAcousti Simulation Data

Data from the 20 second simulations were used to inform the construction of another group 2D of ParAcousti simulations for all five locations using the second set of environmental parameters as well as a delta function for the the source. Models were constructed with a maximum frequency of 750 Hz and were convolved using the calibrated source functions. Cell size was set to 0.2 m, time step was set to 0.00005 seconds, and the overall domain size

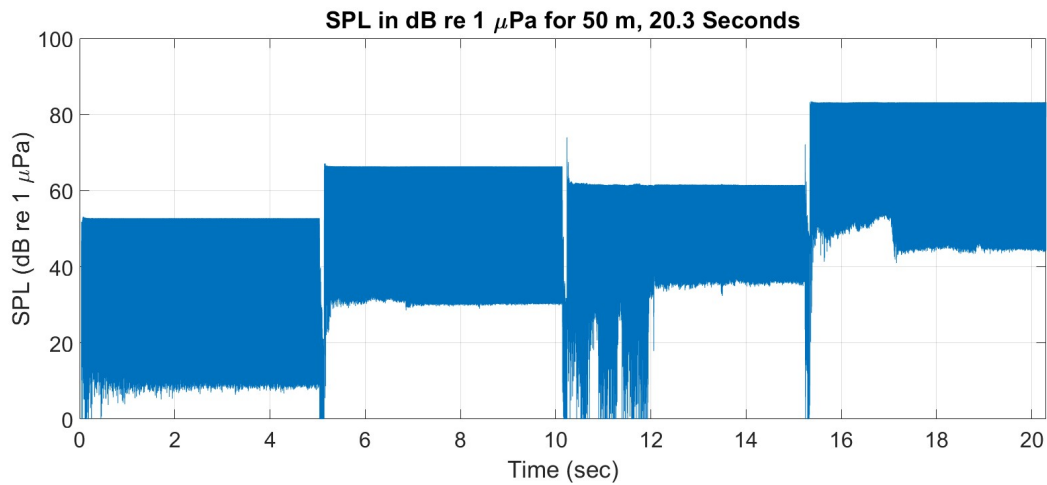


Figure 5.42: SPLs calculated for frequencies 100 - 750 Hz for the 50 m location within Sequim Bay, WA. Data extends to 20.3 seconds as that is the time required to simulate the experimental pulse data out to 750 Hz.

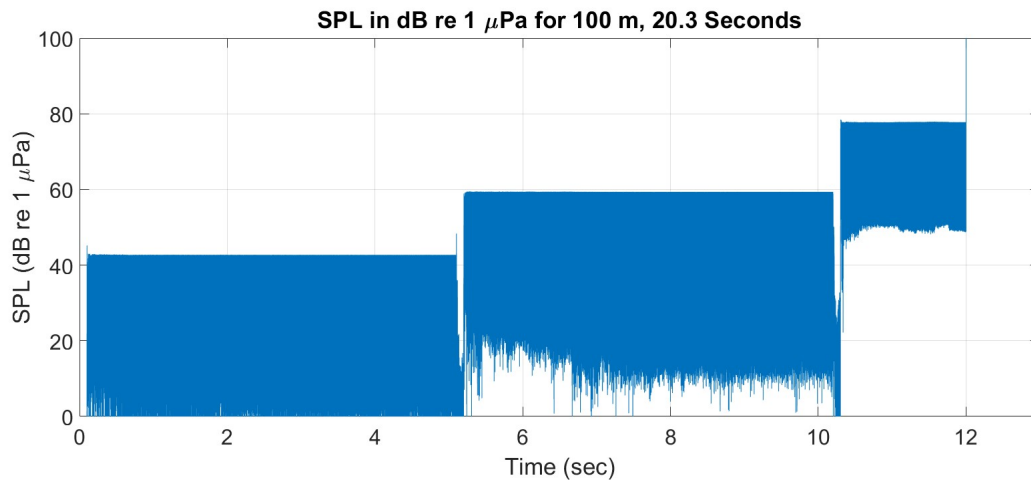


Figure 5.43: SPLs calculated for frequencies 100 - 750 Hz for the 10 m location within Sequim Bay, WA. Data was meant to extend to 20.3 seconds to fully model the pulse time required by the experimental data to reach 750 Hz; however, the model run was cut short due to cluster stability problems and ended at 12 seconds.

depended on the individual cross-section modeled. Model runs were completed to a total of 6 seconds other than the 500 m distance. That model run ended at 4 seconds due to time constraints within the computing cluster. However, there was an adequate amount of data for comparison purposes. Model data was selected for the location of the receiver array and compared to each of the eight pulses from the recorded data set for 100, 200, 500, and 750 Hz. The 200 m data is not presented within this chapter as the files were not viable. The recorded data demonstrated a variability of approximately 10 dB re 1 μPa across the eight recorded pulses for each selected frequency. Note that due to the reduction in data points that was required in order to separate the frequencies from the broadband data set, the recorded data has been muted and variability has been reduced. Comparisons between the recorded values and the simulated data were similar for the 100 and 200 Hz data sets across all locations. Both the 100 and 200 Hz data sets fall at a level equal to the ambient SPL of the bay, which is approximately 70 dB re 1 μPa and greater than the simulated SPL. Figure 5.44 shows the disparity between the the 100 Hz data and the recorded data at a distance of 50 m. The recorded pulses are clearest for the 50 m and 100 m locations. However, the recorded data does not consistently, clearly indicate a pulse for the 100 or 200 Hz data. As ParAcousti does not include ambient sound energy, model results should be below ambient for both of these frequency values.

SPLs were both calculated and compared to the recorded data for 500 and 750 Hz frequency ranges as well. Again, when the recorded data was analyzed, recorded pulses were most evident for the 500 and 750 Hz frequency ranges at 50 and 100 m in distance. The 200 m distance indicated sporadic, fluctuating sound pulses that heavily overlaid with external sound sources that were not generated directly by the study completed by Integral. Figures 5.45 - 5.52 demonstrate the comparison between the recorded and simulated data sets for the 500 and 750 Hz profiles. Notably, for all data comparisons, the time that the sound wave reaches the receiver is identical for the recorded data and the simulated. The

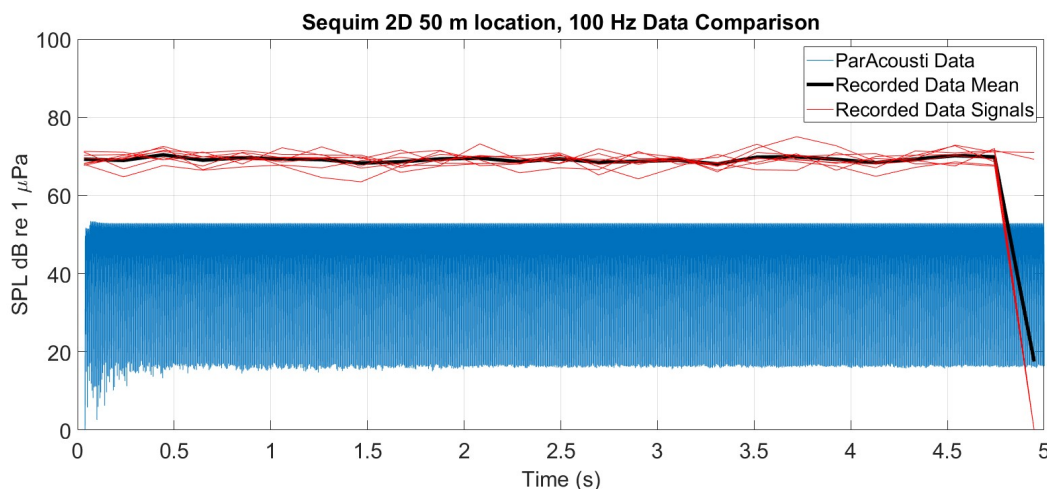


Figure 5.44: A comparison between the eight recorded signal pulses at the receiver array location 50 m from the sound source, with a frequency of 100 Hz.

recorded data is represented by a singular pulses which are removed from the broadband data set and aligned to the simulated data. Separating the frequencies and analyzing the pulses to collate the 5 seconds of pertinent data occasionally causes some of the eight pulses to not be equal in length. That is represented by a zero within the data profile, which is why several of the final data points go to zero at 5 seconds within the figures. All simulated values follow expected decay trends and data reception times indicating that ParAcousti is providing viable data. However, few of the profiles match the recorded data within the range of variability expressed within the recorded pulses. For the 50 m distance, the top of the 500 m profile is within range of the recorded source profiles. However the 750 Hz values are approximately 8 dB re 1 μPa higher than the upper range of the recorded data set. The 750 Hz values have the largest amplitude and amount of energy imparted on the source profile from the calibrated data. The increased energy contribution from the source in combination with the reduced number of interactions in the 2D system as compared to a 3D system may cause the SPLs to be inflated as compared to the recorded data set.

The data comparison for the 100 m location show a discrepancy of the 2 - 5 dB re 1

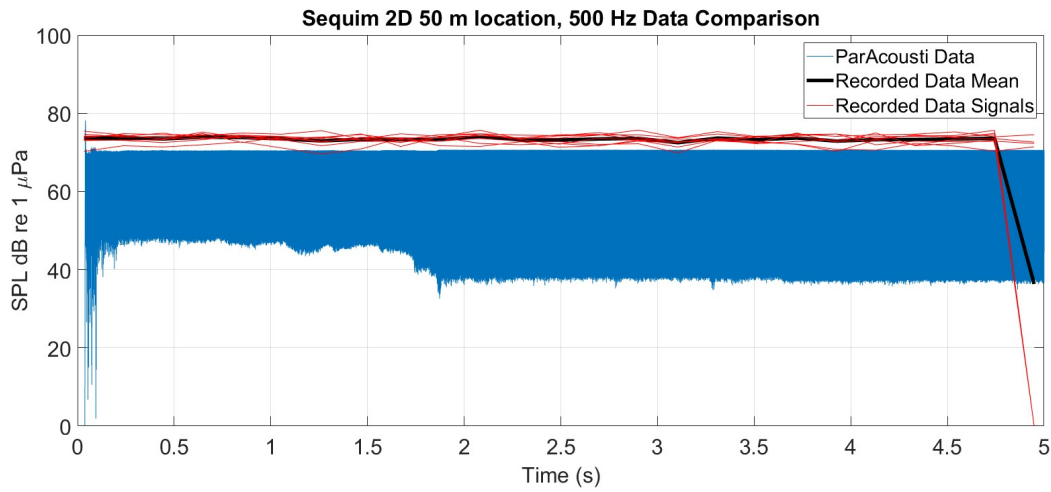


Figure 5.45: A comparison between the eight recorded signal pulses at the receiver array location 50 m from the sound source, with a frequency of 500 Hz.

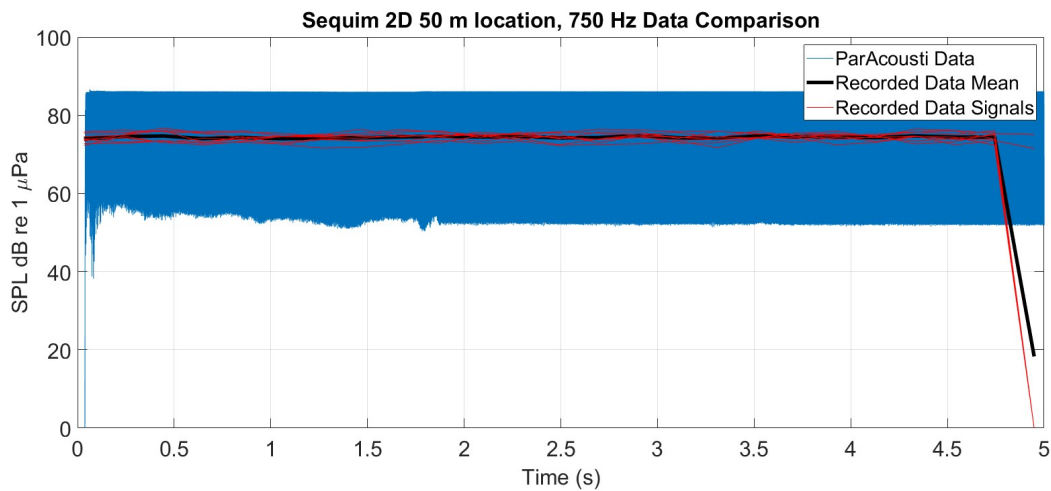


Figure 5.46: A comparison between the eight recorded signal pulses at the receiver array location 50 m from the sound source, with a frequency of 750 Hz.

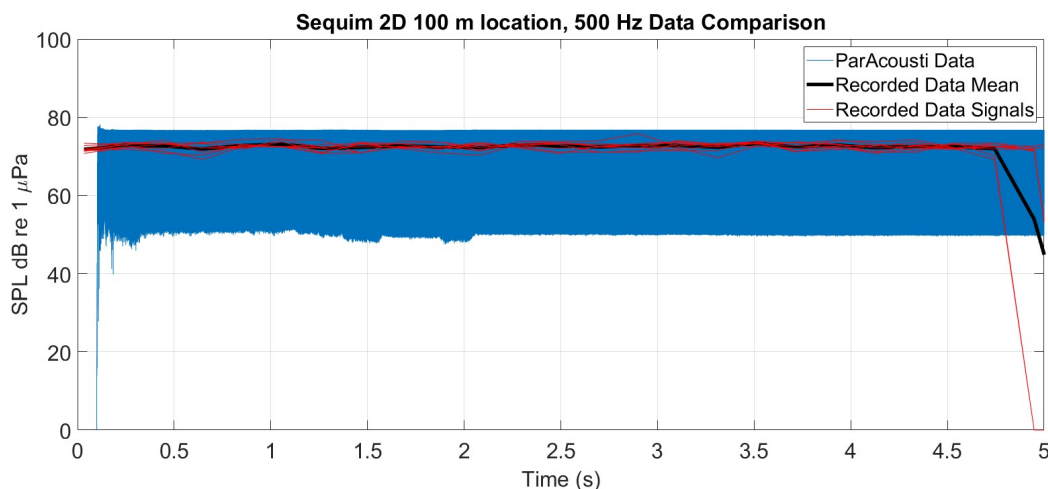


Figure 5.47: A comparison between the eight recorded signal pulses at the receiver array location 100 m from the sound source, with a frequency of 500 Hz.

μPa above that of the upper bounds of the recorded data for the 500 and 750 Hz frequencies, respectively. Values are consistently high indicating that the shape of the bathymetry could be influencing causing the model to predict larger values. The 500 m distances differ in that the 500 Hz data again falls directly in line with the recorded data set; however, the 750 Hz data remains 1 - 4 dB re 1 μPa higher than the recorded data. The recorded data sets additionally increase in variability as the distance from the sound source increases. An increase in distance would increase the number of interactions between the sound wave and the environment or other ambient sound already present within Sequim Bay. As the sound environment becomes more turbulent and the source SPL reaches ambient, variability will grow to match that of the ambient background noise. The pulses dissipate into the background sound profile. SPLs for the 500 Hz simulated data at 500 m is approaching the value of ambient noise.

Finally, the compared values for the simulated data at a distance of 1,000 m was unique as it shows a dramatic reduction in SPL for the 500 Hz data set while the 750 Hz data set is now approaching ambient and is matching the recorded values. The recorded values show a

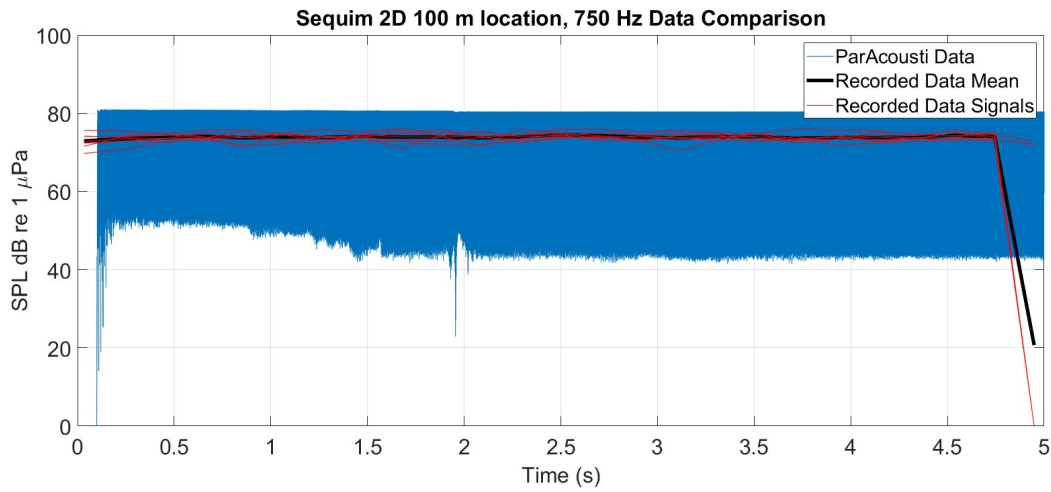


Figure 5.48: A comparison between the eight recorded signal pulses at the receiver array location 100 m from the sound source, with a frequency of 750 Hz.

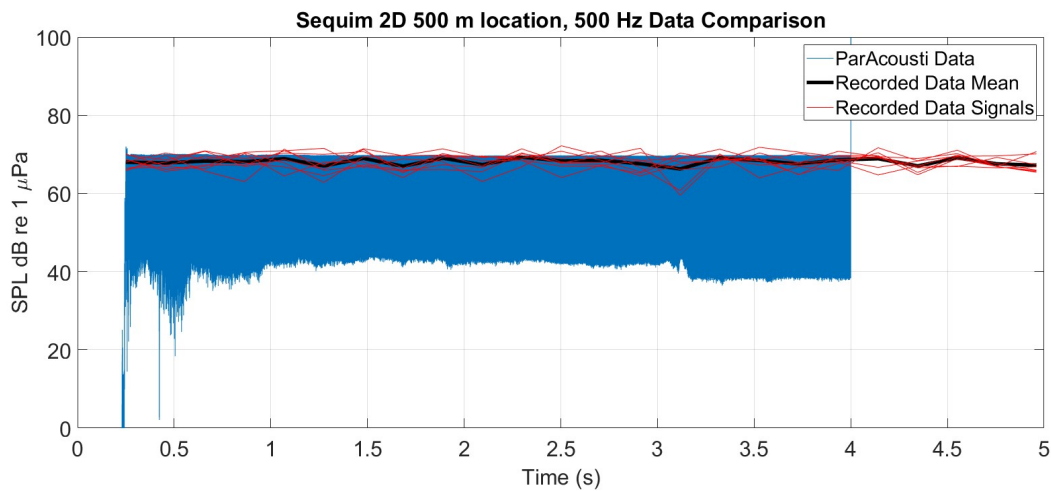


Figure 5.49: A comparison between the eight recorded signal pulses at the receiver array location 500 m from the sound source, with a frequency of 500 Hz.

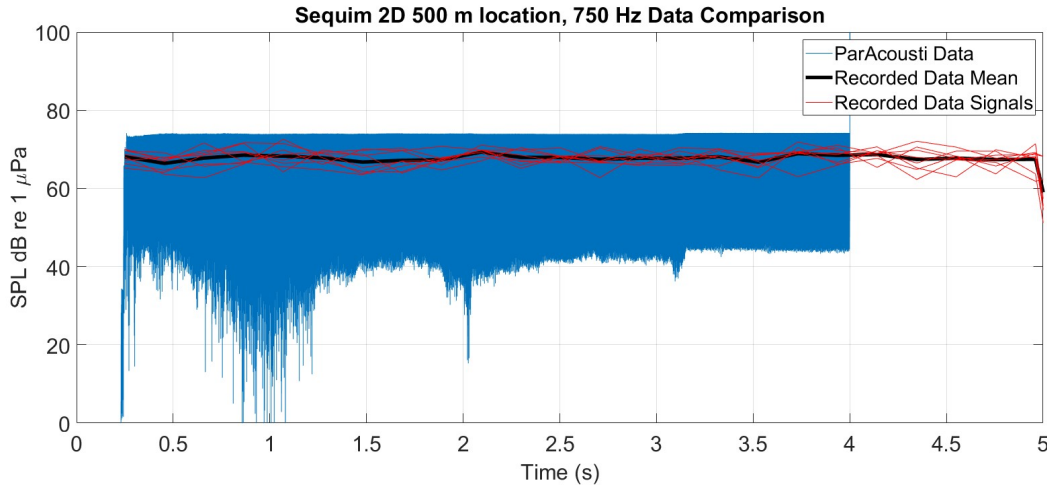


Figure 5.50: A comparison between the eight recorded signal pulses at the receiver array location 500 m from the sound source, with a frequency of 750 Hz.

greater amount of variability of approximately 10 dB dB re 1 μ Pa as opposed to the 1 - 2 dB dB re 1 μ Pa range demonstrated in the 50 m distances. The 500 Hz data at 1,000 m is also distinctive in that it presents a single spike at the initial point when the signal arrives at the receiver location. The SPL values immediately plummet. This particular change in slope in the SPLs is only present in the receiver locations surrounding the receiver array location within the model domain. This suggests that the combination of bathymetry and frequency cause an immediate dampening affect of the sound source at that location. The cross-section for the 1,000 m location does present a sharp depression which descends upwards of 8 m from the elevation of the receiver array, which is also located on the other side of hill. SPLs drop to 20 dB re 1 μ Pa below the recorded values for the 500 Hz, 1,000 m simulated data set.

Potential Error Sources

Overall there is evidence that ParAcousti is appropriate for modeling complex, real world systems with a monopole source function. ParAcousti did not identically match the recorded data sets. Values did, however, fall below ambient at the expected frequency values and were within the range of variability within the recorded data for several of the tested

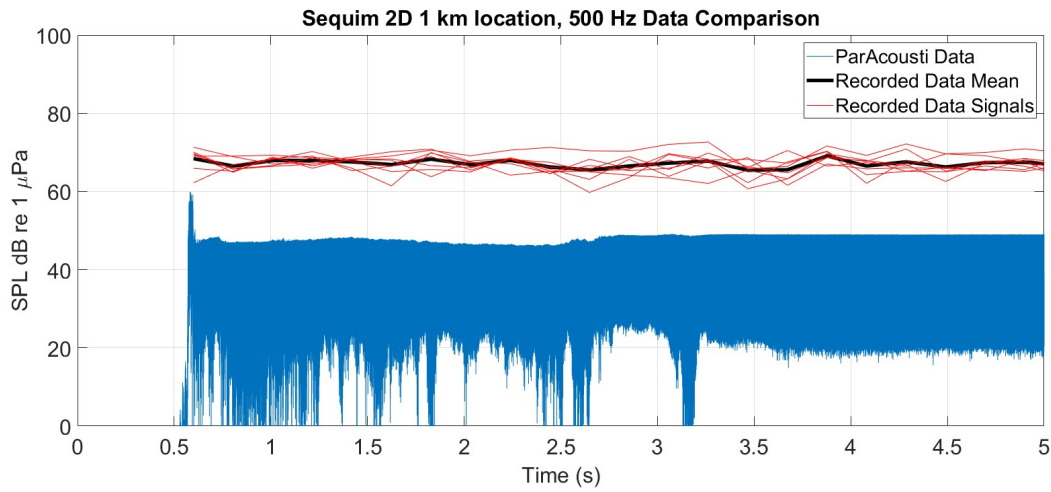


Figure 5.51: A comparison between the eight recorded signal pulses at the receiver array location 1,000 m from the sound source, with a frequency of 500 Hz.

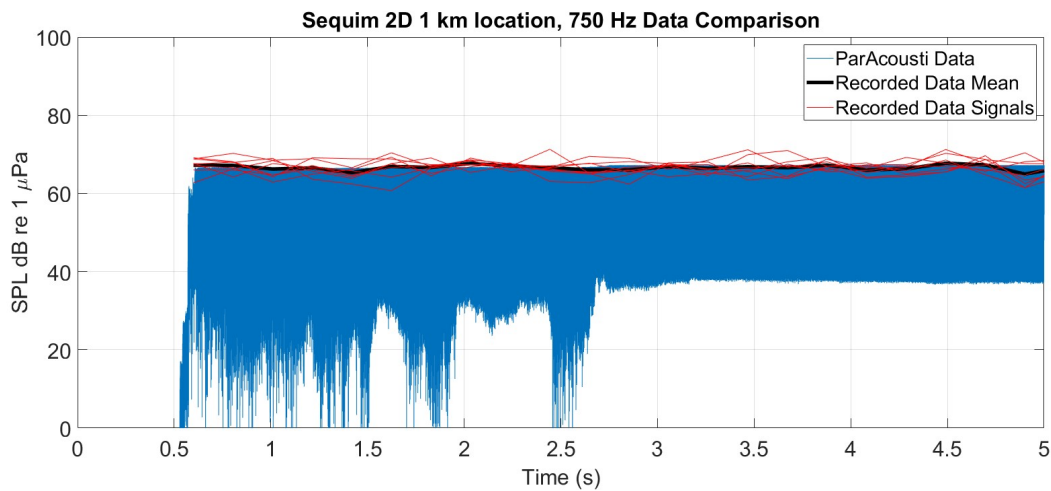


Figure 5.52: A comparison between the eight recorded signal pulses at the receiver array location 1,000 m from the sound source, with a frequency of 750 Hz.

frequencies and locations. Values for the 750 Hz range were consistent high, while the 500 Hz data sets exhibited matching or a singular erratic result. Time to the receiver was as expected. SPLs are As acoustic data is plotted on the log scale, a difference in SPLs does represent an tenfold increase in pressure. The earlier validation efforts provide strong evidence that ParAcosuti and the velocity-pressure equations adequately and accurately model underwater acoustic propagation. Several factors could be contributing to the error demonstrated between the recorded data set and the simulated. Density could be adjusted to represent a higher salinity content and attenuation built into the model to simulate the 'fluff' layer documented in the benthic report. The receiver array is near the bottom and would be situated with the benthic deposits. Attenuation was not included as the contribution was assumed to be small based on published documentation. Notably, the sources were lowered off the side of a ship while the sources were emitting. The orientation of the ship was not documented, which could cause the emitted sound waves to interact with the ship itself resulting in a dampening effect as the sound waves are reflected back into the water column. Bathymetry data was collected with a GPS tracking system which can have an error of up to 5 m. Finally, real world environments are complex. Sequim Bay contains a large number of factors not present within the model in the form of ambient noise, marine fauna sounds, and physical objects present within the bay such as ships that are not present with the model. All of these additions increase the uncertainty within the environmental parameters used to construct the model itself. Building uncertainty into the model would allow the model to account for or indicate the amount of variability within a real world environment.

3D vs 2D Model Comparison

A 3D model was constructed for the entire Sequim Bay for a maximum of 150 Hz with a source location of 50 m. The model had a grid size of 1 m, a time step of 0.0001 seconds, and a total of 720 million grid points. The simulated data was convolved with a calibrated, 100

Hz sound source. SPLs were compared against the simulated 2D values and subsequently the previously provided recorded data for the same parameters. Superimposed data from both the 3D and 2D models at the 50 m receiver location are presented in Figure 5.53. In contrast to the non-calibrated 3D simulation for Sequim Bay, presented earlier in this chapter, the calibrated 3D data is lower than that of the 2D data by 2 dB re 1 μPa . Both models present similar decay rates, arrival times, and wave forms. Modeling the entire 3D Sequim Bay incorporates all reflections demonstrated earlier in the 3D slice profile through time. These reflections may lead to an increased dampening effect or a spike depending on the location of interest. While, values are close to one another, this data set indicates an increased dampening effect of the SPLs within the bay. Sound would both be reflected back in to the bay and be reduced in energy as the sound wave traveled into the sediment layer. Sequim Bay is small enough that sound is reflected back toward the source from all boundaries before the frequency value changes or the sound source stops emitting sound. Source calibration as well as updating the simulated density values to better match the documented soil type resulted in a drop in SPL between the 3D models. Real environments are complex. Rarely do 2D systems fully capture how sound is moving through a 3D system with canyon walls and variable boundary conditions. The 2D cross-section from the 50 m data set provides canyon walls on either side on the cross-section. This would increase the amount of energy that is reflected back toward the receiver and suggests that the 2D, 50 m model may more appropriately match the 3D results than the 500 m or 1,000 m cross-sections, which are flatter and do not represent as much change in bathymetry.

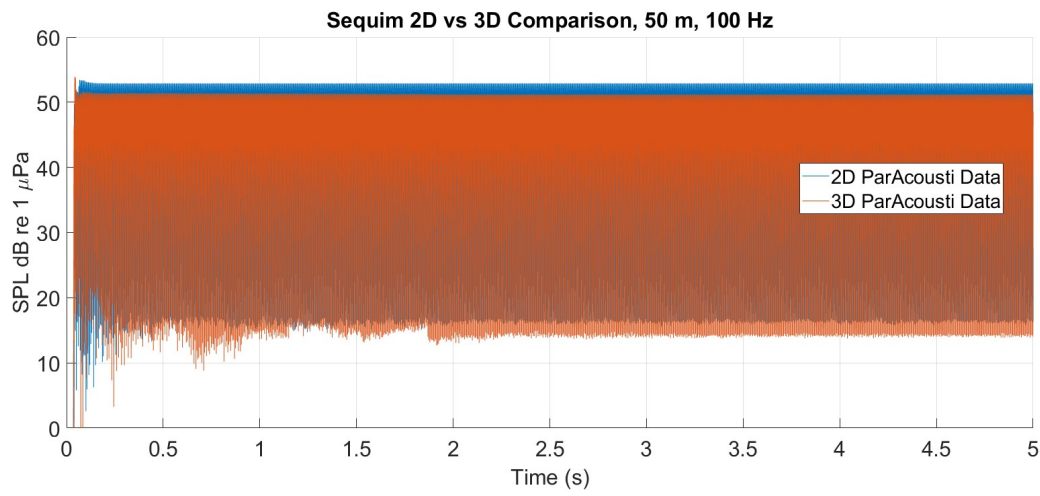


Figure 5.53: A superposition of the the calibrated 3D and 2D ParAcousti solutions at 100 Hz, 50 m from the source location at the receiver array location.

CHAPTER 6: UNCERTAINTY ANALYSIS

Marine hydrokinetic (MHK) energy devices have been in research and development and small-scale testing in the United States for over a decade. This push was initiated to meet renewable energy goals published by the Department of Energy for 2030. Current energy converters (CECs) are a sub-set of MHK devices, which remove energy from water currents, as opposed to wave motion, and are predominately designed as either a vertical- or a horizontal-axis turbine. In addition to their ability to generate electricity, CECs produce a unique sound signature that is determined by the individual design of the device, orientation, and operating conditions; and how that noise is propagated will depend upon the environmental properties of the deployment locations. Any new sound source(s) will interact with those already present in the environment (anthropogenic and natural) [15, 16, 17, 35, 36]. The anthropogenic sound produced by CECs typically fall within the frequency range of 50 – 1500 Hz.

A typical MHK deployment will include an array of devices, working in concert with one another, to maximize energy production at a particular location. However, increasing the number of sources in an area has the potential to increase their relative impact on the environment. Individual sound sources interact with one another, influencing the outward propagating energy levels. As the number of devices increase, minor variations in the generated noise from these sound sources have a possibility of creating uncertainty in the propagated sound environment. Additionally, trends observed at one location may not be general across deployment locations. Previous research of modeling MHK arrays is limited and has generally focused on their layout and orientation in order to maximize power output [33, 40] or to analyze the effect on near-bed velocities and shear stress [42]. Additionally, research conducted on array power optimization often assumes that all devices are operating identically and optimally. Present studies often fail to incorporate variability between each

device within an array. Furthermore, no analyses have been undertaken to investigate the uncertainty associated with parameter variations within an array of MHK devices. For the same site and location of devices, uncertainty in the propagated sound can be linked to the individual source parameters (e.g. frequencies, phase, magnitude, etc.) and operating conditions (how the sound profile changes with different flow conditions or power output requirements). Understanding how variability within a system contributes to uncertainty within the soundscape and the potential range of expected pressure levels and particle accelerations can help minimize potential, negative environmental impacts.

While this version of ParAcousti is deterministic, variability may be included by running hundreds of simulations to analyze potential uncertainty within an array of CEC devices. Previously, work completed for ParAcousti has been centered around validation of the tool and improvements to the model. This particular effort shows how ParAcousti may be applied to reduce potential environmental effects when dealing with an array of devices, where changes in the system or operating conditions may lead to variations within the produced noise levels. Uncertainty may be a result of reduced fidelity and error within measurements, changes in operating conditions, aging of equipment, or temporal variability in environmental parameters that are then unaccounted for within a deterministic model's output. Further, understanding of uncertainty within an array of sources for various underwater environments is necessary to understand how MHK deployments have the potential to affect the surrounding marine life.

Initial Array Modeling

Early modeling efforts were conducted to determine if uncertainty within the source function of an MHK device would be a viable method of understanding variations in operating conditions over the course of a MHK devices' lifespan.

Variable Frequency & Amplitude

A preliminary modeling effort was performed to understand the stochasticism in the noise generated by a singular MHK source. A source in a two-layer wave guide was modeled using ParAcousti to simulate a CEC device. Sound speeds were set at 1,500 m/s and 1,800 m/s for the upper water layer extending to 100 m in depth and the bottom sedimentary layer extending from 100 to 160 m respectively. Density was set at $1,000 \text{ kg/m}^3$ and $1,800 \text{ kg/m}^3$ for the two layers respectively. The source was placed at a depth of 40 m and modeled as a Delta function. A convolution of the pressure and source equations was used to vary the frequency and amplitude for the sources in order to compare them and understand how the combination of individual frequencies and amplitudes interact.

Figure 6.1 below demonstrates the downward trend for SPL values re $1e - 6$ Pa for each ten feet of depth starting at the top in depth (0 m) and zero in the x-counter. The x-counter represents the range repeated every $x = 35$ or 3,500 m. This particular SPL output was calculated for a frequency of 150 Hz and an amplitude of 1 m. SPL values are depth averaged for all other following trace data and shows the peak SPL value at the fourth spike or a location of 40 m in depth. The SPL continues to decrease with both an increase in range and depth. SPLs also decrease as the sound reaches the surface of the water profile ($z = 0$). Depth averaged SPL values for a single source model were considered in order to understand if a change in frequency or amplitude impact sound propagation through a system.

The modeled delta function was convolved with a source function providing frequencies of 50, 100, 150, 200, 250, and 300 Hz respectively with an amplitude of 1 m. Figure 6.2 exhibits the results of the depth averaged SPL values re $1e-6$ Pa. The SPL values consistently increase as frequency increases. However, the slopes for SPLs along the range are more linear for lower frequencies. As the frequency increases, there is a larger initial drop in SPL followed by a more gradual slope. This indicates that higher frequency sources dissipate energy more quickly initially and then continue to propagate at a higher SPL. This follows as an increase

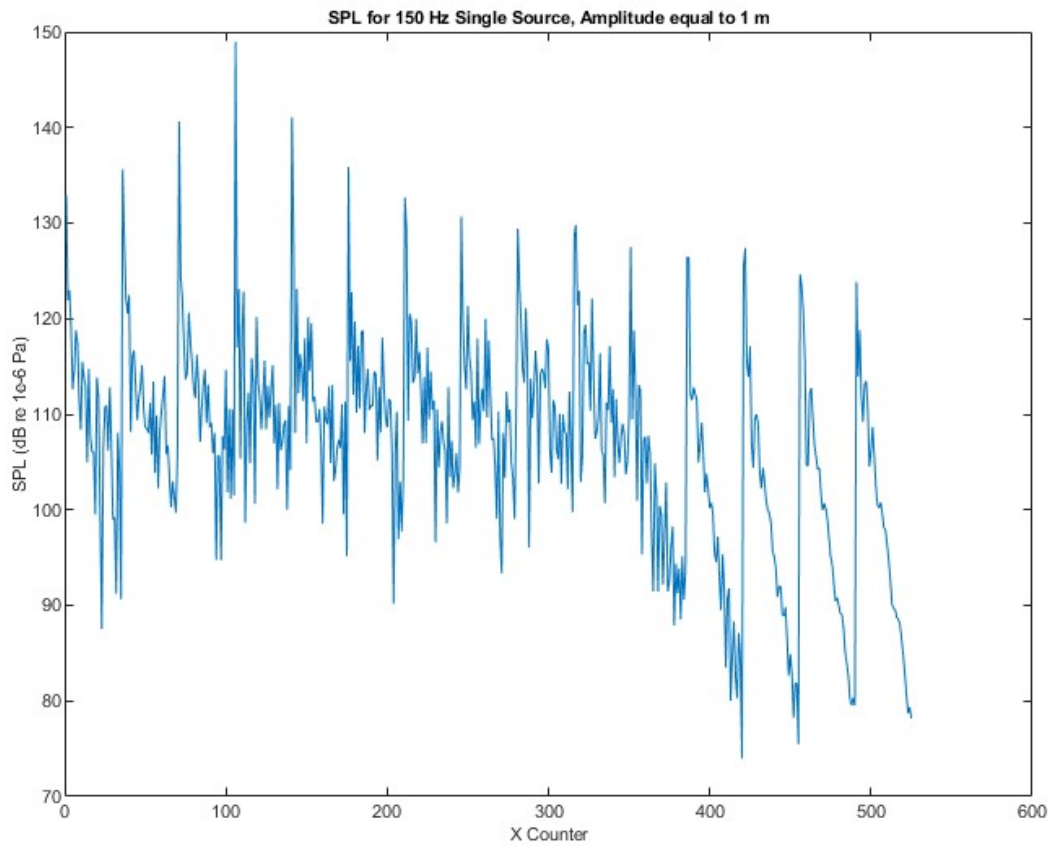


Figure 6.1: SPL for a 150 Hz source, amplitude equal to 1 m. SPL profiles range from 0 to 3,500 m for every 35 x counters left to right. Each group of data represents every 10 m in depth in the water profile. The peak value is located at 40 m in depth.

in frequency also increases the rate at which the sound wave interacts with its surrounding environment. Figure 6.3 shows similar data for a 150 Hz source with amplitudes of 1, 5, 10, 15, and 20 m respectively. Increasing amplitudes result in a higher depth averaged SPL re 1e-6 Pa with the same slope. This was expected as amplitudes change the height (energy) associated with a wave but not the source function overall as the frequency does. However, the overall change of the increase of energy decreases as the amplitude is increased. Larger amplitudes would result in more interaction between the waves and the boundary conditions of the model removing more energy from the system.

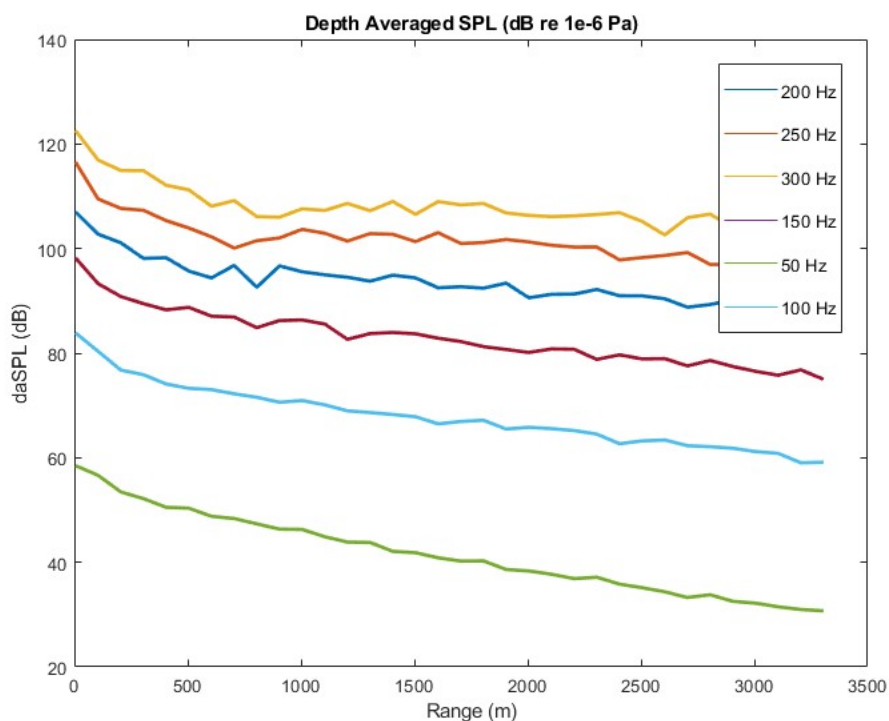


Figure 6.2: Depth averaged SPL for a single source, frequencies 50 – 300 Hz.

Histograms were calculated to compare the occurrence of values of depth averaged SPLs for the changes in frequencies and amplitudes and are shown in Figure 6.4. The histograms indicate a similar but shifted trend with peaks slightly lower for the amplitudes

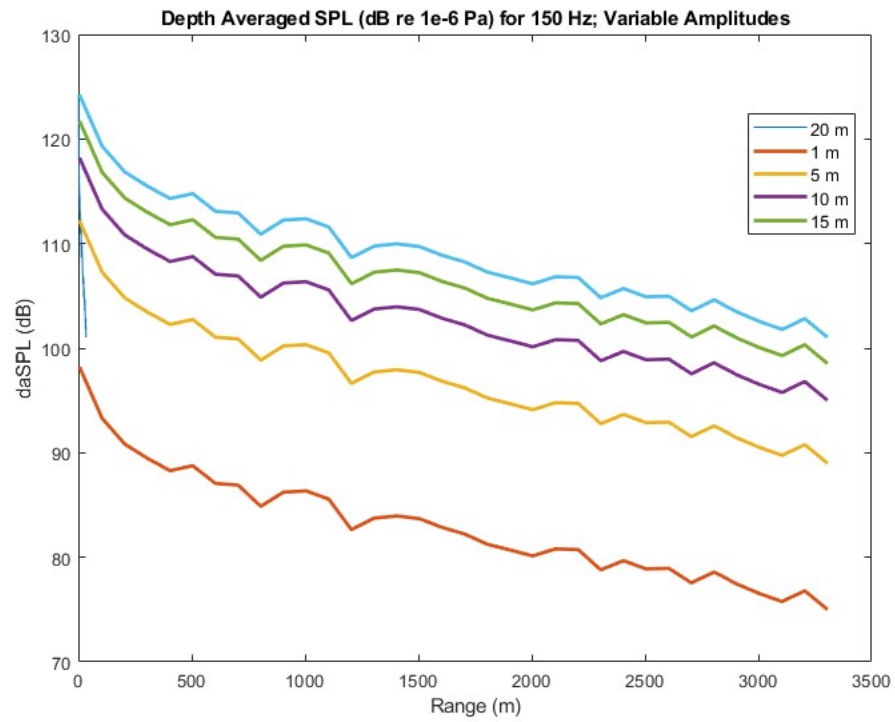


Figure 6.3: Depth averaged SPL for a single source, amplitudes 1 – 20 m.

but not dropping off as fast as the frequencies. It should be noted that the frequency for the amplitude graph is 150 Hz and the frequency graph contains data from frequencies of 150, 200, 250, and 300 Hz. Occurrences demonstrate that most depth averaged SPLs occur in 100 dB range. A 1 Pa amplitude sound source will produce a source decibel level of 120 dB. Initially a large energy loss occurs as sound pressure loss is a function of $1/r$, where r is a measured distance in meters.

Modeling efforts indicate that amplitudes affect SPLs linearly while frequencies are less predictive. While this was applied to a single sound source, an array of sound sources would amplify the variability observed as the sound produced by each source interacts with one another and the surrounding environment. Changes in MHK operating conditions have a large influence on the overall SPL in a domain. Depending on the sound speed (in both the water and sediment layers), source-profile, and domain geometry, a device may operate at a considerable difference from others resulting in a constructive or destructive influence on the overall SPL in a domain. While a simple spherical or cylindrical spreading model may give a fast and conservative estimate of the SPL in a relevant domain, a modeling solution where the environment is considered is necessary to understand the coupling between all of the relevant parameters. Single sources provide a clear indication of affects due to source profiles which compound with an array of sources and the interactions within.

MHK Array Interaction

A second modeling effort was performed to analyze uncertainty within an MHK array, where the sources were arranged in a triangle, square, and hexagon with a seventh source in the center (three, four, and seven sources, respectively) with an inter-device spacing of 10, 15, 20, and 40 m. The orientation of which is shown in Figure 6.5. For this work, a standard two-layer environment with a flat bottom was used. The center of the array was positioned at a depth of 50 m, with a total water column depth of 100 m. Within this domain, a

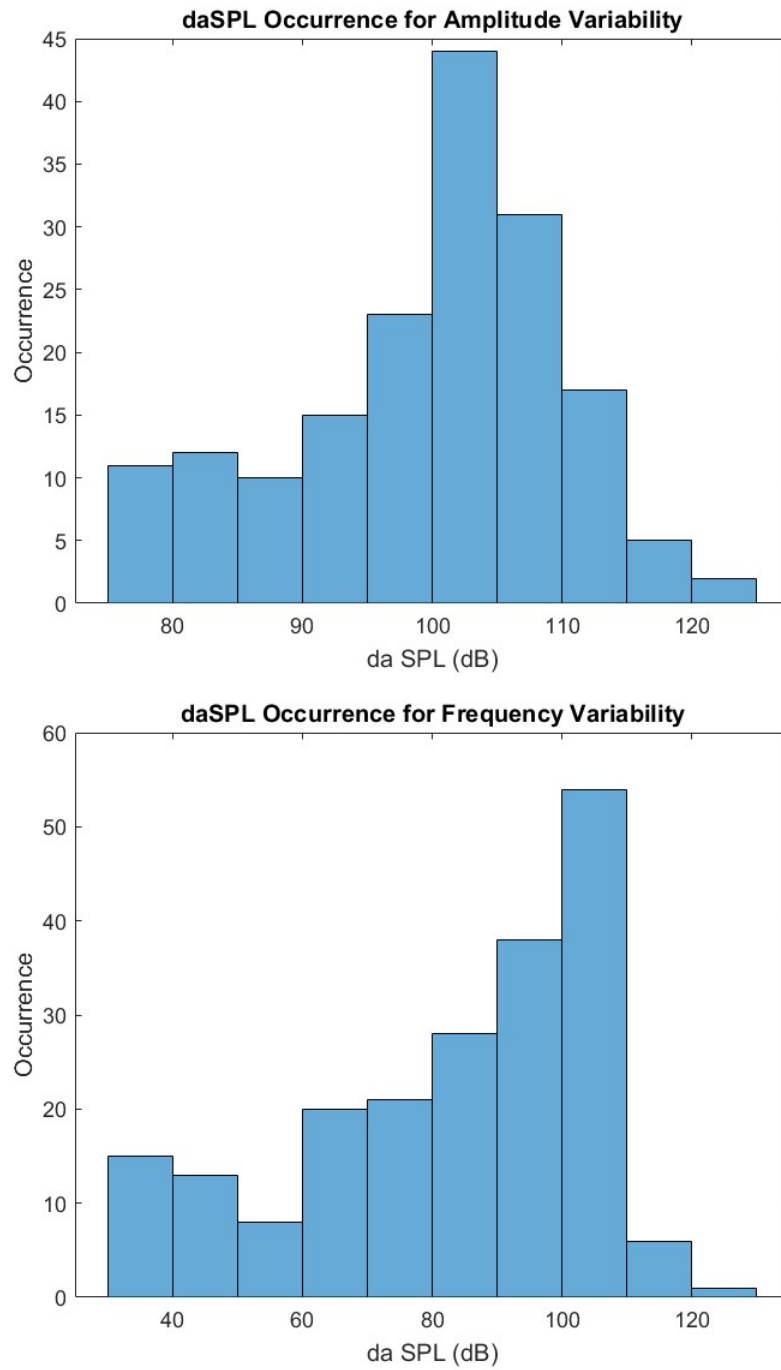


Figure 6.4: The occurrence of depth averaged sound pressure levels for variability within amplitude (above) and frequency (below).

Monte Carlo analysis was conducted with each source frequency allowed to vary about a continuous 150 Hz within Gaussian distribution spanning a 1/3 octave band. Thus, within any number of trials, each source would have a randomly assigned frequency ranging from approximately 133.6 – 168.4 Hz. Sound speeds were 1,500 m/s and 1,800 m/s for the water column and sediment layer, respectively. Densities were 1,000 kg/m^3 and 1,800 kg/m^3 for the water column and sediment layer, respectively. When generating the trials, all of the sources within an array had the same random frequency instead of each being independent. This means the variability observed in the results represent uncertainty of the source tone, but not within the array. It was anticipated that inter-device variability would add more uncertainty to the results. Four hundred trials were run for each array arrangement and each spacing. Each trial was run as a separate simulation, and the time required to generate the required data was prohibitive. That was one of the reasons that a single, relatively low frequency was used. Figure 6.6 below shows the results of that effort, where each dark blue line represents the depth averaged sound pressure level (SPL) data for one trial. The teal and red lines, respectively, represent the analytic solutions for sound propagation when only spherical spreading is used and when spherical spreading is limited to a radius of 50 m from which the solution transitions to cylindrical spreading.

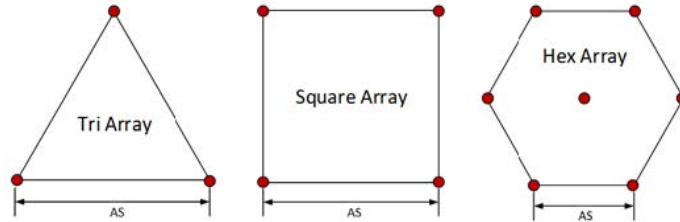


Figure 6.5: A triangle, square, and hexagon (with a seventh device in the center) were considered, with center-line spacings of 10, 15, 20, and 40 m. The center of each array was located at a depth of 50 m. Devices represented a 5-m diameter turbine.

Results from the analysis indicate that as the distance between sources increase,

uncertainty decreases. The additional distance between sources allows the propagated energy to dissipate before interacting with that generated by the other devices. The data also shows that as the number of sources increase, uncertainty increases. An obvious trend is that as the number of sources increase it results in a net increase in the pressure level of the system. The amount that the propagated waves are constructive or destructive is partly dependent upon the arrangement and spacing of the sources. Several of the square and hexagonal array data sets show banding occurring on the edges of the trial data which likely indicates that not enough trials were completed to fully reveal the potential distribution within the system. This is one possible cause for the square array appearing to have a larger amount of uncertainty than the hexagonal array even though it has fewer sources. While the average SPL of each layout does not drastically change with different device spacings across the variability of source frequency, the probability distribution of SPL does. Even though the selected frequencies are pulled from a Gaussian distribution, the depth-averaged SPL is observed to range from biased, unimodal to bi-modal distributions. Beyond a range of 200 m all trial data is less conservative than the combined spherical-cylindrical spreading rule predicts and reinforces that the inclusion of losses to the sediment contributes to the removal of energy in the system and that a careful understanding of the earth properties is required. Spherical spreading assumes that all of the energy generated by a source propagates away uniformly without reflection. Data falling below the spherical solution is interesting in that it indicates that a significant amount of energy is lost due to destructive interactions between an array of devices. Solution data indicates that small variability within an array may result in SPLs which vary greatly from any assumed bounds.

Banding occurs after approximately 200 meters after spreading losses transition from purely spherical to a partially-cylindrical propagation with energy being removed from the water column through the soil. The banding narrows as spacing increases, decreasing the strength of sound interference between successive devices. Both spherical and cylindrical

values initially fall below the banding due to the spreading not accounting for energy reflection and the distance to the edge of the arrays. Values then become conservative as propagation losses in the second layer begin to dominate the trial data. The arithmetic means of the daSPL for all trials within each array spacing are nearly identical. Probability distributions demonstrate a bimodal distribution for the triangular array after 15 m. Both the square and hexahedral configurations show single mode distributions regardless of the spacing. Peak or most probabilistic values in daSPL probability distributions may be an indicator of a preferred SPL values to be compared against regulatory standards. Currently, standards do not make any distinction between the two. Bimodal systems with two values with increased occurrence rate would also need to be considered. Utilizing a random phase-shift for each of the sources results in a significant spread in potential depth-averaged, broadband SPL's propagating from an array of MHK devices. This banding decays as the devices are spaced further apart.

Uncertainty Model Setup & Data Analysis

Uncertainty in propagated acoustics within a system is caused through variations within the environment, device arrangement, and the operating conditions. Variations within the operating conditions may be incorporated into a model through the sound source profile. All three of these contributing factors need to be accounted for or controlled within an experiment or simulation to demonstrate how much uncertainty is derived from any single, or combination, of these contributing factors. Previous research indicates a need to investigate uncertainty within various marine environments while incorporating variability in source signals for an increased number of sources. The models constructed for this effort add variability within the sound profile in four different environments, but with fixed source locations in order to provide a comparison on how the deployment location may further influence the uncertainty. Future efforts to understand the impact of environmental

uncertainty will be accomplished with ParAcousti-UQ, which was created specifically to address measurement uncertainty and temporal variation of the sound speed and density through an intrinsic calculation of the probability density functions.

Previous investigations into uncertainty revealed that completing the project with a Monte-Carlo simulation approach could be prohibitive due to the number of simulation hours required to attain a meaningful amount of data. Each source sound profile was created and written to a specific model simulation. Inducing variance within a model then required a full simulation run for every source profile combination, or trial. To provide a full distribution to statistically account for any potential interaction in sound waves in an environment, 1000s of simulations are typically required. ParAcousti provides a second option to model a source signal by simulating a delta function for each sound source. The delta function is an impulse and provides a nearly source-agnostic solution for any given model domain. Time-history results for a specified location within the domain can be convolved with any source profile to simulate multiple solutions using only one model run. The grid and time-step constraints are still limited by the highest frequency of interest and the source locations and environmental parameters remain fixed. To simulate multiple, independent sources, one simulation per source location must be constructed and run and the data sets are then convolved separately. These individual results are then superimposed to provide the total pressure within the domain caused by the propagating sounds. Thus with this approach, a Monte-Carlo simulation for one environment with 16 independent sources only requires 16 simulation runs. The random variations in the sound profiles are introduced as a post-processing step, with the convolution and superposition of 1000s results being significantly faster than an individual model run.

Model Setup

Three unique model domains were chosen to represent both shallow- and deep-water domains. Presently, CEC deployments have been proposed for a wide range of water depths and the sound environments have the potential to be drastically different. The two environments modeled are: 1) deep ocean and 2) water column and flat sediment layer. Locations vary with respect to bathymetry complexity and range from a fully deep water system with zero change in density to the two-layer waveguide, which incorporates a bathymetry in a vary shallow system.

The two locations are contrived to provide standard bathymetries, that represent well-defined shallow- and deep-water systems. For the deep ocean model simulations, the air-water interface was removed to allow the boundary conditions to mimic a fully submerged domain. The traditional, flat bottom, two-layer model domains was constructed as a water column with an air-water interface and a sediment layer 51 m below the surface. The two-layer model has a constant depth and does not have any changes in bathymetry throughout the model domain. Incorporating a repeating sand wave into the bottom of the two-layer domain was investigated as well. Sand wave crests are linear, with continuous development and have stable wave heights and lengths. The real sand profiles are asymmetric and found in water depths ranging from 28 – 51 m. Typically, linear waves are found in one-way currents and the sediment is composed of medium and fine sand with resulting wave lengths and heights ranging from 2.3 – 8.0 m and 0.37 – 0.97 m, respectively [124]. That considered, there was minimal evidence to state that the size of the standard sand waves would impact the model data enough to differentiate it from that of the standard two-layer, flat bottom domain. The option of including the sand waves was not completed as impact was considered minimal. For all of the environments, one-way flows are ideal for CEC development and so the models were designed to mimic that requirement with sound source arrays placed to one end of the model domain unless the bathymetry prevented that.

All three locations use a CPML boundary condition on the remaining, below-water boundaries to allow propagated sound energy to leave the model domain and not be reflected back into the system. All sound speed and density properties are assumed to be constant through either the water column or sediment layer. Water column properties are set to 1,500 m/s and 1,000 kg/m^3 for sound speed and density, respectively. All sediment was assumed to be fine grained sand, with sound speed and density values set to 1,650 m/s and 1,900 kg/m^3 , respectively [55]. A four-by-four (16 total) grid of sound sources was arranged and centered at the far left of each domain. The sources were designed to approximate a 5 m diameter turbine, which was tested and modeled by Penn State ARL and SNL in 2013 [57, 58]. During that effort, a blade for this turbine was simulated as both a solid and a hollow structure with some notable changes in the generated sound, most significantly the hollow blade was marginally louder and exhibited more monopole-dominated radiation. The sound signature from the hollow blade is approximated for this work. Sound sources within ParAcousti were each built as a single, monopole source, which does not physically occupy space within the model domain. The spacing between sources was assigned to be 2.4 times the turbine diameter (vertically) and 15 times the diameter (horizontally) to allow flow moving through a linear array from left to right. The length scale for the domain grid and the time step both depend on the maximum frequency of the source profile. The choice to have a vertical (depth varying) spacing of 2.4D is in part a consequence of how sources must be placed within the model domain, whereas the 15D downstream distance is the approximate location at which the current velocity has returned to 90 percent of the undisturbed value. Sources can only exist on a nodal intersection within the domain grid and may not be interpolated between grid points. Additionally, the maximum frequency for this project was set to 500 Hz, to allow for variability within the source profile generated by SNL in 2013.

For all three cases, the source profiles were set as a monopole, sinusoidal function with frequencies dictated by what type of source was being replicated. Sources were either a single

frequency or the previously mentioned 5 m diameter recorded turbine. The turbine source was comprised of eight frequencies generated from the hollow, 5 m turbine. The original profile is shown below in Figure 6.7 as it was presented in [58]. All dipole energy peaks were simplified to a single monopole frequency which correlated the peak with the larger energy signature of the two. The frequencies are 12, 32, 64, 106, 159, 231, 308, and 377 Hz. The source time function of the turbine source is represented as equation 6.1:

$$S(t) = \sum \left[\frac{B_i c^2}{\pi \omega_i^2} (1 - \cos(2\pi \omega_i t)) \right] \quad (6.1)$$

where ω is the frequency of the source (Hz), c is the sound speed, t is the present simulation time for the source (S), and B is the desired pressure amplitude (Pa). The subscript i indicates that those parameters may have uncertainty incorporated into the variable. Phase may be adjusted as well. Uncertainty may be built into amplitude, frequency, or phase. These three variables drive all variation within the source profile over time for a single monopole source. In a real world deployment, uncertainty would also be tied to the environment, the materials the turbine is built from, the construction and installation, and the interaction of the environment with the turbine over time. Including uncertainty only within the source profile limits the scope and increases the control associated with the source to understand how only variation within the sound produced by the turbine itself affects the surrounding environment. Variation within amplitude has a linear output, so only frequency and phase were allowed to fluctuate to mimic changes in operating conditions over time or at distinct events within the lifespan of the turbine.

All models were set to a standard pressure amplitude of 1 Pa. Uncertainty was generated by within the source profile by varying the frequency or the frequency and the phase. Each key frequency was varied by a maximum of 1/3 octave band within a Gaussian distribution. The phase was selected randomly from a range of 0-360°. Values for both the frequencies

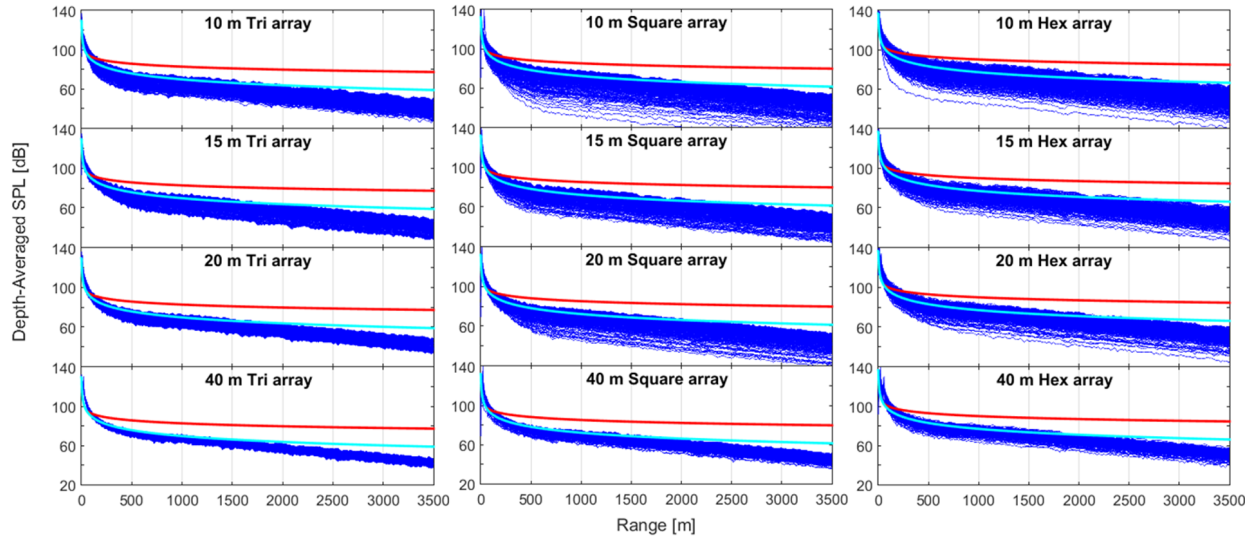


Figure 6.6: The results from the Monte Carlo analysis for 400 trials where the frequency is allowed to vary along a 1/3 octave band about 150 Hz with a Gaussian distribution. The dark blue lines represent individual trials. The teal and red lines represent the analytical solutions for spherical spreading and a combination of spherical and cylindrical spreading.

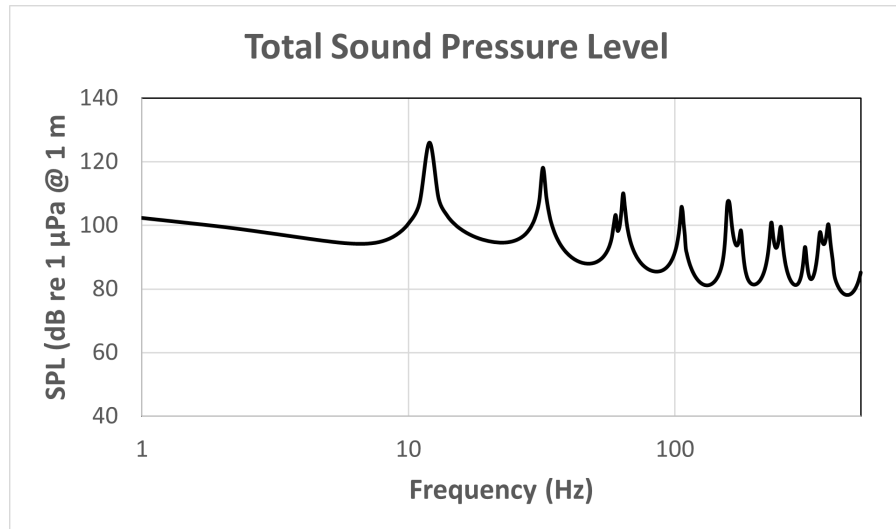


Figure 6.7: The sound source profile for provided by SNL for a 5 m diameter turbine. The eight main frequencies from the profile were selected to generate the model source profile. Each dipole mode was simplified to a monopole by selecting the frequency with the larger SPL of the two.

and phase were randomly selected based on the above parameters and applied to the source time function of each individual source. To facilitate an analysis focusing on uncertainty, most models were run with delta functions; however, it is then necessary to convolve this data with a source time function in order to be converted to pressure data. All pressure values from each source of interest within the model domain (maximum of 16) are converted to SPLs and added together to provide the complete picture of the total SPL at designated locations within the domain. This was repeated 1000 times to provide an initial view of the variability that may occur within a CEC array for a specified turbine profile. For example, if a random selection is repeated for each of 500 trials over the 8 unique frequencies, 4000 total unique frequency variations would be applied to the number of designated sources. Figure 6.8 shows one example of the frequency distribution and occurrence around the lowest frequency, 12 Hz. Figure 6.9 shows the frequency distribution and occurrence for all 4000 frequencies sampled and applied to 16 sources. An approximate normal distribution appears around each of the dominant frequencies; though higher frequencies are closer together in value, causing the 1/3 octave bands to run together. Because slice data output is an instantaneous snapshot, they may not be convolved and therefore the majority of the analysis performed here is derived from a grid of traces. The few planar slices shown are from pre-specified, deterministic runs of the model. The open ocean and the two-layer waveguide with a flat bottom are the only two cases for which slice data was calculated and presented. Results for model runs where frequency and both frequency and phase together were allowed to vary are presented for each of the three cases below.

Open Ocean Waveguide

The open ocean waveguide was chosen to represent a deep water condition where there are no changes in density from a sediment layer. Typically, MHK devices are deployed in shallow water systems; however, designs do not always require that a turbine be fixed to the

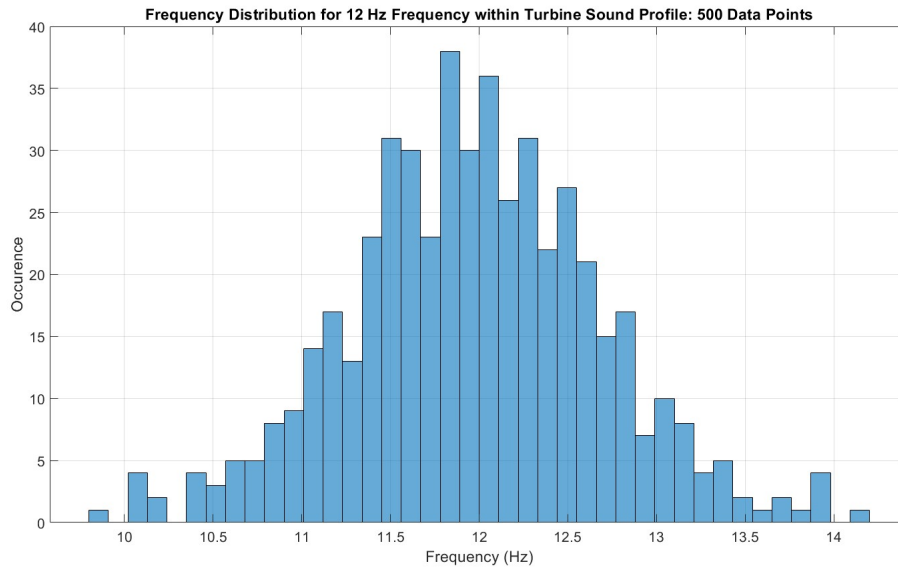


Figure 6.8: The 500 randomly selected frequencies using a Gaussian distribution in a $1/3$ octave band about 12 Hz.

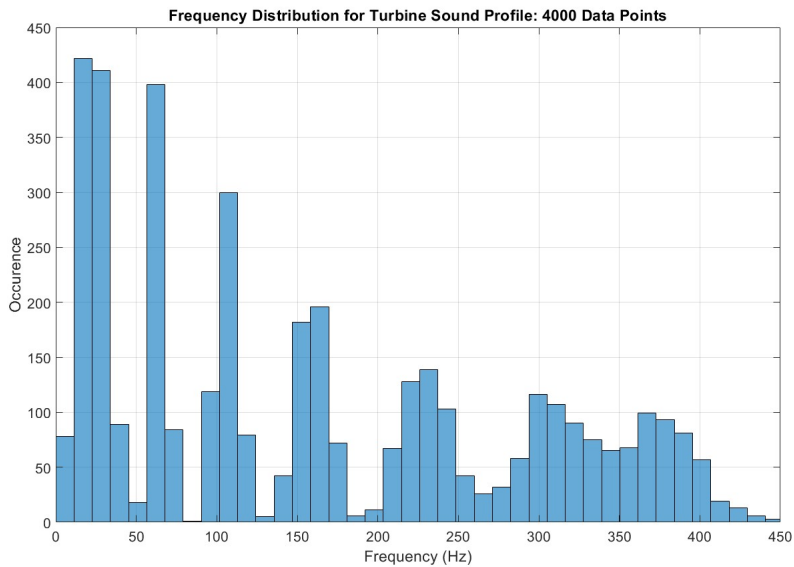


Figure 6.9: The 4,000 randomly selected frequencies using a Gaussian distribution in a $1/3$ octave band about each of the eight main frequencies present in the SNL 5 m turbine sound profile.

bottom of a channel. Turbines may be suspended within the water column allowing a deep water location to now be a viable option for deployment. Sources were set to spacings of 12m in depth and 75m in range, or along the x-axis. The source array of 16 sources was then centered within the model domain. The first column of turbines is places at $x = 0$ m in the model domain. The model has a grid spacing of 0.3 m and a time step of 0.00008 sec. A four-by-four array of sources was chosen as this is an large enough number of sources to amplify interactions between each source. As a baseline, a deterministic model run was completed to provide an instantaneous cross-section, where each source profile was set to either a continuous 300 Hz with a 0° phase and an amplitude of 1 Pa or by overlaying the dominant frequencies present for the 5 m diameter, SNL turbine. These frequencies are the true tones and do not incorporate the random variation. The steady state SPLs for of each of these model runs are shown in Figures 6.10 and 6.11. Sources are indicated by black dots.

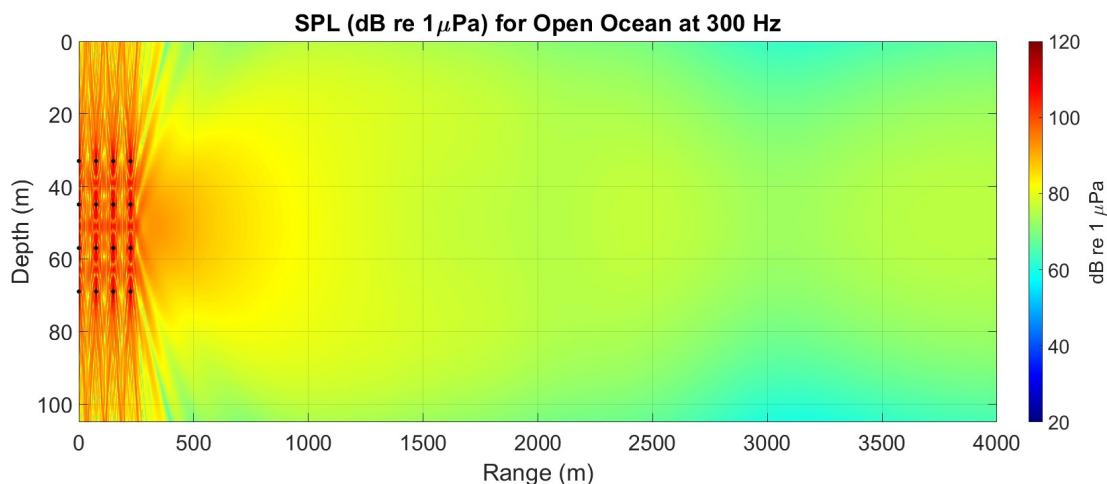


Figure 6.10: SPLs for an open ocean model domain with a single frequency of 300 Hz applied to each source. Maximum values of SPLs are approximately 132 dB re 1 μPa .

The maximum SPL increases from 132 dB re 1 μPa re 1 m to 143 dB re 1 μPa re 1 m. The modal shape reduces as the sound waves propagate outward from the array. Deep-water models have few boundary conditions and do have have any changes in density due

to a sediment layer to create energy reflections. Energy losses are due to interactions within particles in the water column only. Sound pressure values decay more evenly with a reduced wave number. The sound energy imparted by the 5 m diameter turbine profile is significantly higher due to the range of frequency tones which are all imparting energy to the system as opposed to a singular frequency at each source location. The patterns within the pressure waves are additionally less structured within the 5 m turbine source model run and the SPL dissipates at a faster rate as compared to the 300 Hz models. This suggests more destructive interaction between the eight frequencies as opposed to single tones.

Uncertainty about the source frequency was then convolved with the data collected in time at a various locations within the model domain. Two locations of interest are presented within this document. Locations were selected at the center of the array and 3,000 m down range along the centerline of the array, where the distance is measured from $x = 0$. Every 200th SPL value was plotted for the median and the 5th, 25th, 75th, and 95th percentiles of the collected data over six seconds. Each data set was calculated for 1000 individual random frequencies, which compounds to over 8000 data points in total. Data is shown in Figures 6.12 and 6.13. Variability decreases as distance from the sound source increases. The greatest number of sound source interactions will occur near the source as the close proximity heightens the probability of waves interfering with one another and minimal energy dissipation has occurred. Variance falls between 2 and 5 dB re $1 \mu Pa$ from the mean for positive pressure values depending on the point in the time. The overall uncertainty is also more consistent in value as the sound source propagates away from the source location. Fewer interactions and reflections as well as increased energy reduction and dampening reduced the noise within the data set.

The same locations in space are presented with variability in both frequency and phase included. Similar trends are observed as mentioned above as uncertainty decreases with distance; however, uncertainty additionally has increased in overall value when phase is

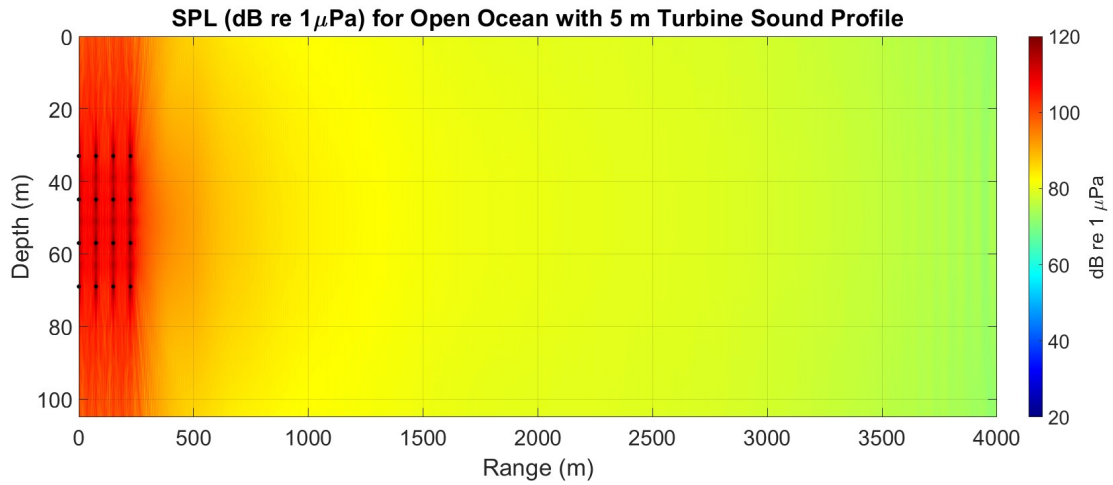


Figure 6.11: SPLs for an open ocean model domain where each source is modeled with the SNL 5 m diameter turbine sound profile. Maximum values of SPLs are approximately 143 dB re 1 μPa .

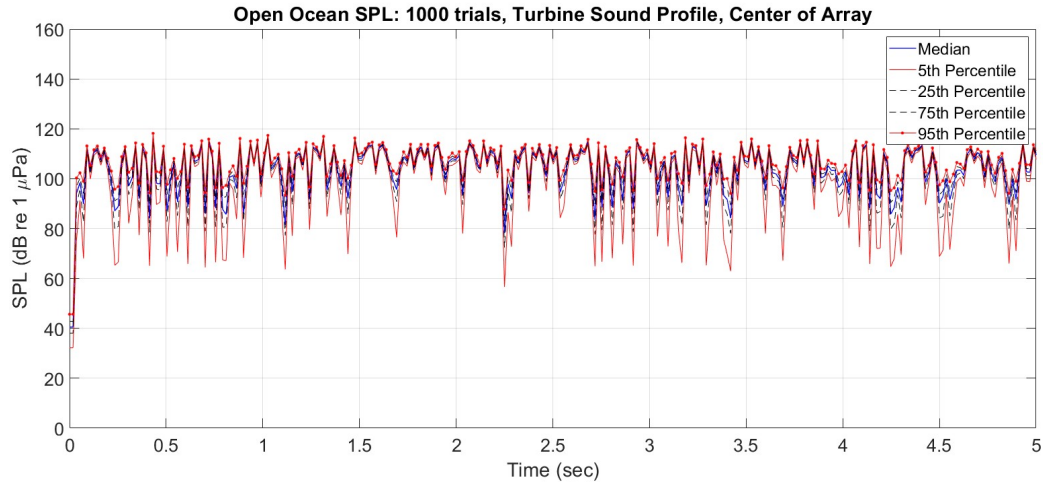


Figure 6.12: SPLs generated from 1000 trials with variation about frequency only for the open ocean model domain where all 16 sources are present and the SNL 5 m diameter turbine sound source profile was used for the convolution. Data was collected at array center, where $z = 51$ m.

allowed to vary between 0 and 360 degrees along with frequency. Variability about the mean now falls consistently over 10 dB re 1 μPa and in cases extend over 20 dB re 1 μPa . For all cases, uncertainty and noise increases for negative pressure values from the generated acoustic data. Maximum values are those considered of concern with respect to acoustic regulations and model comparisons.

Two-Layer, Flat Bottom Waveguide

The second location was for a two-layer, flat bottom model domain where 16 sources were arranged with spacings of 12 m in depth and 75 m in range, or along the x-axis. The source array was centered within the water column and the first column of turbines is placed at $x = 0$ m in the model domain. The model has a grid spacing of 0.3 m and a time step of 0.00008 sec. Within the model domain, the center of the source array was set at 30 m in depth and the sediment layer was set at 51 m in depth. A two-layer system was chosen as the second location as it includes the additional complexity of a sediment layer which leads to a change in density and sound speed depending on the location within the domain. A depth of 51 m represents as shallow-water system which have a more complex soundscape due to the reflection and refraction that occurs as sound waves interact with both the air-water interface and the sediment layer. Similar to the open ocean waveguide, a deterministic model run was completed to provide an instantaneous cross-section, where each source profile was set to either a continuous 300 Hz with a 0° phase and an amplitude of 1 Pa or by overlaying the dominant frequencies present for the 5 m diameter, SNL turbine. Again, these frequencies are the true tones and do not incorporate the random variation. The steady state SPLs for each of these model runs are shown in Figures 6.16 and 6.17. Sources are indicated by black dots. The maximum SPL increases from 132 dB re 1 μPa re 1 m to 144 dB re 1 μPa re 1 m for the 300 Hz and 5 m turbine profile, respectively. Again, the 5 m turbine profile imparts a larger amount of starting energy which then propagates outward. However, when

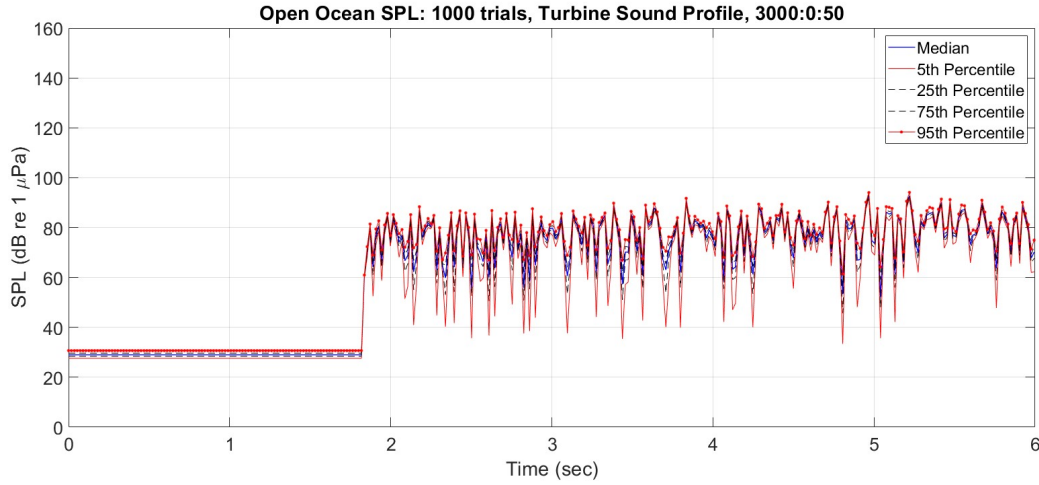


Figure 6.13: SPLs generated from 1000 trials with variation about frequency only for the open ocean model domain where all 16 sources are present and the SNL 5 m diameter turbine sound source profile was used for the convolution. Data was collected at $x = 3,000$ m and $z = 51$ m.

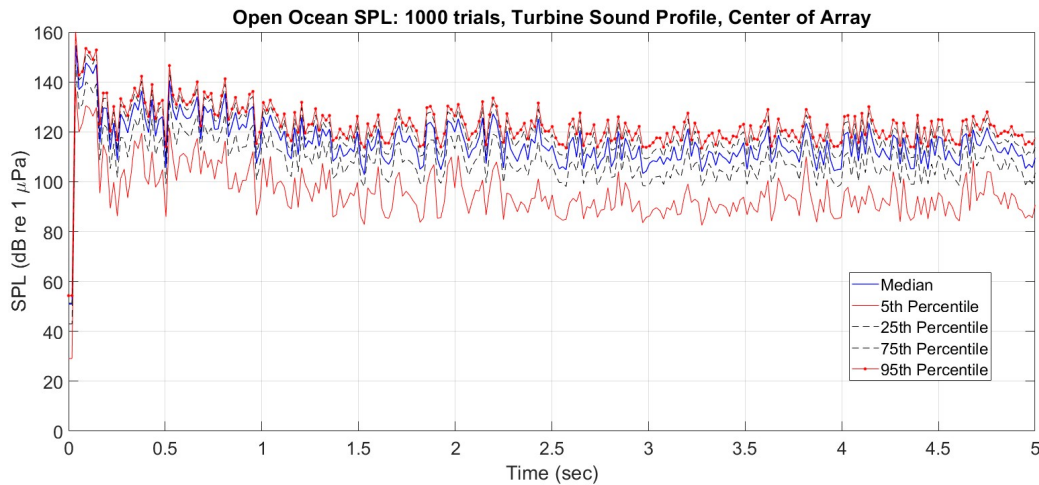


Figure 6.14: SPLs generated from 1000 trials with variation about frequency and phase for the open ocean model domain where all 16 sources are present and the SNL 5 m diameter turbine sound source profile was used for the convolution. Data was collected at array center, where $z = 51$ m.

comparing the two-layer to the open ocean model, the sediment layer causes sound waves to reflect back into the water column, which retains energy within the water column as the sound propagates down range. Sound waves increase in length as they enter the sediment layer, which has a higher density. Additionally, the sound wave patterns for the 5 m turbine profile are less structured and the SPL dissipates at a faster rate as compared to the 300 Hz models and SPLs remain 20 dB higher 4,000 m down range of the source profile. Energy levels again are increased for the two-layer as compared to the open ocean system due to the increased number of interactions and reflections suggesting that any MHK device would have a larger impact to a shallow water system than a deep water system. This material also suggests more destructive interaction between the eight frequencies as opposed to single tones.

Sound pressure levels were calculated for two locations within the two-layer model domain when a variation in frequency was included in the source profile about each of the turbine frequencies for 1,000 trials. These locations are located at the center of the model array and 3,000 m from the array center, both along the center line of the water column as the source array was centered in the water column with respect to depth. The sample points for the two-layer model were at nearly the same range but varied slightly in depth due to how the data was collected on the grid (27 and 30 m for locations one and two, respectively). Every 200th time-step is plotted for the median and the 5th, 25th, 75th, and 95th percentiles of the collected data over six seconds. On average, the maximum observed SPL is within 5 – 10 dB re 1 μPa of the median. SPLs were generally larger for the shallow water environment, as expected from the presence of reflective boundaries, though the root mean square of the uncertainty is smaller for the two-layer system. Results are shown in Figures 6.18 and 6.19 for the first location (300 m) and Figures 6.13 and 6.19 for the second (3000 m) for the open ocean and flat-bottomed waveguide, respectively.

The results indicate a possible variance of up to 30 dB re 1 μPa that may occur in SPL

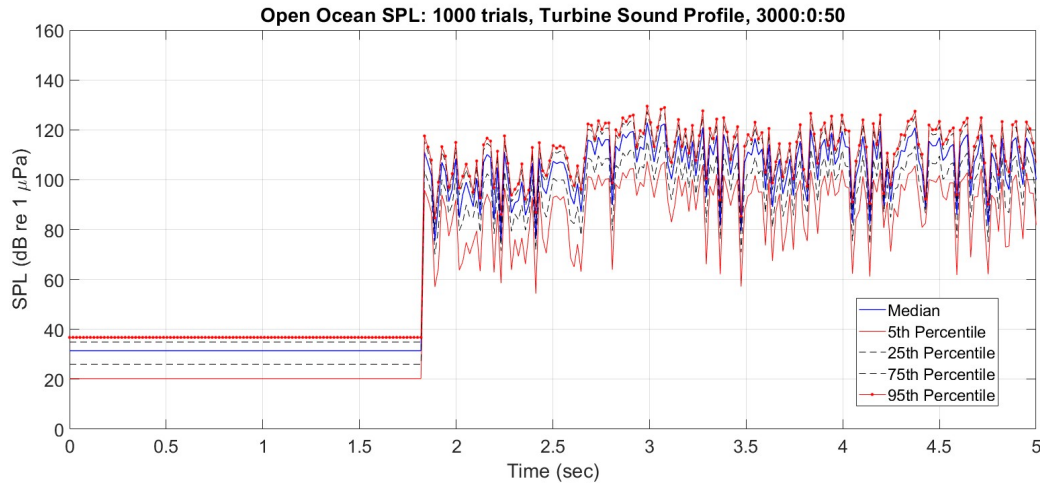


Figure 6.15: SPLs generated from 1000 trials with variation about frequency and phase for the open ocean model domain where all 16 sources are present and the SNL 5 m diameter turbine sound source profile was used for the convolution. Data was collected at $x = 3,000$ m and $z = 51$ m.

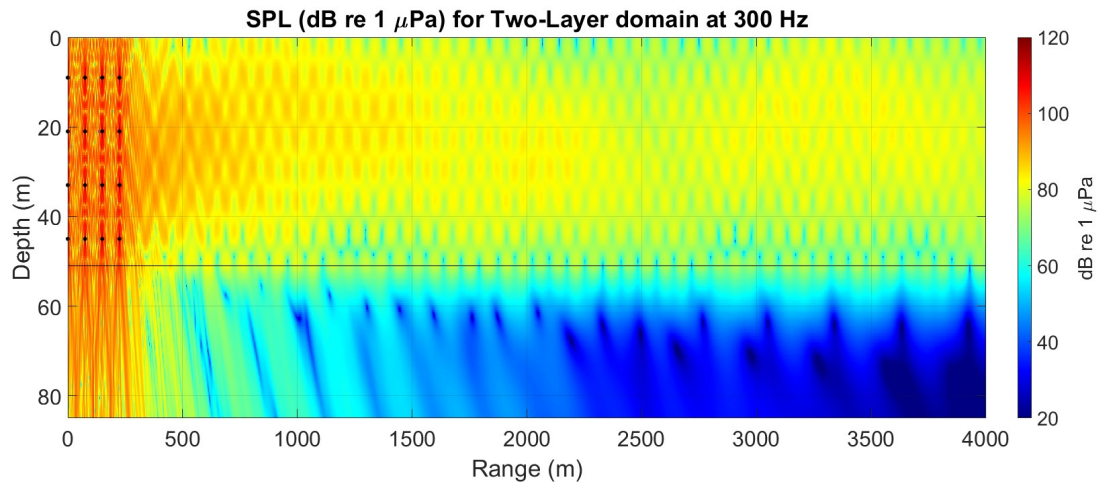


Figure 6.16: SPLs for a two-layer model domain with a single frequency of 300 Hz applied to each source. Maximum values of SPLs are approximately 132 dB re 1 μPa .

for both the open ocean model and two-layer model. On average, the maximum observed SPL is within 5 – 10 dB re 1 μPa of the median. SPLs were generally larger for the shallow water environment, as expected from the presence of reflective boundaries, though the root mean square of the uncertainty appears to be slightly smaller. Results are shown in Figures 6.18 and 6.19 for both locations in time for the two-layer, flat-bottomed waveguide, respectively. Uncertainty decreases slower for the two-layer system over distance as compared to the open ocean. As indicated by the earlier steady-state plots over the model domain, the addition of the sediment layer increases reflections and interactions within the system, overall increasing the amount of uncertainty as compared to the open ocean. Strong evidence suggests that uncertainty in the source profiles continues to significantly influence the sound pressure levels as they propagate away from the array.

Similar to the open ocean case, the same locations in space are presented with variability in both frequency and phase included in Figures 6.20 and 6.21. Uncertainty continues to decrease with distance; however, uncertainty additionally has increased in overall value when phase is allowed to vary between 0 and 360 degrees along with frequency. Variability about the mean now falls consistently over 20 dB re 1 μPa and in cases extend over 30 dB re 1 μPa . Maximum SPLs increase from approximately 120 dB re 1 μPa to 160 dB re 1 μPa for variability about frequency only and frequency and phase, respectively. For all cases, uncertainty and noise increases for negative pressure values from the generated acoustic data. Maximum values are those considered of concern with respect to acoustic regulations and model comparisons. Overall variability about phase provides a larger contribution to uncertainty than frequency alone. Increases in complexity to the system in a form of a sediment layer increase the number of interactions between wave forms, increasing the amount of recorded variability. For all plots included, general trends in the data match with calculated arrival times and overall data shape.

The data serves to show that potential uncertainty within operating conditions could

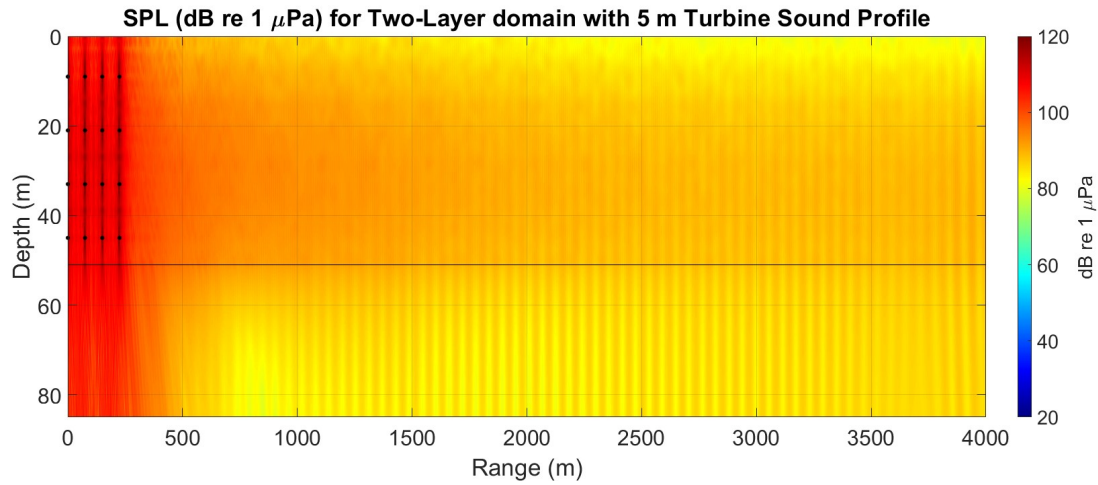


Figure 6.17: SPLs for a two-layer model domain where each source is modeled with the SNL 5 m diameter turbine sound profile. Maximum values of SPLs are approximately 144 dB re $1 \mu Pa$.

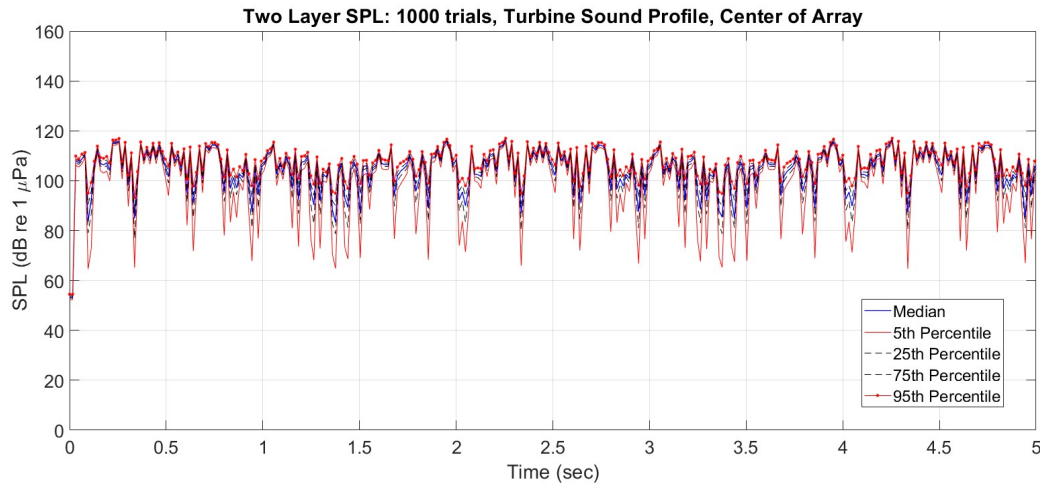


Figure 6.18: SPLs generated from 1,000 trials with variation about frequency only for the two-layer model domain where all 16 sources are present and the SNL 5 m diameter turbine sound source profile was used for the convolution. Data was collected at the center of the array, where $z = 30$ m.

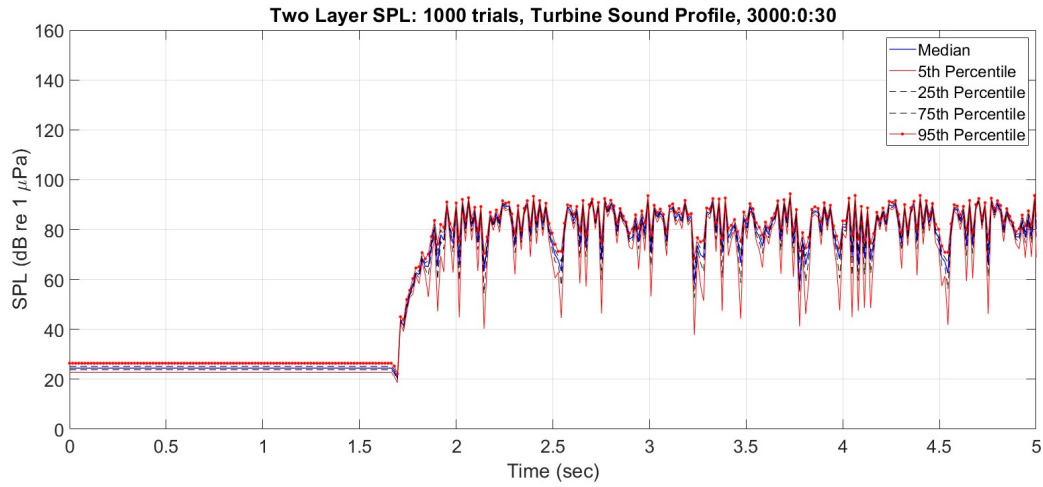


Figure 6.19: SPLs generated from 1,000 trials with variation about frequency only for the two-layer model domain where all 16 sources are present and the SNL 5 m diameter turbine sound source profile was used for the convolution. Data was collected at $x = 3,000$ m and $z = 30$ m.

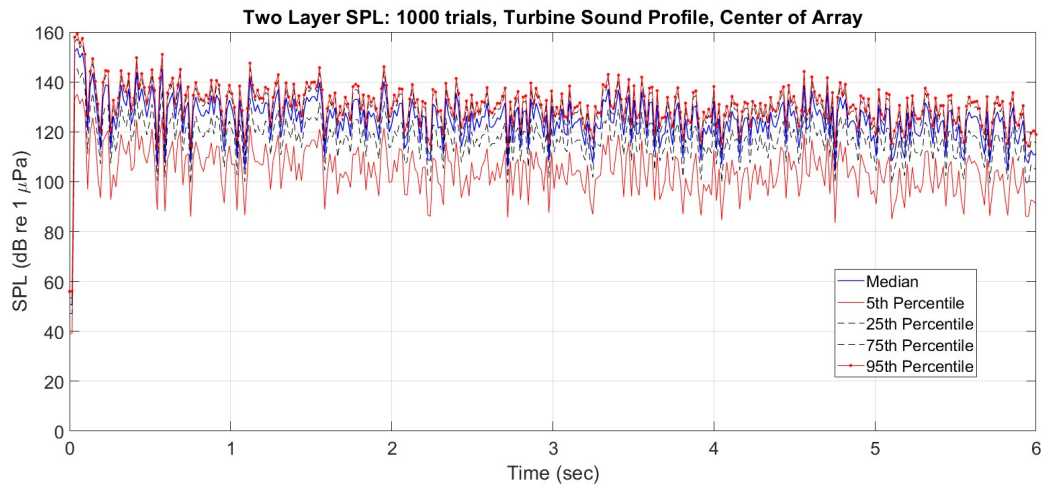


Figure 6.20: SPLs generated from 1000 trials with variation about frequency and phase for the two-layer model domain where all 16 sources are present and the SNL 5 m diameter turbine sound source profile was used for the convolution. Data was collected at array center, where $z = 51$ m.

cause predicted MHK SPLs to fluctuate well above suggested model values. Most available models are deterministic and fail to account for any variability within the collected data set, environmental parameters, or sound source profile as was presented in this chapter. Strong evidence suggests that although uncertainty levels were greater than expected, the model still accurately predicts how the sound emitted from an array of MHK devices would propagate outward through increasingly complex environments. The data suggests that standard propagation models may not be adequately capturing the uncertainty that may occur within a natural system. In real world environments, variability about phase may not fluctuate about the entire 360° available. However, the purpose of this work was to document the potential uncertainty that may occur about an established and expected sound source profile. As compared to the earlier data calculated about uncertainty, the number of sources in the array additionally contributes to the overall uncertainty of the system by increasing the overall energy as well as the number of potential interactions and reflections between source profiles. Incorporating uncertainty into the development and design prior to the deployment of MHK devices may prove vital to understanding the potential impact on marine environments and whether an array is contributing 120 dB re 1 μPa or 160 dB re 1 μPa in the same environment.

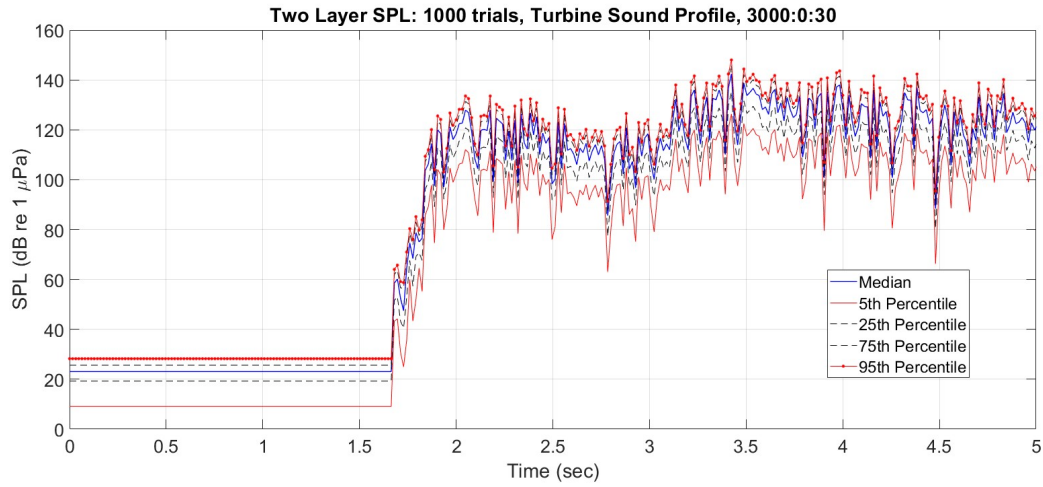


Figure 6.21: SPLs generated from 1000 trials with variation about frequency and phase for the two-layer model domain where all 16 sources are present and the SNL 5 m diameter turbine sound source profile was used for the convolution. Data was collected at $x = 3,000$ m and $z = 51$ m.

CHAPTER 7: CONCLUSIONS & DISCUSSION

This dissertation presents a detailed analysis for the validation and application of a novel acoustic propagation model, ParAcousti, to shallow, underwater sound systems with sound profiles which replicate MHK sources. ParAcousti solves the velocity-pressure equations, rather than other possible acoustic propagation techniques and algorithms available such as the wave equation or the Helmholtz methods. The individual solutions to both the wave equation and the Helmholtz methods are limited to a specific range of frequencies and environmental parameters and are only solved for single sources most often in a 2D environment. In contrast, the velocity-pressure equations are based on the conservation of linear momentum, Cauchy's equations of motion, a relationship for stress on a mass particle, and the thermodynamic conservation of entropy. This combination of equations addresses the transfer of force from an energy source to the surrounding particles, inducing a pressure wave. Additionally, the finite difference solution developed by SNL and used in ParAcousti allows for a full 3D solution of particle velocities and pressures in time with any number of complex sources. While the wave equation does solve in time, all three of the Helmholtz methods solve in the frequency domain. The potential increased accuracy and range of applicability available to ParAcousti make it an ideal system for modeling MHKs. This is because MHKs are most often deployed in shallow domains with potentially complex bathymetry in arrays, making sound source functions dependent on multiple frequencies. MHK devices provide an opportunity to generate up to 57 % of the total United States Energy needs yearly. Additionally, approximately 50 % of the countries population lives within 50 miles of the coastline, allowing for increased access to energy produced by MHK sources with minimal line and transportation losses [5]. MHK devices have the potential to impact a significant number of people across the country.

While MHKs provide a significant opportunity for coastal and riverine energy gen-

eration, these devices are in their infancy and contribute additional sound sources to an already saturated underwater environment. Frequency levels produced by MHK devices fall in the 50 - 1,500 Hz range, which overlaps with the frequencies produced by whales, seals, and dolphins for communication. MHK frequency levels are those that marine fauna can both hear and will react to. Ethical considerations should be taken to determine how MHK devices may impact an environment or how that impact can be minimized. Increased pressure levels have the potential to temporarily and permanently alter both behavioral responses, such as feeding and mating activities, as well as physically harming individual species. MHKs have the potential to be a significant alternative energy generation source as long as marine ecosystems are preserved and operate in harmony with the additional sound sources. ParAcousti provides an alternate model to further the understanding of sound propagation for MHK devices and reduce potential impacts before deployment with respect to a full 3D space in the time domain. Calculated pressures may inform designers, engineers, regulators, and biologists as to an optimal location, arrangement, and system design to maximize power generation while minimizing harmful sound emissions and therefore negative impacts.

Conclusions & Contributions

ParAcousti was developed and implemented for solid media, as well as validated for a number of geophysical applications including seismic modeling [94]. The program had not been previously applied to an underwater environment with MHK sound sources. Validation work was completed to determine the validity of applying ParAcousti to hydro-acoustic environments that replicate increasingly complex systems. Analytical solutions and benchmark scenarios were chosen from literature and compared to ParAcousti. A spherical spreading Gaussian pulse in an unbounded domain, a continuous monopole source in an ideal 2D domain, a continuous monopole source in a shallow water two-layer (Pekeris) 2D

domain, and a 3D range dependent sloping bottom case with a single monopole source were explained. While the spherical spreading case matched the calculated data with a maximum root mean square deviation of $5.4\text{E-}07$ Pa, the Ideal case showed a maximum root mean square deviation of $6.39\text{E-}04$ Pa. Attention should be given that for any sound pressure comparison between models, concern is placed on the maximum positive pressure values and not the minimums. For both the Ideal and Pekeris comparisons, agreement was seen between the time to arrival for any given location, the wave length, shape of the waveform, and peak pressure value of each waveform. Values for the Pekeris waveguide were confirmed with Jensen [55] and demonstrate that the introduction of a sediment layer increases the number of sound wave reflections back into the water column while increasing the wave length of the pressure wave. Peak values, arrival times, and generalized wave formation for the 3D sloping bottom case was compared to a Parabolic Equations (PE) solution in Jensen, 1995 [55], as well as a secondary solution provided by Sturm in 2005 [109]. PE are a cylindrical wave, forward marching acoustic propagation solution, which is heavily range dependent. Values for ParAcousti and Sturm vary depending on location across the y-axis of the slope. However, agreement was identified in the time to arrival of the receiver location and the visibility of specified interaction points along the slope. As energy is reflected both away from the change in density of the slope and reflected down into the slope, those changes in wavelength and location are observed in both Sturm's 3D model and ParAcousti. Depth averaged values agree for the source parameters and the initial distance required to drop below 70 dB re $1 \mu\text{Pa}$. ParAcousti incorporates a greater amount of variability into the model itself as compared to a PEs method and that is indicated in the difference in depth averaged values. Comparisons show strong evidence that the model agrees to analytical solutions. Differences between ParAcousti and published PE methods were expected and indicate moderate evidence that wave form trends and interactions within the domain are upheld when comparing two very different solution methods.

Initial validation efforts provided confidence in ParAcousti as an underwater propagation model and the program was applied to a real-world environment, comparing 3D and 2D model data to the experimental data from Sequim Bay, WA. ParAcousti was released to the public in 2018 by SNL as a viable alternative to the Helmholtz equations. This research provided a unique opportunity to understand how a full 3D model may affect how sound propagates and interacts with a complex environment. Sequim Bay is a shallow water system with maximum depths approaching 40 m. It is also nearly surrounded by land except to the north, where the bay is separated from Puget Sound by a jetty. The jetty extends approximately 3/4 of the way across the bay. Clear induced pulses were apparent within the ambient recorded sound levels for the 50 m and 100 m source distances and for any frequency above 500 Hz. Pulses for the 200 Hz data were sporadic and had a large overlap with additional sound sources in the bay generated from marine fauna and shipping noise. Overall ambient noise values were nearly 68 dB re 1 μPa .

Data comparisons between the 3D and 2D model runs indicate that the 2D models fail to capture many of the additional interactions between sound waves being reflected back into the bay off the bay floor as well as the sound being concentrated from sound waves reflecting out of the canyon on the West side of the bay. The 3D models demonstrate the complexities of a 3D system and indicate that the SPLs calculated from the non-calibrated source data are elevated because of these added constraints. Calibrating the source profiles reduced the SPLs for the 50 m, 100 Hz, simulation sound pressure levels. This is indicative of an increased dampening affect as compared to the 2D simulations. SPLs were more variable for the 3D solutions across the duration of the source; however, the time to receiver and the wave length remained constant between the 2D and 3D models. As wave length is a function of frequency and sound speed, any difference in wave length would indicate that one of the model solutions needed to be re-evaluated. Other propagated sound models that do not consider full 3D systems could be under-reporting the potential impact of a MHK source

or array of sources, especially within a confined, shallow water environment. A pseudo 3D system would also not quantify all of the 3D interactions as it would only simulate one 2D slice at a time.

The comparison between the Sequim Bay recorded data set and the modeled data demonstrate that at source distances of 200 m and greater and frequencies of 200 Hz and below, ParAcousti values fall below the ambient noise of the bay. At all locations, the simulated recorded frequency of 750 Hz was considerably lower than that of the modeled data. The 500 Hz data was a closer match and SPLs fell within the variability of the recorded data. The time to arrival from the signal source to the receiver matches the recorded data. The recorded sound data was noisy, increasing the variability associated with the recorded data. Pulse variability ranged from 2 - 8 dB depending on the particular recorded data set, and increased with distance from the source. Additionally, the evidence provided with the validation efforts as well as the trends shown in the Sequim Bay modeled data indicate that results likely do not match because of the added background energy levels interacting with the sound sources, as well as a variability in environmental parameters that was not factored into the model. Background energy levels are not included within the ParAcousti model; however, incorporating the background broadband noise levels into the simulated signal is possible. More information would be required to identify particular sound sources from the spectrogram data and select which sources impact that of the recorded pulse data. Variability in measured environmental parameters within the bay which were unaccounted for at the time of the data collection effort would further influence the modeled data. Source and ship orientation were unknown and could influence how sound reflects off the side of ship and propagates outward.

Ultimately, 3D environments produce incredibly complex soundscapes that cannot be modeled unless, 1) a full 3D solution is provided and 2) measured data required for the model domain is available. It is statistically improbable for a model to identically match

an environment. A model can very closely approximate recorded values given that all environmental parameters are accounted for, the parameters are exact, and an unlimited amount of computational expense is available. While models continue to progress, that is not a current reality and all measured values contain some form of error. ParAcousti incorporates additional required complexities associated with an MHK source and evidence suggests that for a real environment, the model overestimates pulse values. A further investigation on model sensitivity to environmental parameters is suggested.

To provide economical energy generation, MHKs are typically deployed as an array of devices. When deployed in real world environments, the systems experience a range of operational conditions over time. Although the devices are designed to be identical and therefore should produce identical noises, continual operation and changes within the environment may impact the sound source produced by an individual device. ParAcousti allows for the consideration of multiple, complex sources which are comprised of multiple frequencies. An uncertainty analysis was performed to understand how variability in frequency and phase in the sound source affects the sound produced by a maximum of 16 devices for various locations. In any deployment of CECs, for example, a single device will produce a range of frequencies unique to the function of the particular device. For all locations, uncertainty was largest when variability was included from both phase and frequency, almost 25 dB more as opposed to just frequency. Anytime variability is introduced into a model parameter or a variable that the model is highly sensitive to, uncertainty will increase dramatically. This indicates that one of the main drivers of uncertainty within the source function is the phase. Any real world CEC will be responding to changes in the environment around it as well as specific design parameters which alter its functionality. All interactions between source functions will be amplified closer to the source as the probability of each sound source interacting with another increases. Uncertainty decreases as distance from the source increases. Distance from a source allows for increased sound

energy dissipation so even when pressure waves interact from a sound source, the effect is reduced.

Further investigations demonstrated that uncertainty was larger for systems with more complex bathymetry, for example a two-layer system including sediment as compared to an open ocean. The two-layer system causes portions of any pressure wave generated by a sound source to reflect back off the sediment layer and free surface into the water column and continue to interact with all other sound sources present. The uncertainty in all of the data presents a very large variation in simulated SPL output. This variation indicates that there is more fluctuation with proposed MHK output than has been previously considered. The results from ParAcousti suggest that the source functions chosen are highly responsive to a change in phase as well as frequency. Any CEC or WEC is going to experience variations in both of these parameters over the lifespan of the devices.

ParAcousti may be leveraged to inform the design of an array and determine a range of acceptable operational conditions which will minimize potential impact and reduce SELs over time. Any changes to the design, layout, source parameters, or orientation may be completed before the array is deployed. Measured data may be used retroactively to inform design; however, any amendment to a deployed device or array of devices would require either maintenance or complete removal. Combining ParAcousti's ability to model 3D environments with representing the uncertainty in multiple complex sources makes this model a powerful tool for demonstrating and addressing any potential impacts to a marine environment and MHK design. This work has provided a better understanding of the complexities surrounding sound source functions for an MHK device, determining the potential impact of a MHK, and how those devices may compare with current regulations. The data suggests that the sound produced by MHKs is more substantial and nuanced than previously determined. The increased uncertainty of a MHK sound source should be incorporated into potential impact studies even though it has the potential to disrupt long-standing, best practices. To further

support the deployment of MHK devices, it is imperative that underwater sound propagation be properly characterized and the potential impact minimized. This work contributes to the overarching body of underwater acoustic propagation modeling by providing, validating, and applying a previously untested seismic model to complex and variable 3D model domains with multiple sources. Additionally, this work furthered the understanding of potential uncertainty in generated and propagated sound from MHK sources in marine environments to characterize future impacts.

Future Work

Based on the understanding of underwater sound propagation demonstrated within this document and in previous research, there are several lines of future work that would benefit ParAcousti as an acoustical and ecological MHK modeling tool. There is a large potential for continued research, some of which has already been considered in other projects funded by SNL. Outlined are several recommendations for future work involving the acoustic propagation algorithm ParAcousti.

Ecological Response Model

In 2013, Rossington developed an ecological response model referred to as an eco-hydraulic-acoustic tool. The tool was designed to predict the response of marine species to underwater sound by combining a range dependent (pseudo) 3D PE model with data from a hydrodynamic model, which in turn generated data for an ecological response model. Each individual animal within a species is represented as a particle that is subject to both advection and behavioral rules [101]. These types of models are referred to as Eulerian-Lagrangian Agent Method (ELAM) models and consider any fish or singular marine fauna to be a particle within a greater fluid system to determine the statistical probability of behavioral changes. Both velocities and pressure inform behavioral changes within marine

fauna. Incorporating ParAcousti into one of these ELAM tools would be advantageous to understanding the potential impacts of MHK sound sources on the marine environment. While quantifying SPLs for a domain of interest are important to the Marine Mammal Protection Act and regulations, the ability to predict a fish or marine mammal's response to any noise level would be ideal.

For ELAM models to incorporate the required input data for an environment of interest, a hydrodynamic model is included with the acoustic and behavioral models. SNL has completed some work directed at this with a comprehensive collection of programs called SEAT, the Spatial Environmental Assessment Toolkit. SEAT previously incorporated the ability to model the MHK device itself and the hydrodynamics associated with a location. ParAcousti was incorporated into SEAT in 2023 in order to characterize underwater acoustic propagation modeling with the goal that future work can address any and all potential impacts of a MHK deployment to an area. SEAT currently has the ability to determine the power, sound, and turbulence generated by an MHK device, as well as the hydrodynamics, sediment transport, water quality, and now acoustic propagation. SEAT provides an ideal platform to include additional behavioral parameters for an ecological response model [56].

3D Environments

The use of a delta function within this work to simulate a pseudo Monte-Carlo method could be further applied to analyze the impact of the variability of different model parameters on 3D environments. This work has demonstrated that ParAcousti may be used to simulate those 3D environments, which more accurately portray how underwater sound propagates in a real environments. Options for parameters include variability in sediment profiles within the model and inclusions of possible obstructions or objects that would exist in a real world system, such as the ship or dock yards within Sequim Bay, WA. A ship's hull would protrude down into the water column while floating in the bay, influencing the dynamic of propagating

sound waves. Additionally, uncertainty was applied to sound propagated from an array of sources, but that work could be furthered to optimize the orientation or layout of an array to minimize sound impact and maximize power generation. This is especially possible if SEAT was leveraged to model the sound, power, and turbulence generated by a single MHK device or array of devices.

Complex Source Types

All the simulated systems provided within this research leveraged a monopole sound source profile, which emits sound equally in all directions. Most sound sources other than that of a speaker are directional. MHK sources in particular are typically bi-directional at a minimum as a turbine has two distinct sides which both radiate sound outward from the device. As a stress tensor is included within the derivation for the Velocity-Pressure equations resulting in a moment density tensor, other complex source profiles may be modeled. The other two types of complex sources are dipole and quadrupole, which emit sound outward in two and four distinct quadrants, respectively. A comparison of simulations including variability in source type and direction would provide further data to understand how single MHK devices or an array of devices interact with the surrounding environment.

Variable Grid Spacing & Non-Rectangular Domains

ParAcousti implements a finite difference solution to the Velocity-Pressure equations in which values are calculated on a uniform, Cartesian grid. Grid node spacing is defined by the sound speed of a medium in order to appropriately capture the wave length of a pressure wave. Variable grid spacing determined by the particular medium being modeled would potentially reduce the number of grid cells for a simulation domain while preserving model accuracy. For example a sediment layer would have a higher sound speed and would have a larger minimum grid cell size as opposed to the water column to appropriately capture a specified wave length. Overall, a reduction in grid nodes would reduce computation time.

The inclusion of non-rectangular model domains would additionally reduce computational time. For any 3D environment of interest, the domain grid must be extended to fully encompass all six boundaries with distances being allowed to vary in the x, y, and z directions. In the example of a 3D bay which is not rectangular, the boundaries may result in a large number of unnecessary grid nodes required to square the edges of the bay bathymetry and more of the surrounding sediment layer is modeled than essential to the model output. A domain that is not limited to a 3D rectangle and that could include a sloped slide would be advantageous to reduce grid cell numbers and computational time. Modification to the ParAcousti meshing functions would allow the domain and boundary conditions to better represent the bathymetry and reduce any unnecessary calculations in the sea bed material.

ParAcousti Executable

For this research, MATLAB has been the program of choice for all pre- and post-processing of inputs and outputs required for ParAcousti. Tutorials and documentation are also available for Python and the end user may use any program which can read .cdf files as well as large matrices. However, for large models, MATLAB becomes computationally inefficient and matrices may be too large for the program to handle. Development of a Graphical User Interface (GUI) in association with an executable built to manage the data requirements associated with ParAcousti would be of great benefit, especially for new users. The GUI would build all necessary input files and evaluate the output data from ParAcousti. Arbitrary domains could be constructed with inputs for sound speed and density profiles based on selected environmental parameters and would allow for an incorporated hydrodynamic model. The GUI would set all necessary model source and algorithm parameters for a specified domain based on a user defined source and required outputs.

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APPENDIX

SEQUIM BAY FIGURES

This appendix is a collation of additional figures not directly included in chapter 5: Sequim Bay Comparison. Please reference that chapter for a discussion on the figures presented. The additional data presented falls into four collections: Un-calibrated SPLs for 100 Hz at 100, 200, 500, and 1,000 m locations; spectrograms for the simulated 100 Hz data and the recorded data; the recorded signal data; and the comparison of recorded signal data to simulated. The remaining plots all pertain to visualizing the recorded signal data collected January, 2018 in Sequim Bay, WA. Signal values are for the 100 - 750 Hz range, at the 50, 100, 200, 500, and 1,000 m source distances. The second section contains the remaining data comparison plots which show the eight processed signal profiles from the recorded data as compared to the simulated data for the same locations. Comparison plots are available for 50, 100, 500, and 1,000 m locations. Frequencies included are generally the 100 and 200 Hz values for all locations other than the 100 Hz, 50 m location is available in the main text of chapter 5.

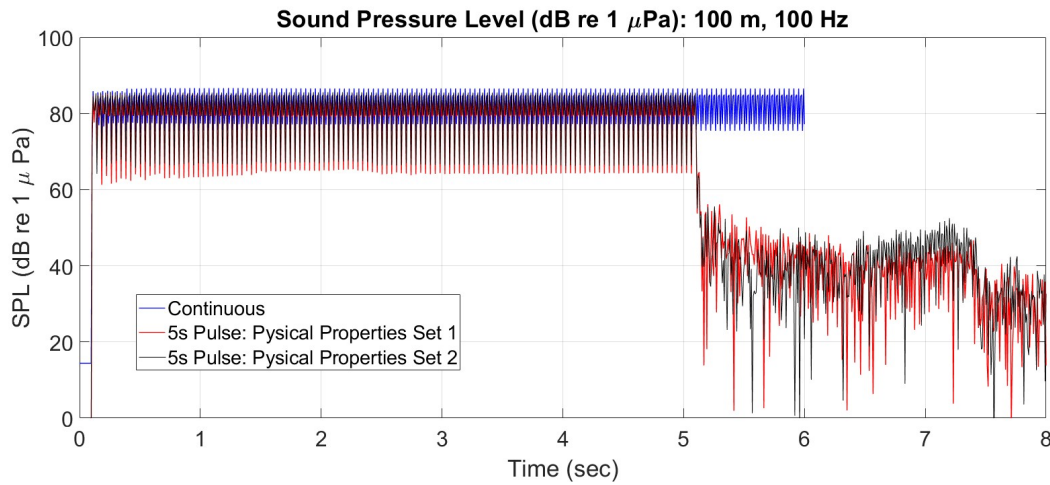


Figure A.1: SPLs in time located at the sensor array, 100 m from the source produced by all 2D, 100 Hz ParAcousti models at that distance.

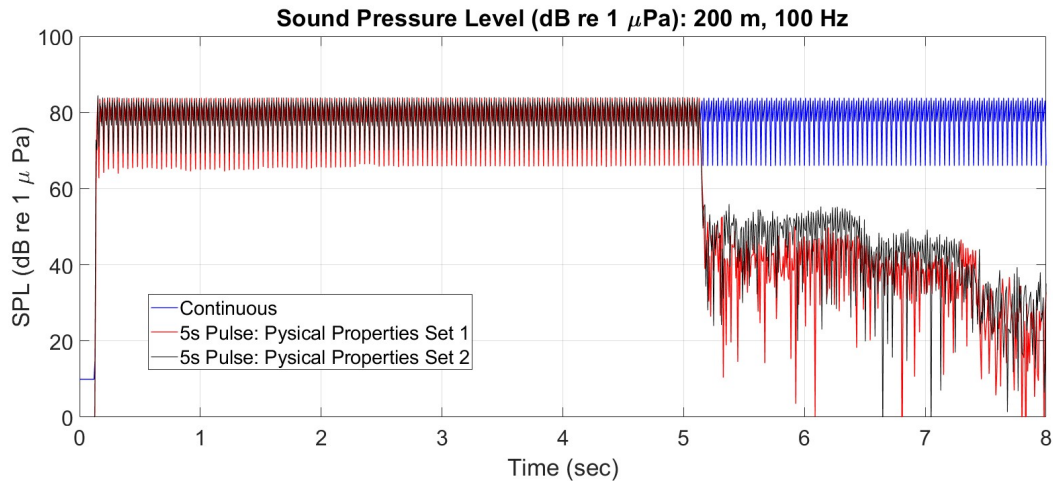


Figure A.2: SPLs in time located at the sensor array, 200 m from the source produced by all 2D, 100 Hz ParAcousti models at that distance.

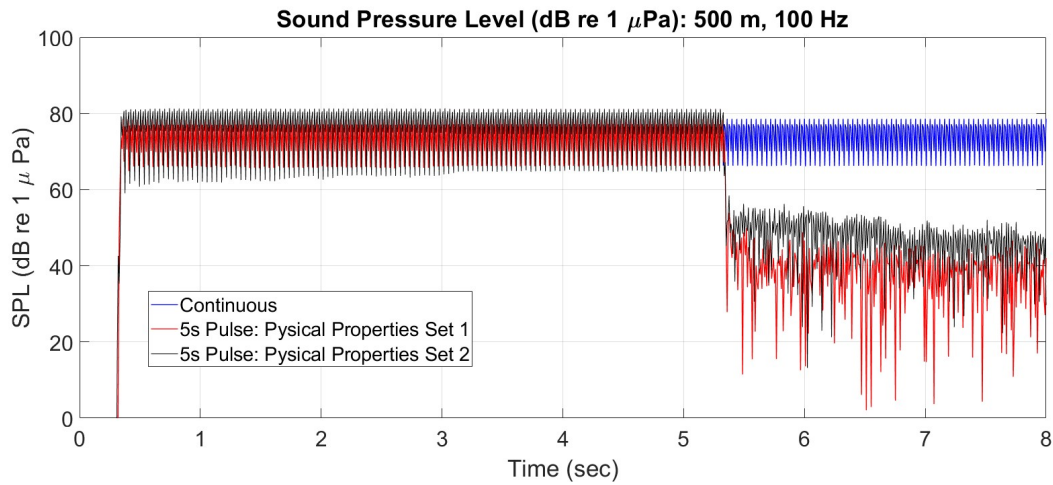


Figure A.3: SPLs in time located at the sensor array, 500 m from the source produced by all 2D, 100 Hz ParAcousti models at that distance.

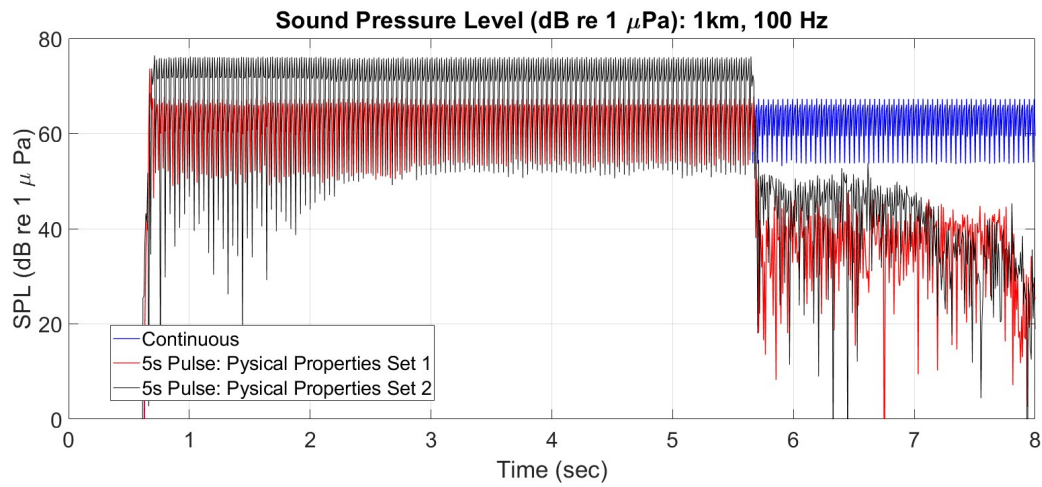


Figure A.4: SPLs in time located at the sensor array, 1 km from the source produced by all 2D, 100 Hz ParAcousti models at that distance.

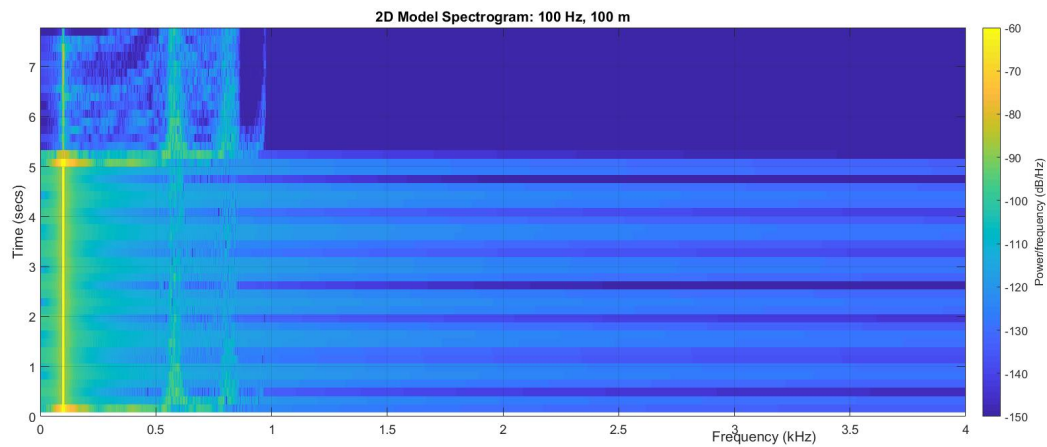


Figure A.5: Spectrogram analysis of the 2D ParAcousti pressure output in time modeling a 100 Hz source located 100 m from the sensor array. Data is located at the sensor array.

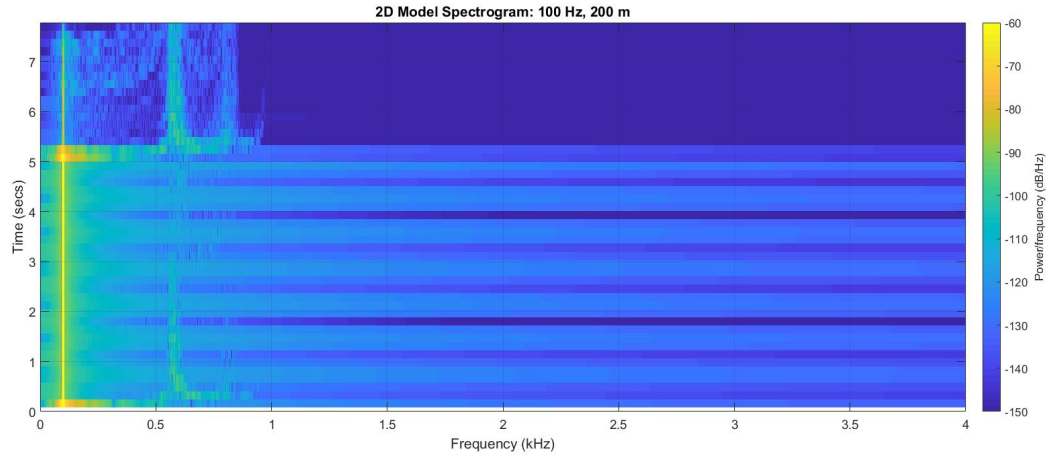


Figure A.6: Spectrogram analysis of the 2D ParAcousti pressure output in time modeling a 100 Hz source located 200 m from the sensor array. Data is located at the sensor array.

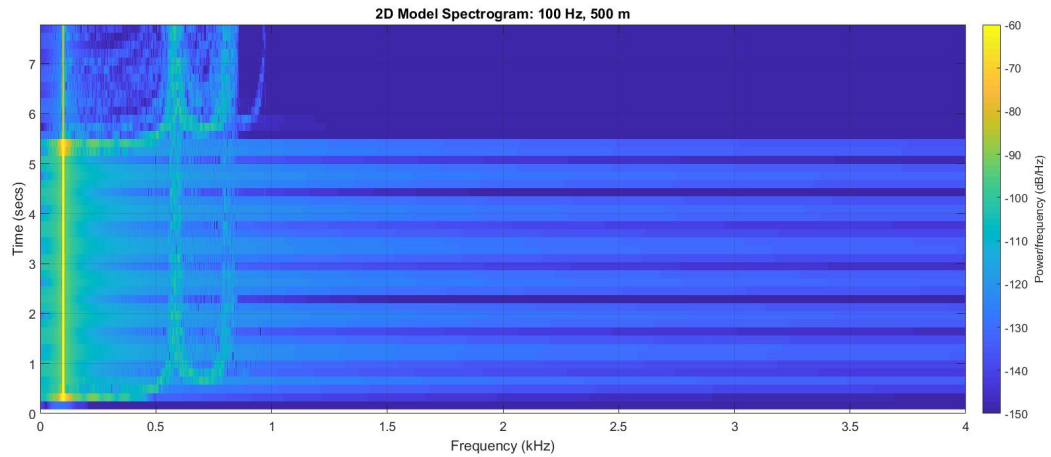


Figure A.7: Spectrogram analysis of the 2D ParAcousti pressure output in time modeling a 100 Hz source located 500 m from the sensor array. Data is located at the sensor array.

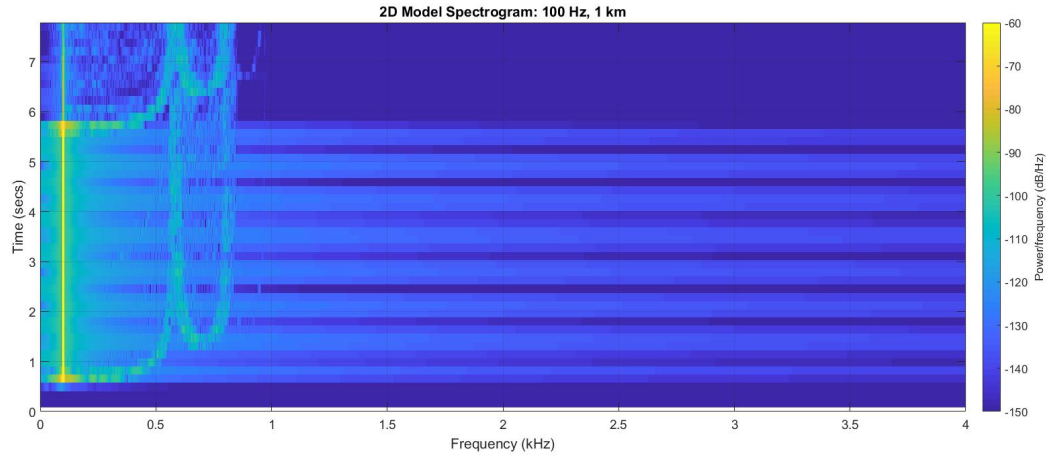


Figure A.8: Spectrogram analysis of the 2D ParAcousti pressure output in time modeling a 100 Hz source located 1 km from the sensor array. Data is located at the sensor array.

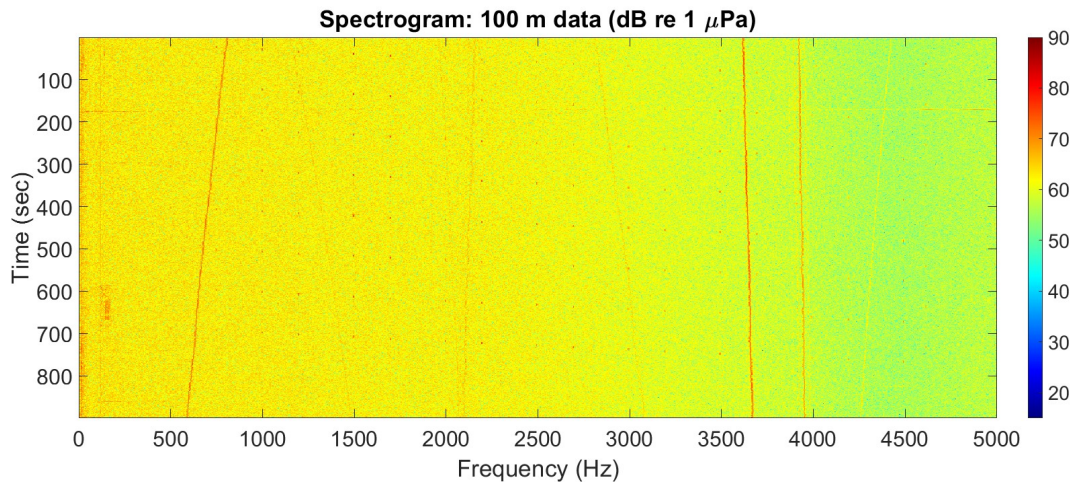


Figure A.9: Spectrogram of all recorded Sequim Bay data in time at the source array location, 100 m from the source.

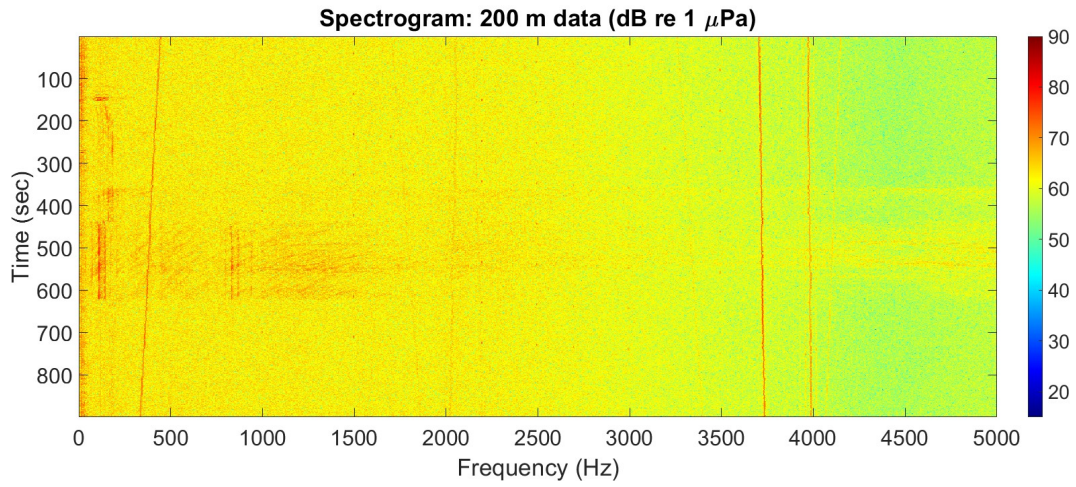


Figure A.10: Spectrogram of all recorded Sequim Bay data in time at the source array location, 200 m from the source.

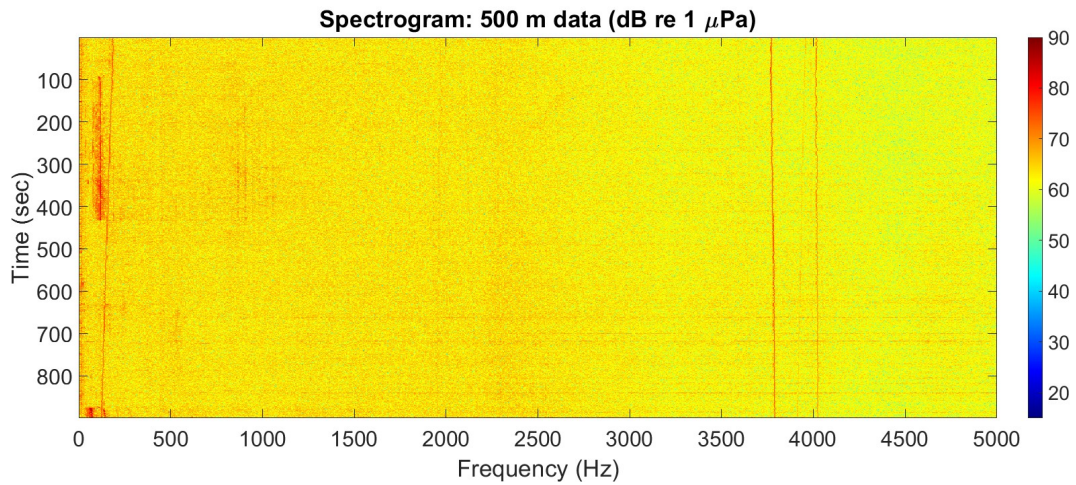


Figure A.11: Spectrogram of all recorded Sequim Bay data in time at the source array location, 500 m from the source.

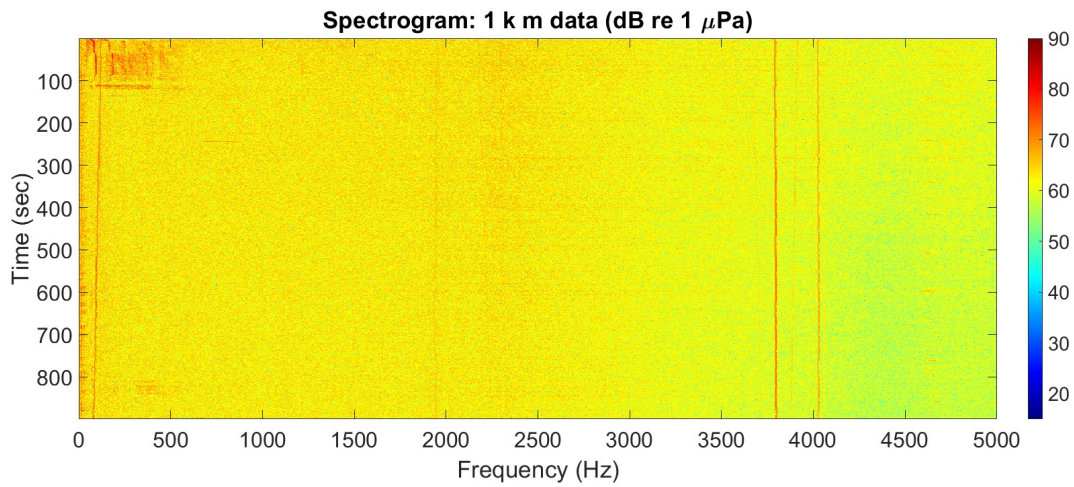


Figure A.12: Spectrogram of all recorded Sequim Bay data in time at the source array location, 1 km from the source.

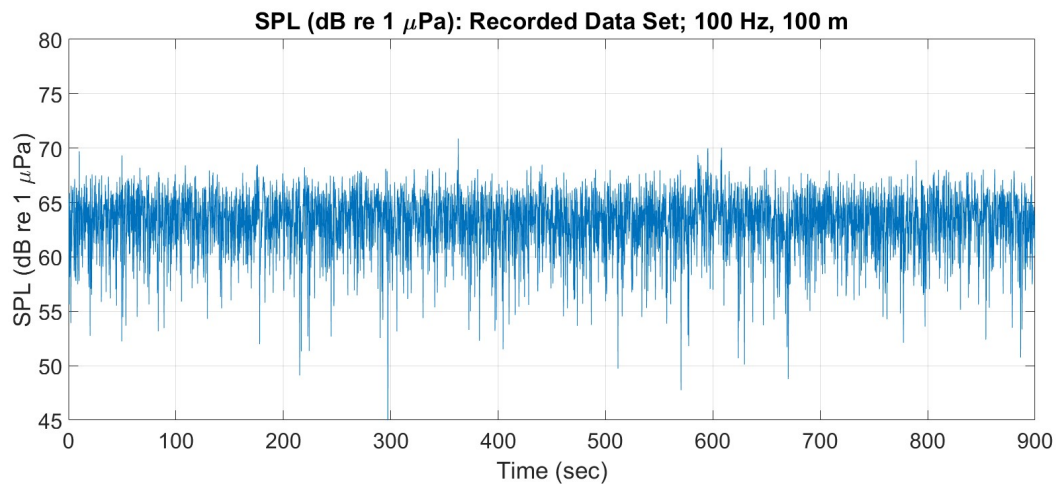


Figure A.13: The 100 Hz recorded Sequim Bay data files converted to SPLs in time for the 15 minute emission period; located at the sensor array, 100 m from the source.

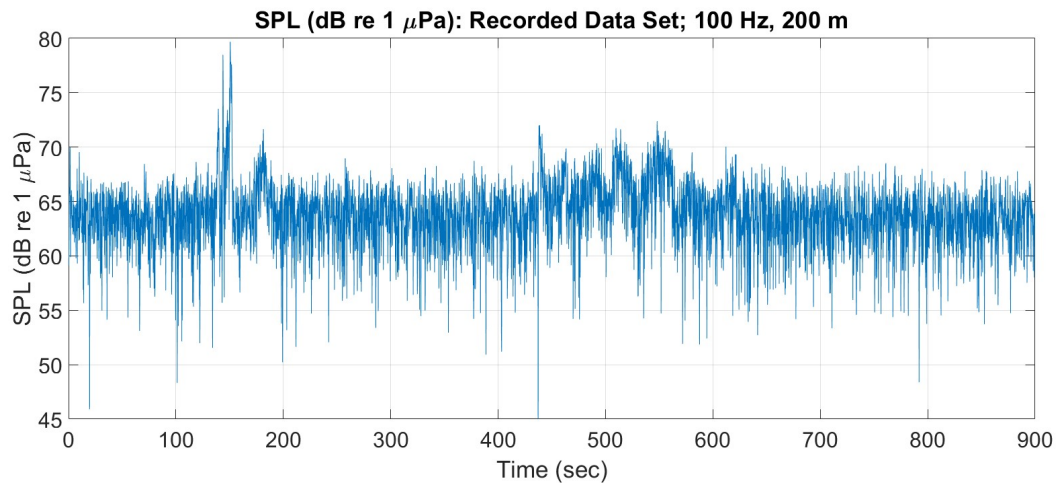


Figure A.14: The 100 Hz recorded Sequim Bay data files converted to SPLs in time for the 15 minute emission period; located at the sensor array, 200 m from the source.

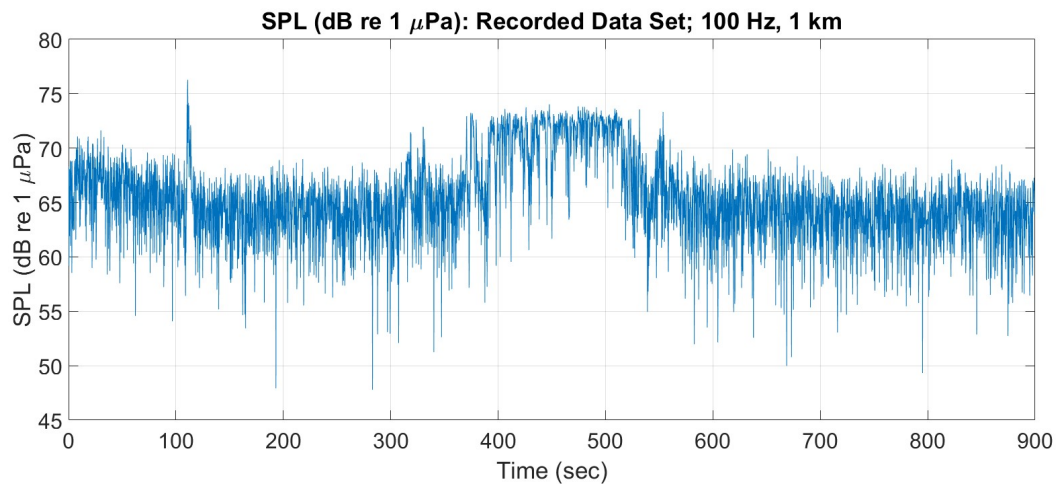


Figure A.15: The 100 Hz recorded Sequim Bay data files converted to SPLs in time for the 15 minute emission period; located at the sensor array, 1 km from the source.

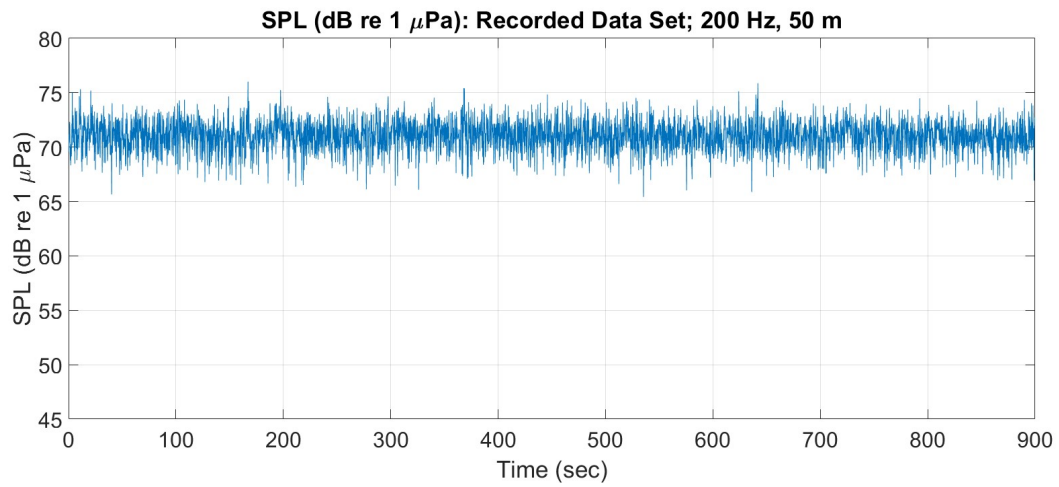


Figure A.16: The 200 Hz recorded Sequim Bay data files converted to SPLs in time for the 15 minute emission period; located at the sensor array, 50 m from the source.

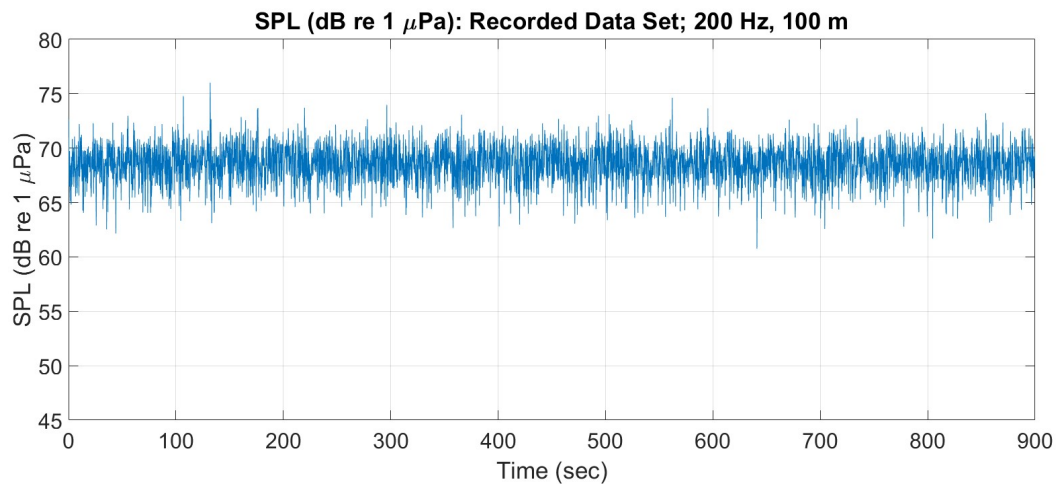


Figure A.17: The 200 Hz recorded Sequim Bay data files converted to SPLs in time for the 15 minute emission period; located at the sensor array, 100 m from the source.

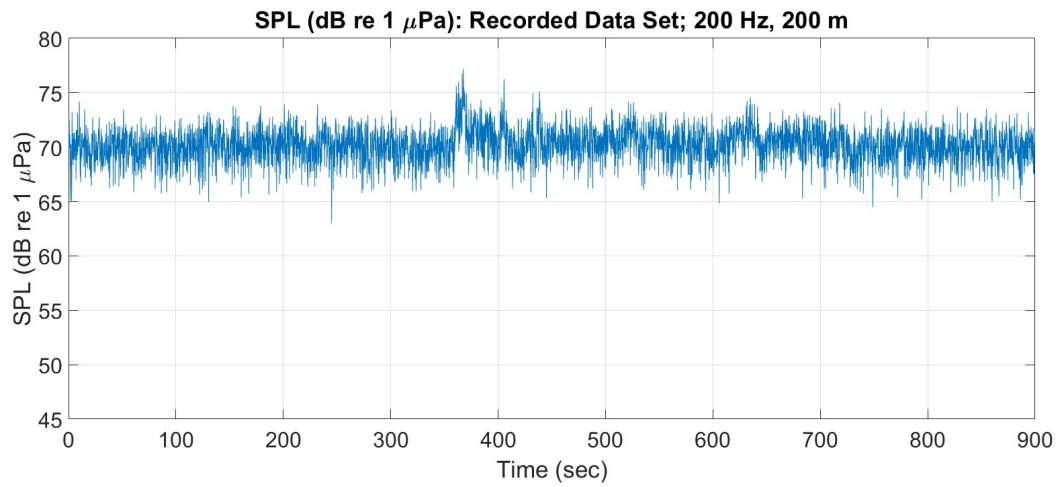


Figure A.18: The 200 Hz recorded Sequim Bay data files converted to SPLs in time for the 15 minute emission period; located at the sensor array, 200 m from the source.

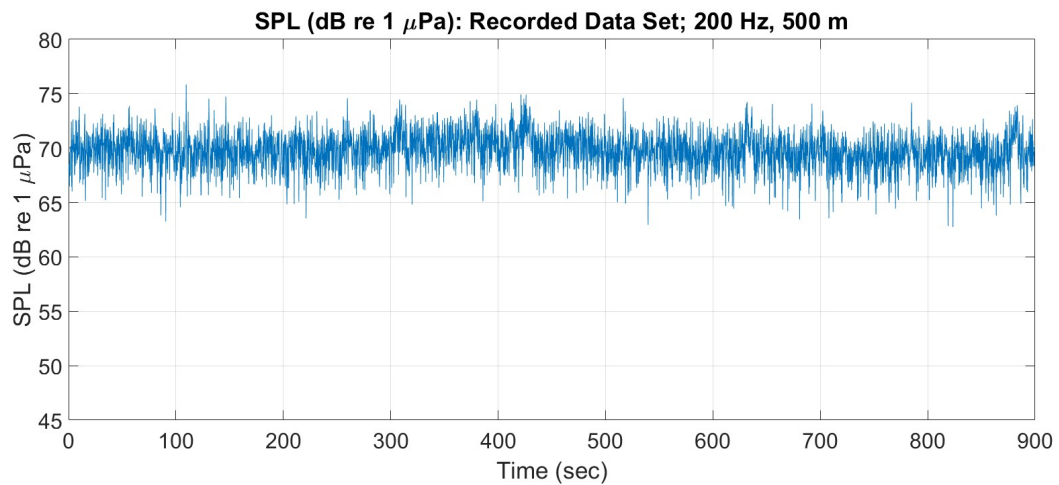


Figure A.19: The 200 Hz recorded Sequim Bay data files converted to SPLs in time for the 15 minute emission period; located at the sensor array, 500 m from the source.

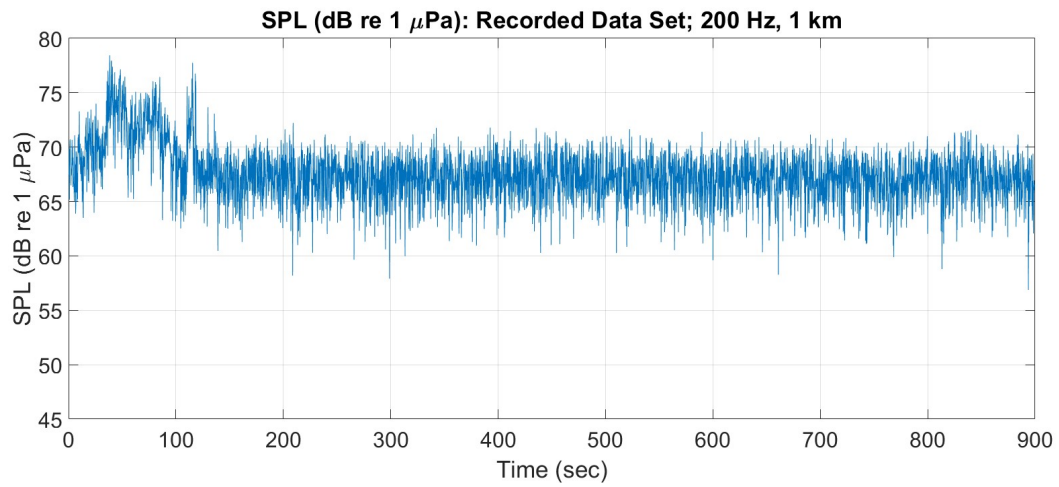


Figure A.20: The 200 Hz recorded Sequim Bay data files converted to SPLs in time for the 15 minute emission period; located at the sensor array, 1 km from the source.

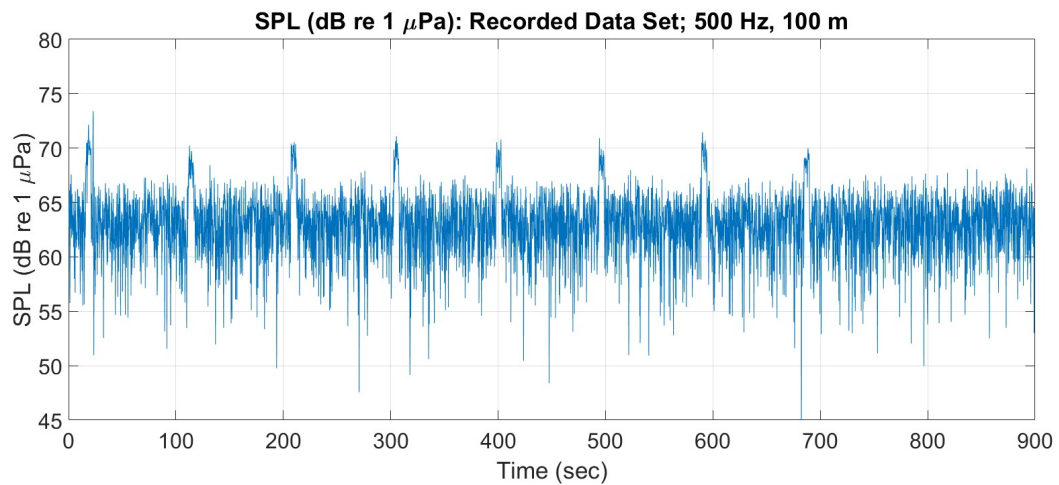


Figure A.21: The 500 Hz recorded Sequim Bay data files converted to SPLs in time for the 15 minute emission period; located at the sensor array, 100 m from the source.

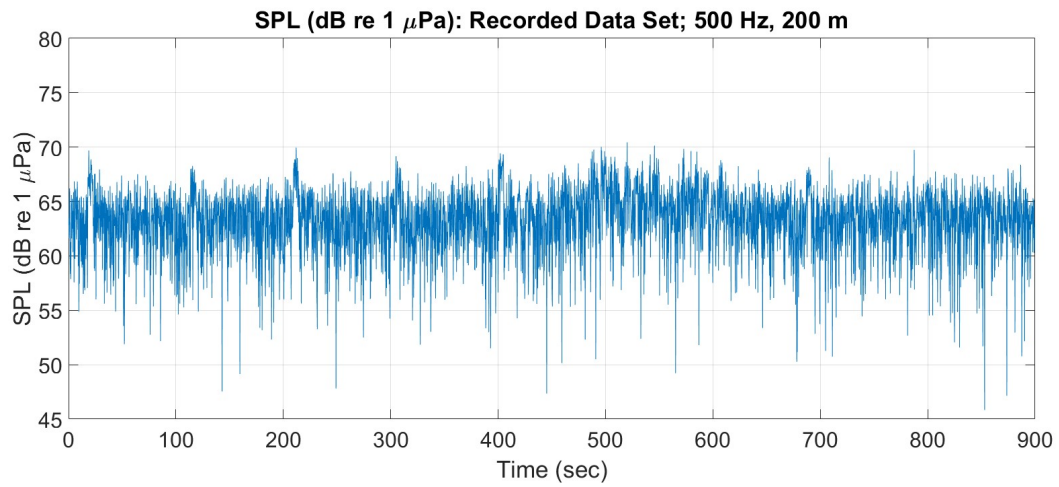


Figure A.22: The 500 Hz recorded Sequim Bay data files converted to SPLs in time for the 15 minute emission period; located at the sensor array, 200 m from the source.

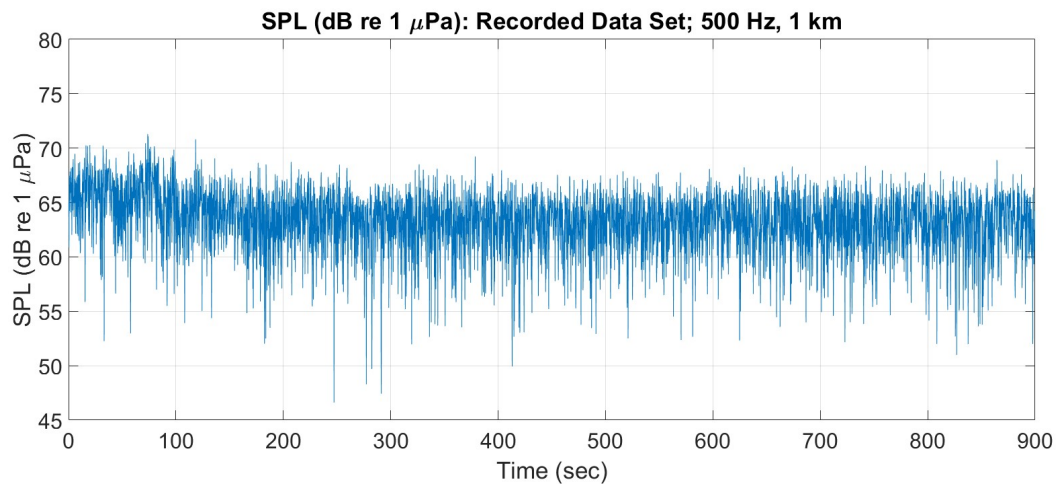


Figure A.23: The 500 Hz recorded Sequim Bay data files converted to SPLs in time for the 15 minute emission period; located at the sensor array, 1 km from the source.

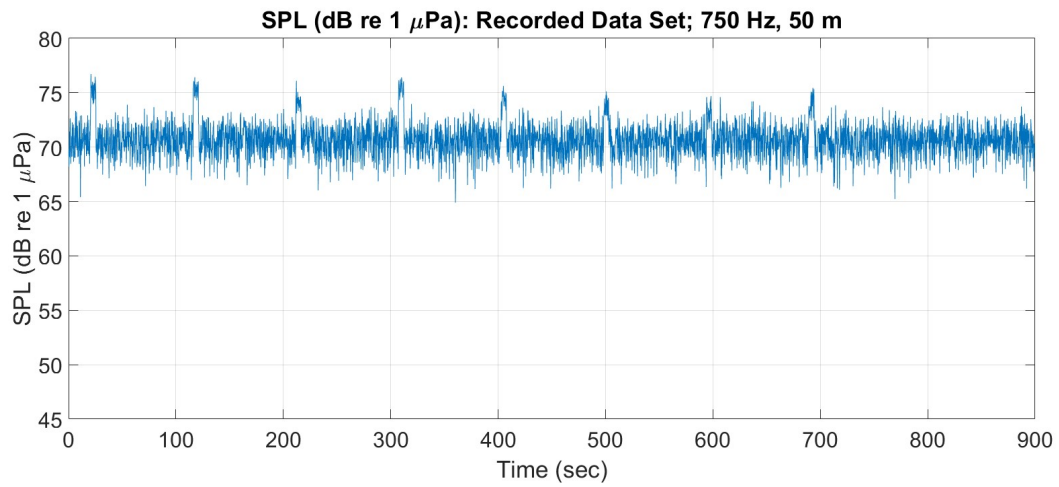


Figure A.24: The 750 Hz recorded Sequim Bay data files converted to SPLs in time for the 15 minute emission period; located at the sensor array, 50 m from the source.

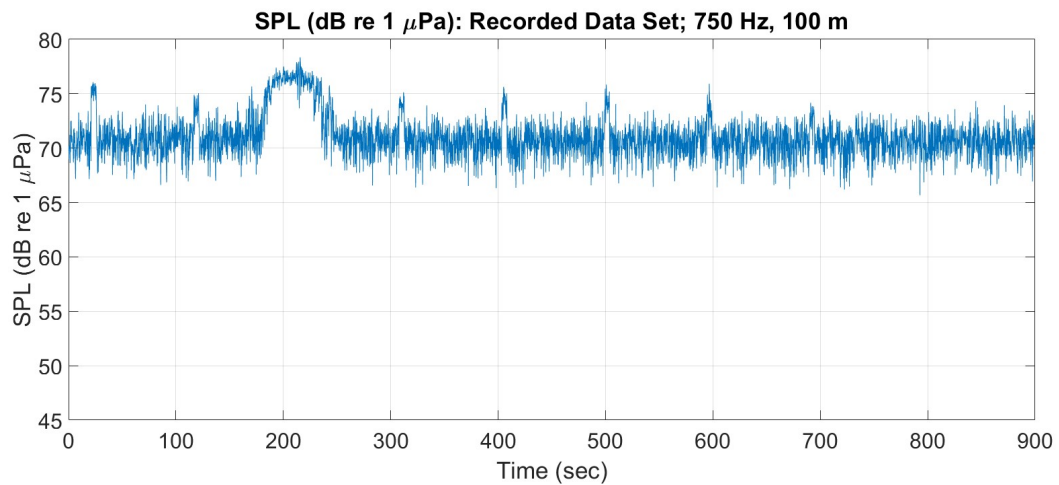


Figure A.25: The 750 Hz recorded Sequim Bay data files converted to SPLs in time for the 15 minute emission period; located at the sensor array, 100 m from the source.

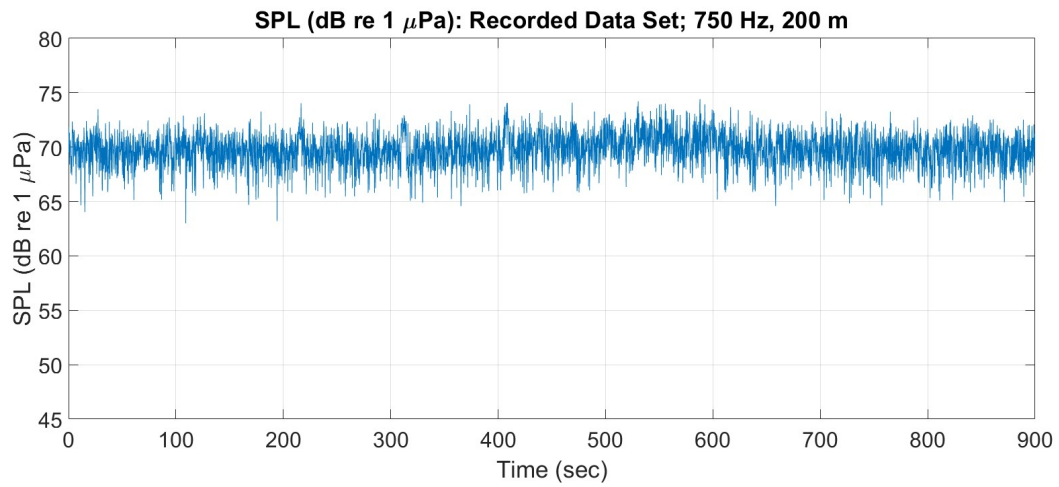


Figure A.26: The 750 Hz recorded Sequim Bay data files converted to SPLs in time for the 15 minute emission period; located at the sensor array, 200 m from the source.

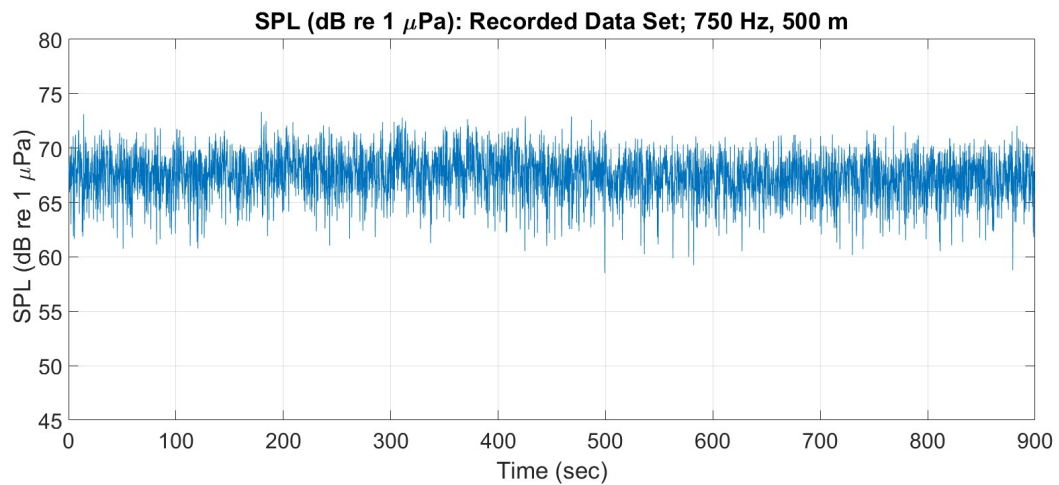


Figure A.27: The 750 Hz recorded Sequim Bay data files converted to SPLs in time for the 15 minute emission period; located at the sensor array, 500 m from the source.

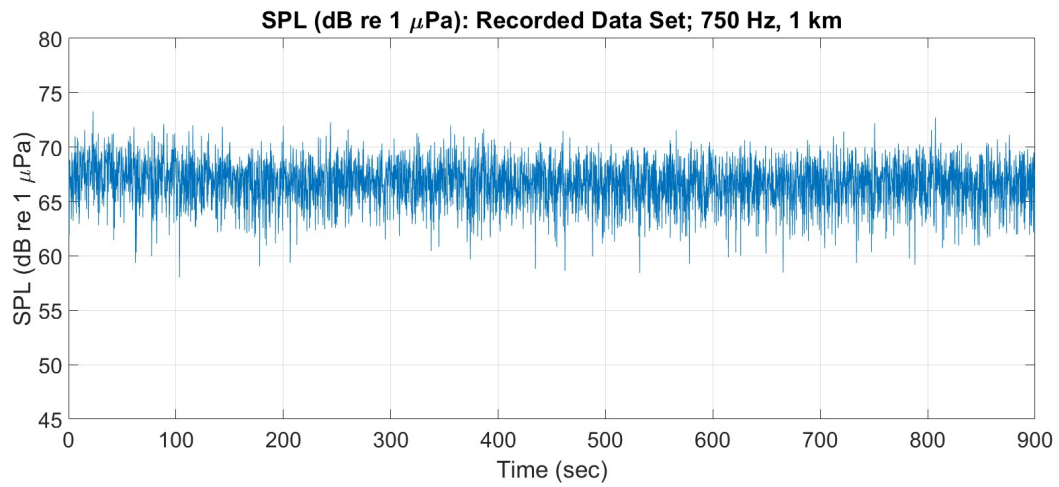


Figure A.28: The 750 Hz recorded Sequim Bay data files converted to SPLs in time for the 15 minute emission period; located at the sensor array, 1 km from the source.

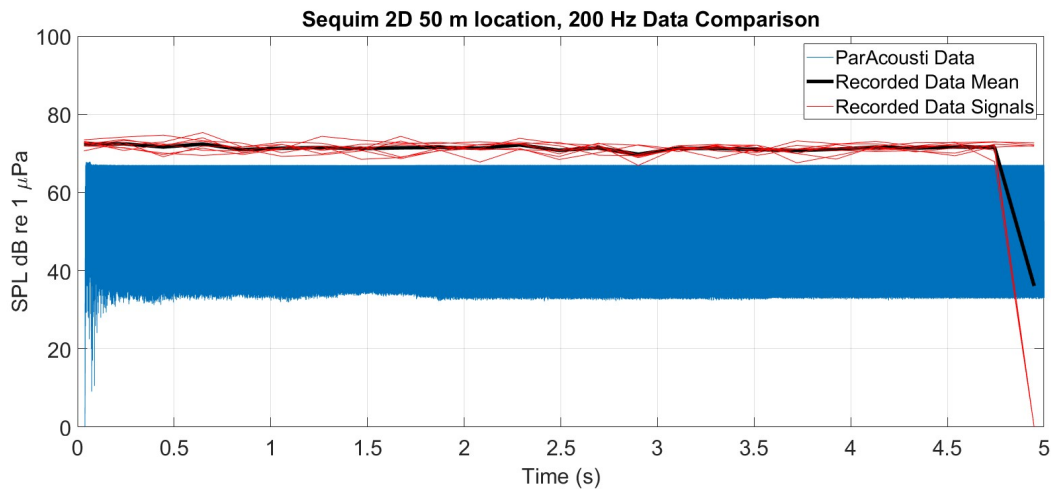


Figure A.29: A comparison between the eight recorded signal pulses at the receiver array location 50 m from the sound source, with a frequency of 200 Hz.

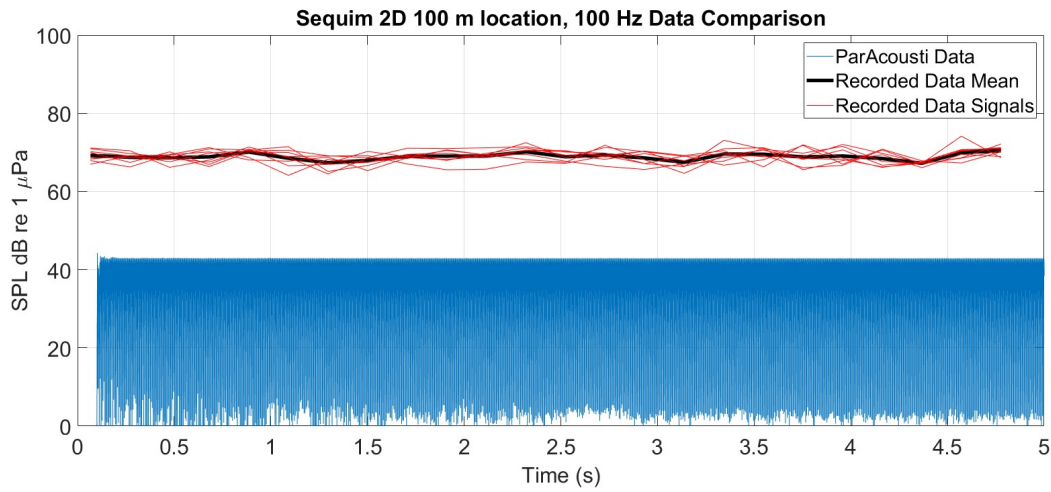


Figure A.30: A comparison between the eight recorded signal pulses at the receiver array location 100 m from the sound source, with a frequency of 100 Hz.

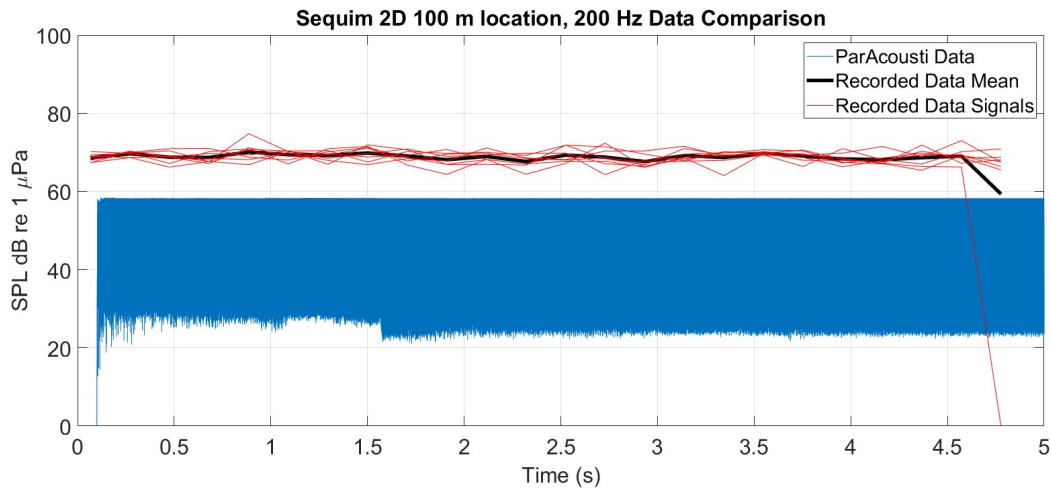


Figure A.31: A comparison between the eight recorded signal pulses at the receiver array location 200 m from the sound source, with a frequency of 200 Hz.

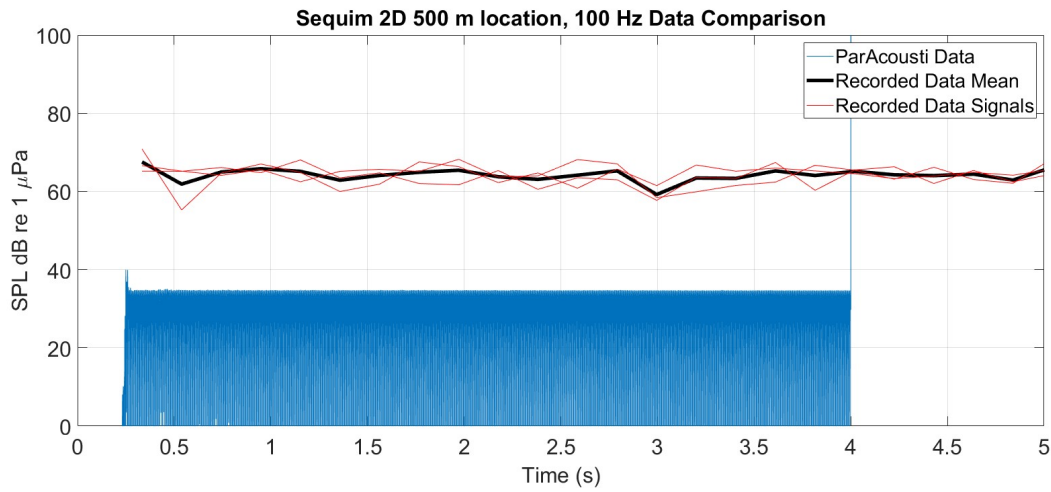


Figure A.32: A comparison between the eight recorded signal pulses at the receiver array location 500 m from the sound source, with a frequency of 100 Hz.

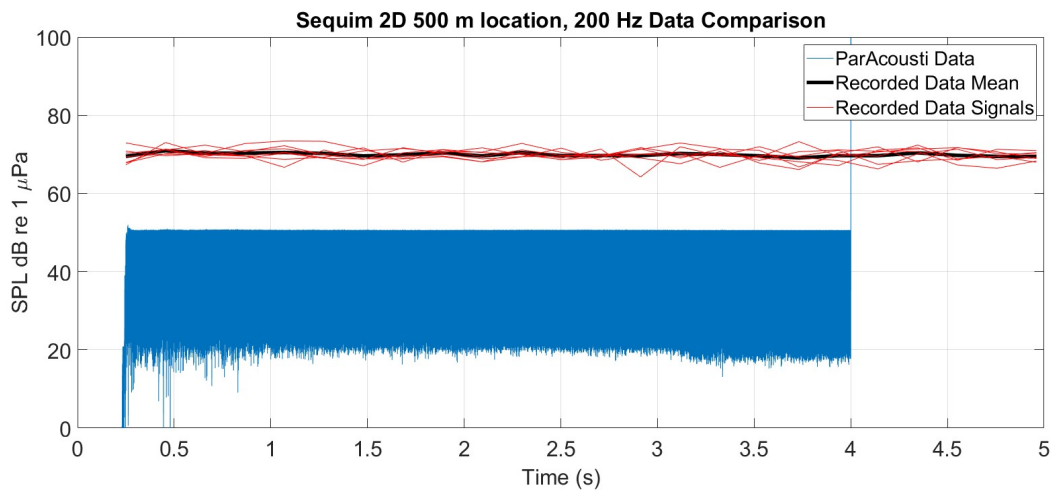


Figure A.33: A comparison between the eight recorded signal pulses at the receiver array location 500 m from the sound source, with a frequency of 200 Hz.

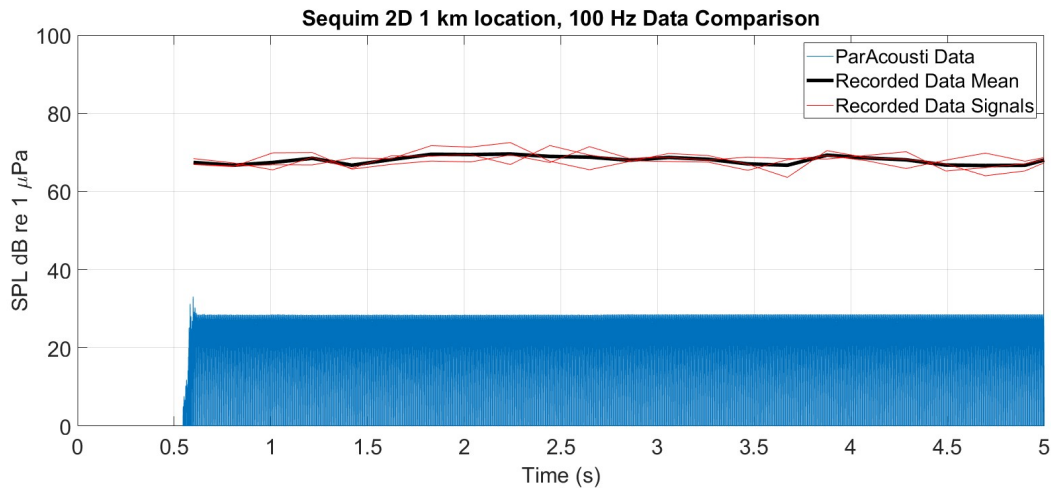


Figure A.34: A comparison between the eight recorded signal pulses at the receiver array location 1,000 m from the sound source, with a frequency of 100 Hz.

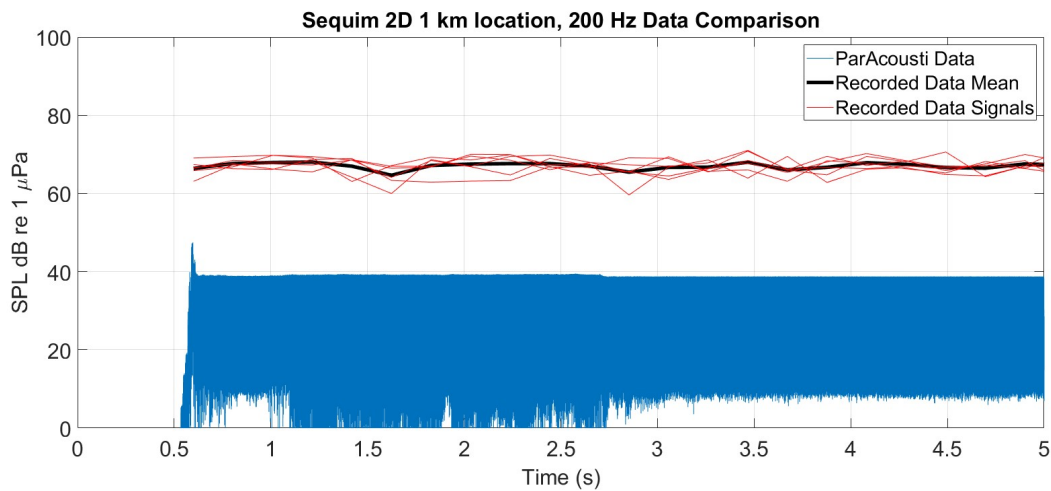


Figure A.35: A comparison between the eight recorded signal pulses at the receiver array location 1,000 m from the sound source, with a frequency of 200 Hz.