

ACOUSTIC PROPAGATION MODELING FOR MARINE
HYDROKINETIC APPLICATIONS

by

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ABSTRACT

The combination of riverine, tidal, and wave energy have the potential to supply over one third of the United States' annual electricity demand [1]. However, in order to deploy and test prototypes and commercial installations, marine hydrokinetic (MHK) devices must meet strict regulatory guidelines. These regulations mandate the maximum amount of noise that can be generated and sets particular thresholds for determining disturbance and injury caused by noise. In the absence of measured levels from in-situ deployments, a model for predicting the propagation of a MHK source in a real hydro-acoustic environment needs to be established. An accurate model for predicting the propagation of a MHK source(s) in a real-life hydro-acoustic environment has been established. This model will help promote the growth and viability of marine, water, and hydrokinetic energy by confidently assuring federal regulations are met and harmful impacts to marine fish and wildlife are minimal. A 3D finite-difference solution to the governing velocity-pressure equations is presented and offers advantages over other acoustic propagation techniques for MHK applications as spatially varying sound speeds, bathymetry, and bed composition that form complex 3D interactions can be modeled. This solution method also allows for the inclusion of complex MHK sound spectra from turbines and/or arrays of turbines. A number of different cases for hydro-acoustic environments have been validated by both analytical and numerical results from canonical and benchmark problems. Several of these key validation cases are presented in order to show the applicability and viability of a finite difference numerical implementation code for predicting acoustic propagation in a hydro environment. With the model successfully validated for hydro-acoustic environments, more complex and realistic MHK sources from turbines and/or arrays can be modeled. A systematic investigation of MHK relevant scenarios is presented with increasing complexity including a single- and multi- source investigation, a random phase change study, and a hydro-acoustic model integration

1. INTRODUCTION

With great power comes great responsibility. From the first fire created by gathering wood, to the first steam engine propelling the industrial revolution, to the electricity used to power the first lightbulb, humanity's existence literally depends on "power". It creates our food, keeps us warm, and drives technological progress. The demand for power is immense and only appears to be increasing. So far, supply has been able to keep up with demand, but to what end? Are the current practices of harvesting energy by humanity sustainable? Many think not. The majority of conventional energy comes from non-renewable sources with limited supplies. In the last few decades, a movement has gained momentum to shift humanity's dependence on conventional non-renewable energy sources to more sustainable and renewable sources of energy. A sense of responsibility to the environment is felt by an increasing majority of the population and has driven new policies, regulations, and milestones. In 2013, the United States federal government issued a presidential memorandum directing the U.S. to pursue a goal of having 20% of its energy demand supplied by renewable sources by 2020 [2]. Other countries committed to a similar goal including the European Union and China. These goals have driven policy, research, and investment into non-conventional, renewable energy sources and technology.

Marine Hydrokinetic (MHK) energy is one form of non-conventional, renewable energy gaining momentum around the globe. Energy harvested from the motion of waves and tidal currents are characterized as MHK. The total recoverable energy in the U.S. from current and wave MHK energy is projected to be approximately 1,700 TWh per

year. This is enough energy to power around one third of the annual electrical consumption in the U.S. [1]. As the smallest contributor, even the recoverable energy in the continental U.S. from riverine environments is approximately 120 TWh per year [1]. To put this in perspective 1 TWh per year is enough power to supply 85,000 U.S. households with energy for one year; or rivers alone can power 10.2 million homes. It's no wonder why governments, large companies, and entrepreneurs alike are pursuing MHK and putting a great deal of resource into the research, design, and installation of MHK technology.

There are a wide range of MHK devices and much of the research and interest is in the design and optimization of these devices. Increasing performance of MHK devices to make them economically viable is a large driving force behind the technology and is extremely important; however, as environmental stewards we must insure that the design, installation, and operation of these devices create as little harmful impacts to the environment as possible. Careful consideration of the effects of putting devices in an already impacted and sensitive environment is crucial to the success and viability of MHK technology. The National Environmental Policy Act (NEPA) of 1970 lays the framework for assessing environmental effects of any federal action, including the installation of MHK devices, by requiring environmental assessments and environmental impact statements to be developed. The Marine Mammal Protection Act of 1972 specifically prohibits the act of or attempt to hunt, kill, capture and/or harass a marine mammal. Some potential concerns of MHK devices include physical injury from contact; behavioral disturbances stemming from the emission of light, sound, and/or

electromagnetic fields; emission of chemicals; and physical hazards to shipping. Many of these concerns are similar to those identified in oil, gas, and wind energy activities. Of particular concern, and the focus of this thesis, are the impacts to marine wildlife and the environment caused by the emission of sound, or pressure disturbances.

Sound can cause direct injury to marine mammals and wildlife by damaging tissue and indirect injury by changing behavioral patterns that are important to various life cycle stages, that reduce access to food, or that simply cause them stress. In order to assess the type and/or severity of impact to the marine environment cause by sound emission, the sound generation from MHK devices and sound propagation through the environment must be well understood.

While real world experiments and *in-situ* monitoring of sound in certain deployments is important, the ability to numerically model and predict the noise generation and propagation of a proposed device and/or installation offers several advantages. First, instead of needing a complete, manufactured device to test, computational fluid dynamics can accurately model a device's performance, including noise generation, without a physical system and can drastically save time and money during the design stage. Similarly, any tweaks or improvements to the design of the MHK device can be quickly analyzed through numerical modeling without the need for a new physical prototype. Next, numerical acoustic propagation modeling can give accurate results of the transmission of generated noise through the environment without the need for expensive, and often intrusive, monitoring and instrumentation. Finally, many different device placements, configurations and generated noise sources can be

considered with a numerical model that frankly would be nearly impossible to analyze otherwise.

This thesis is aimed at making progress towards a framework that a developer or researcher of MHK energy may use to analyze a potential deployment site by accurately modeling the propagation and transmission of sound energy in a marine environment. Chapter 2 provides a background on common acoustical solution techniques as well as some analogous applications of underwater acoustics to MHK. The choice acoustic propagation algorithm as well as its pre-processing input file building and post-processing output file reading is described in the Methodology Chapter 3. Chapter 4 contains verification of the acoustical propagation algorithm with benchmark and canonical scenarios from underwater acoustics. A single-source investigation of MHK relevant domains and sources are in Chapter 5 followed by a multi-source (array) study in Chapter 6. An integration between the acoustic propagation algorithm and a hydrodynamics code is outlined in Chapter 7. Chapter 8 gives some future work for this research project followed by conclusions from this work in the conclusion Chapter 9.

2. BACKGROUND

This chapter outlines past and present techniques for modeling acoustic propagation including the various assumptions/simplifications of each technique as well as providing some analogous applications to MHK technology that have been conducted in the field of acoustics.

Acoustic Propagation Techniques

Acoustics have a long history. In 6th century B.C., Pythagoras discovered the harmonic overtone series by expressing the ratio of the length of the strings that produce harmonic tones. Aristotle described sound in 4th century BC as consisting of contractions and expansions of air that fall upon and strike the air which is next to it. With the development of calculus in the eighteenth century, acoustics saw major advances via Helmholtz in Germany and Lord Rayleigh in England [3]. Underwater acoustics for both shallow- and deep- water was used during the First World War for the detection of submarines and further developed into SONAR for deep water during the Second World War and continuing into the Cold Wars. After the Cold War, research on noise propagation in shallow waters increased with the main areas of focus on active SONAR and how to detail oceanographic circulation near the continental shelves as well as how the bathymetry and sedimentary bed properties influences propagation [4] [5].

Wave-Equation Based Techniques

Most acoustic propagation techniques are based on the wave equation. The conservation of mass, Euler's equation of motion for Newton's second law, and the adiabatic equation of state are used as starting points for the derivation of the nonlinear wave equation. Through linear approximations and retaining only first-order terms, the linear acoustic wave equation is obtained.

$$\nabla^2 p(\mathbf{r}, t) - \frac{1}{c^2} \frac{\partial^2 p(\mathbf{r}, t)}{\partial t^2} = f(\mathbf{r}, t) \quad 2.1$$

where p is pressure and is dependent upon the position vector $\mathbf{r}$, and time t , c is the speed of sound, and f is a forcing term which represents the acoustic sources.

This linear, second-order partial differential equation can be solved by using the finite difference method (FDM), which approximates the differential operators through a direct discretization in space and time, or the finite element method (FEM) which discretizes the medium into small blocks with explicit definitions and solves time with FDM. While the direct and discrete methods of FDM/FEM are beneficial to a general solution, the required spatial discretization of the wave equation to a fraction of a wavelength means these methods are computational intensive. Due to the intensiveness of the computations and lack of sufficient computational resources until the last couple of decades, various numerical methods attempting to solve the wave equation have been developed through mathematical manipulations. These alternate solutions are in widespread use in the acoustic community and reduce the numerical requirements to solve. However they also come at the cost of generality through the various assumptions

and approximations that are required for mathematical manipulation and simplification of the wave equation, thereby reducing the applicability of its solution.

These alternate techniques utilize the frequency-dependent Helmholtz equation

$$\nabla^2 p(\mathbf{r}) + k(\mathbf{r})^2 p(\mathbf{r}) = f(\mathbf{r}) \quad 2.2$$

where $k = \omega/c(\mathbf{r})$ is the acoustic wavenumber. If the forcing and pressure terms of the wave equation are assumed to be a continuous wave and harmonic i.e.,

$$f(\mathbf{r}, t) = f(\mathbf{r})e^{-i\omega t} \quad 2.3$$

$$p(\mathbf{r}, t) = p(\mathbf{r})e^{-i\omega t} \quad 2.4$$

with ω as the angular frequency, the wave equation can be transformed into the frequency domain Helmholtz equation.

The advantages to working with the frequency domain Helmholtz equation are a reduction in the dimension of the PDE being solved, a more tractable solution by considering one frequency at a time, and a decoupling from any unsteady transience of a system. The Helmholtz equation is relatively simpler to solve than the original wave equation but there is no universal solution technique. FDM and FEM are still an option, however more mathematical manipulations can be applied to further reduce the complexity of a solution to the Helmholtz equation.

There are three main categories of well-known and established acoustic propagation techniques based on the Helmholtz equation: 1) ray theory, 2) normal modes, and 3) parabolic equations. Each technique has its own set of assumptions, approximations, and mathematical manipulations inherent in its derivation that limit the

range of applicability of each technique. The actual solution technique that can be applied depends on the dimensionality of the problem, the source frequency and bandwidth, and the need for range dependence. Range-independence assumes a constant-depth domain (1D), while range-dependence allows for a change in depth as a function of distance (2D/3D). Shallow water is commonly defined as having a depth less than 200 m, as there is significant interaction with the sea floor. Low frequency is defined as being below approximately 1 kHz due to breakdowns in assumptions and model efficiencies around this range. Table 2-1 compares where the different Helmholtz models are most efficient [6]. Filled (black) cells in Table 2-1 designated solution applications that are both computationally and physically feasible. Hashed cells are practical but limited in scope, either the solution technique is computational intensive or is limited in accuracy. The blank (white) cells are not computationally or physically feasible. Table 2-1 also includes a time-domain solution of the Velocity-Pressure equations. This model has been chose for this work and is discussed in more detail later in the chapter.

Models	Shallow Water				Deep Water			
	Low Frequency		High Frequency		Low Frequency		High Frequency	
	1D	2/3D	1D	2/3D	1D	2/3D	1D	2/3D
Ray Theory								
Normal Modes								
Parabolic								
Velocity Pressure								

Table 2-1: Applicability of the three principal acoustic propagation methods in representative domains and the Velocity Pressure system, adapted from [6]. Filled cells are both computationally and physically applicable, hashed cells are practical but limited in scope.

Ray Theory

Ray theory was derived for high-frequency, range-dependent applications and is viable for both shallow- and deep- water [6] [7]. The focusing effect over long-scale propagation of sound within the Deep Sea Channel was demonstrated using the ray theory method [8]. The ray theory technique seeks a solution of the Helmholtz equation in the form of a ray series and calculates propagation loss on the basis of ray tracing, or bending. The Helmholtz equation is separated into an infinite sequence of eikonal and transport equations. The standard simplification involves ignoring all but the first term in the ray series which is known as the high frequency approximation, and why ray theory is not often used for frequencies under 1 kHz [9]. The eikonal equation is usually solved by the method of characteristics where a family of curves or rays that are perpendicular to the level curves, or wavefronts, are introduced resulting in a new coordinate system that reduces the eikonal equation into a far simpler linear ordinary differential equation [9]. The transport equation solves for the amplitude of each ray and its derivation uses the divergence theorem and Jacobean to provide a simpler and more intuitive view of how ray amplitudes evolve [9]. Initial conditions must be specified by using the method of canonical problems and are chosen so that ray results agree with a simpler problem in which the exact solution is known. Most ray codes treat the bottom layer as a simple reflector and ignore the subsequent splitting of the transmitted ray. Incorporating plane-wave reflection and transmission coefficients can provide more detailed solutions to account for a more complex bottom layer.

The high frequency assumption applied to the pressure term in the Helmholtz equation is fundamental to ray theory, with the pressure taking the form,

$$p(\mathbf{r}) = B(\mathbf{r})e^{i\omega\tau(\mathbf{r})} \quad 2.5$$

Where $B(\mathbf{r})$ and $\tau(\mathbf{r})$ are slowly varying functions of position along a particular ray. A continuous wave is approximated as set of discrete rays allowing for a path of individual wave-fronts to be traced. An individual wave front consists of a sound wave with the same phase, so multiple solution runs are required for a sound source consisting of multiple phases or frequencies. Propagation of the ray trace starts from the end of the previous ray and continues to travel a small distance and can change direction. The direction change stems from localized reflections and refractions (Snell's Law) determined by medium properties including temperature, salinity, and boundary conditions that account for the surface and sea floor interfaces. Interference and diffraction cannot be calculated using ray theory because the rays do not contain phase information. Ray theory calculations can create a few flaws including caustic and shadow zones. Caustics are areas where the cross-section of a ray tub vanishes and therefore the predicated pressure is infinite. Shadow zones can create a pressure field that is nearly zero in areas where no rays pass through [6] [9].

Normal Modes

Normal modes were developed for depth-dependent domains [6]. A series of integral transforms are applied to the Helmholtz equation in a range-independent and horizontally-stratified environment in which layer properties are functions of depth only

[9]. This reduces the original four dimensional partial differential equation into a series of ordinary differential equations in the depth coordinate. Integral representations of the Helmholtz equation within each layer are characterized by unknown coefficients. These coefficients are found by matching boundary conditions simultaneously at all interfaces and the total field is determined by evaluation of the integrals [9]. The solution has a set of modes of vibration whose frequencies give the horizontal wave-numbers associated with the modal propagation. A summation of all contributions of each of the modes weighted according to the source depth gives the complete acoustic field [9].

The advantage of this technique is a very efficient method for solving range independent problems [9]. The mode functions only have to be evaluated once and the pressure can be evaluate at any range by using a simple summation. The pressure term is described by,

$$p(\mathbf{r}, z) = \frac{1}{4\rho(z_s)} \sum_{n=1}^{\infty} \Psi_n(z_s) \Psi_n(z) H_0^1(k_{rn} \mathbf{r}) \quad 2.6$$

where Ψ_n is the normal mode (the eigenfunctions for the system), H_0^1 is the Hankel function of the first kind of order zero, k_{rn} are the horizontal wave numbers (the eigenvalues), and z_s the depth of the source.

While the normal mode technique is computational very efficient, it only accounts for energy that is trapped within the waveguide by total internal reflection. This creates inaccuracies in the solution at a short range where energy that is only partially reflected from the seabed is significant [6]. There is a range-dependent formulation of the normal mode technique that is coupled to a ray formulation and provides a more exact and

generalized model [10] [11]. This coupled mode provides an more accurate solution for a higher frequency range and better captures wave interactions [12].

Parabolic Equation

The parabolic equation derivation starts with an assumed solution form,

$$p(\mathbf{r}) = \Psi(\mathbf{r}, z) H_0^1(k_0 \mathbf{r}) \quad 2.7$$

Where $\Psi(\mathbf{r}, z)$ is assumed to be a slowly varying function of range and k_0 is a reference wavenumber. The Helmholtz equation is simplified into a reduced elliptical wave equation by use of the Hankel function and farfield assumption ($k_0 r \gg 1$) [9]. The elliptical wave equation is then replaced with a parabolic equation by utilizing the paraxial, or small-angle, approximation [9]. From here additional approximations are made to further simplify the solution, including ignoring the commutator term based on a weak range dependence assumption and negating backscattering. These assumptions create a genuine one-way wave equation and provides an efficient solution for sound propagation that can be solved numerically with relative ease [13].

A number of different parabolic approximations lead to various solutions and representations of the pseudo-differential operator that all have inherent phase errors that limit their applicability to a certain range of azimuthal angles around the main propagation direction. The standard parabolic equation is,

$$2ik_0 \frac{\partial \Psi}{\partial r} + \frac{\partial^2 \Psi}{\partial z^2} + k_0^2 \left(\left[\frac{c_0}{c} \right]^2 - 1 \right) \Psi = 0 \quad 2.8$$

Where c_0 is the reference sound speed corresponding to k_0 . In order to arrive at a solution to a parabolic equation, specification of both initial and boundary conditions are

required based on the considered marine environment. Also, starting fields are needed to specify the complex pressure versus depth at the starting range. The free surface is usually treated as a pressure release boundary and in practice the bottom layer is dealt as an artificial absorption layer of several wavelength thicknesses. The parabolic equation techniques are best suited for a low frequency range and both shallow or deep water application [9] [6].

There have been works and additional techniques that attempt to increase the accuracy and applicability of the parabolic equation. The wide angle PE increases the accuracy closer to the source and helps alleviated the small angle approximation [14] [15]. The rotated PE provides a pseudo-3D solution in which a collection of $n \times 2D$ solutions are solved over a range of azimuthal angles and a 3D solution comes from the accumulation of the 2D solution slices [16].

Velocity Pressure System

The velocity pressure equations are an alternative to the wave equation for solving acoustic propagation. They are a set of coupled, linear partial differential equations that are solved using the finite difference method. The derivation of the velocity pressure equations start from the fundamental principles of continuum mechanics and conservation of linear momentum for all material parts of a continuous body. Cauchy's equation of motion in the lagrangian reference frame are used,

$$\begin{aligned} \rho(\mathbf{x}, t) \left(\frac{\partial \mathbf{v}(\mathbf{x}, t)}{\partial t} + (\mathbf{v}(\mathbf{x}, t) \cdot \mathbf{grad}) \mathbf{v}(\mathbf{x}, t) \right) - \text{div} \boldsymbol{\sigma}(\mathbf{x}, t) \\ = \mathbf{f}(\mathbf{x}, t) + \text{div} \mathbf{M}^{asm}(\mathbf{x}, t) \end{aligned} \quad 2.9$$

The dependent variables are $\mathbf{v}(\mathbf{x}, t)$ and $\boldsymbol{\sigma}(\mathbf{x}, t)$, the particle velocity vector and stress tensor, respectively. The medium is characterized by a space- and time-dependent mass density $\rho(\mathbf{x}, t)$, and is subject to applied body forces and body moments. Forces are represented by the force density vector $\mathbf{f}(\mathbf{x}, t)$ and moments are represented by the asymmetric part of the moment density tensor $\mathbf{M}^{asm}(\mathbf{x}, t)$. With the assumptions that 1) the continuum mechanical fields, including velocity, stress tensor, body force- and momentum- and mass- density, are an additive superposition of ambient and perturbation components, and the medium is 2) fixed, 3) possesses no prior stress, and 4) is at rest, Cauchy's linearized equations of motion are obtained,

$$\begin{aligned} \rho(\mathbf{x}) \frac{\partial \delta \mathbf{v}(\mathbf{x}, t)}{\partial t} - \mathbf{div} \delta \boldsymbol{\sigma}(\mathbf{x}, t) \\ = \delta \mathbf{f}(\mathbf{x}, t) + \mathbf{div} \delta \mathbf{M}^{asm}(\mathbf{x}, t) \end{aligned} \quad 2.10$$

where the ambient medium mass density is taken to be independent of time and δ implies perturbation. The linearized Cauchy equations do not contain a material derivative term as in the original Cauchy equation. Next, constitutive relations are used to relate and manipulate the stress tensor. The fluid supporting acoustic wave propagation is considered to be a linear, viscous medium where the bulk viscosity coefficient is used. By careful manipulation and recombination, the stress tensor may be expressed in terms of the pressure as,

$$\begin{aligned}
\delta\sigma(\mathbf{x}, t) = & -\delta p(\mathbf{x}, t)\mathbf{I} \\
& + \mu(\mathbf{x}) \left((\mathbf{grad}\delta\mathbf{v}(\mathbf{x}, t)) + (\mathbf{grad}\delta\mathbf{v}(\mathbf{x}, t))^T \right. \\
& \left. - \frac{2}{3} \text{div}\delta\mathbf{v}(\mathbf{x}, t)\mathbf{I} \right) + \delta\mathbf{M}^{sym}(\mathbf{x}, t) - \frac{1}{3} \text{tr}\{\delta\mathbf{M}(\mathbf{x}, t)\}\mathbf{I}
\end{aligned} \tag{2.11}$$

Under the condition of vanishing velocity coefficients, setting the shear viscosity $\mu(\mathbf{x})$ and bulk viscosity equal to zero, and differentiating with respect to time gives, the above equations may be assembled into a system of two coupled, first-ordered partial differential equations governing the particle velocity vector $\delta\mathbf{v}(\mathbf{x}, t)$ and the pressure fluctuation $\delta p(\mathbf{x}, t)$, equations 2.12 and 2.13.

$$\rho(\mathbf{x}) \frac{\partial \delta\mathbf{v}(\mathbf{x}, t)}{\partial t} + \mathbf{grad}\delta p(\mathbf{x}, t) = \delta\mathbf{f}(\mathbf{x}, t) + \text{div}\delta\mathbf{M}^{dev}(\mathbf{x}, t) \tag{2.12}$$

$$\frac{\partial \delta p(\mathbf{x}, t)}{\partial t} + k(\mathbf{x}) \text{divr} \delta\mathbf{v}(\mathbf{x}, t) = -\frac{1}{3} \frac{\partial}{\partial t} \text{tr}\{\delta\mathbf{M}(\mathbf{x}, t)\} \tag{2.13}$$

Acoustic Propagation Applications

Modern underwater acoustics have been used for many different applications, including noise generation and propagation from ship vessels and/or propellers [17], pile driving impacts used in the offshore oil and gas and wind energy industries [18], and wind turbines, both off and onshore [19] [20]. The following is a synopsis of a few areas of study that pertain to MHK acoustics. Information from several works are summarized and related to MHK acoustics.

Ships and Propellers

Issues and concerns involving acoustical noise stemming from ships and other vessels are similar to that of the MHK sector. The International Maritime Organization (IMO) agree that noise from commercial shipping and its adverse impact on marine life is a high priority item; this has prompted research in the area of noise generation and propagation from ship components, mainly propellers, and entire vessels [21]. Unlike the stationary acoustic source of a MHK device, the vessel is traveling in a marine environment. However, the acoustical characterizations and analysis are analogous.

Ianniello et al. claim to be the first to conduct acoustical analysis on a complete scaled ship model [22]. 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 & 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 [22]. 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 [22].

Pile Driving

Noise produced during pile driving events for the installation of offshore wind turbines and oil and gas activities have similar environmental concerns as MHK devices and fall under similar federal regulations. While the cyclic on and off noise source due to repetitive impacts of the pile driver differs from a normally continuously operating MHK source, it serves as a good surrogate for the propagation of anthropogenic noise in a marine environment. The deployment sites are similar and the acoustical characterizations for both generation and propagation of MHK versus pile driving can provide similar approaches and insights.

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. [23] A basic finite element (FE) model represents the pile itself and 50 m around the pile. The results from the FE model are used to generate acoustic source properties as input to a wavenumber integration code, an alternative form of the normal mode technique, which is the main propagation method used for long ranges in this study. Feasible simplifications to the pile's acoustic source is investigated and 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 FE model results are compared in the 50 m overlapping region between the two models. Good agreement between the two techniques are observed, verifying the validity of the wavenumber integration code at long ranges [23].

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 [24]. 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 FE 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 wavenumber 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 [24].

Similar acoustical techniques can be applied to MHK applications for both the prediction and generation of underwater noise. A coupled model, similar to the studies above, could provide accurate and efficient results.

Wind Turbines

Acoustical noise originating from wind turbine structures also serve as a surrogate to MHK noise propagation. While the medium, air, for wind turbine structures is different than MHK medium, water, the acoustic propagation techniques are similar. The major difference comes from the relatively high compressibility of air compared to water. Density and sound speed properties of air are orders of magnitudes less than water. Offshore wind turbines have an underwater noise emission component associated with the turbines mooring and support structure, including the submersed tower.

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 [19]. 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 [20]. 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 [25].

Biological Response to Noise

The response of fish and other marine wildlife to anthropogenic influences is a complex and often hard to predict set of interactions. Studies have been conducted on the effects on fish and invertebrates. For example, [26] showed that the feeding behavior of the common shore crab is affected by decreasing foraging time in response to an active ship noise stimuli. [27] and [28] 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 temporary or permanent damage to a species ability to hear sound or other physical damage such as bursting of the swim bladder in fish [29] [30] [31].

Several researchers have used predictive underwater noise models to map zones of influence for marine species based on dB thresholds [29] [32] [33]; however many of these underwater noise models are over-simplified, range-independent solutions that lack the complex 3D interactions from bathymetry, attenuation, varying sound speed, temperature, salinity, and density profiles. Additionally, most of these works do not predict how a species may react to noise and only calculate zones of influence.

Rossington et al. [33] 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 that fish that could “hear” or respond to the environment and noise took seven days longer to reach their destination than the control “deaf” fish. It should be noted that 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.

3. METHODOLOGY

Model

Paracousti is a parallelized acoustic-wave propagation package developed at Sandia National Labs that solves velocity-pressure equations discussed in the last chapter. It solves the system of equations using the finite-difference method, which are second-order accurate in time and fourth-order accurate in space. Paracousti simulates sound-wave propagation within realistic 3D earth-, atmosphere-, and hydro-acoustic domains, and includes 3D variations in medium densities, acoustic sound speeds, and topography or bathymetry. The code assumes that the densities and sound speeds are fixed in time over the duration of a simulation. Paracousti uses a massively parallel design and can be scaled nearly linearly across a single machine to a cluster with 1000's of cores. Paracousti was originally developed for sound propagation in atmospheric environments and has been successfully validated for a number of different geophysical models, to include seismic activities [34]. As Paracousti had already been developed for general media, the code has the capability of being modified for hydro-acoustic environments and was selected for modeling acoustic propagation around MHK arrays due to its accuracy and adaptability. Inputs into Paracousti are: 1) the domain model with medium properties in all dimensions, 2) the source location(s), type and strength, and 3) the desired outputs [34].

The three-step modeling process for simulating acoustic wave propagation is depicted in general terms in Figure 3-1. The numerical simulation algorithm (center box)

accepts various inputs (left column) and then calculates and outputs various data types (right column) for further post-processing. The “earth model” 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. Another input file contains a description of the recording geometry (i.e., 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) “timeslices” or 2D pictures of time-evolving acoustic wavefields; and 3) 3D wavefield volumes [34]. Visualization software, such as plotting within MATLAB®, is needed to display these data types.

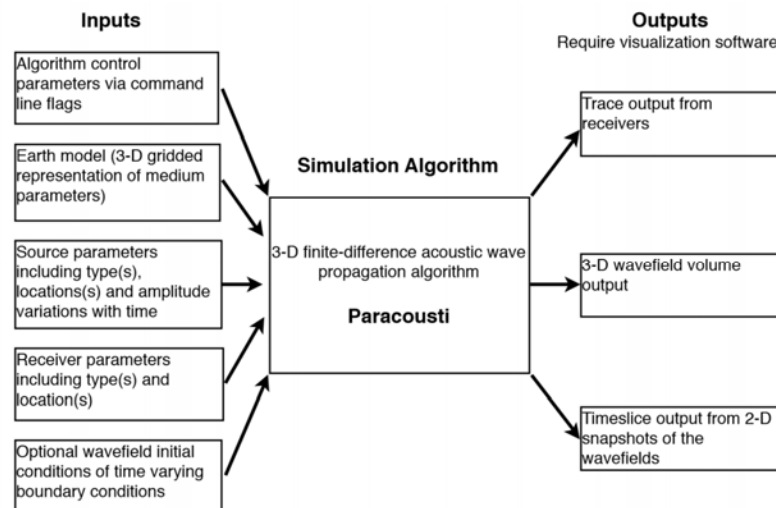


Figure 3-1: Depiction of the acoustic wave propagation modeling process with Paracousti

A set of coupled, first-order, linear partial differential equations, known as the velocity-pressure system, are solved:

$$\frac{\delta v_i(\mathbf{x}, t)}{\delta t} + \frac{1}{\rho(\mathbf{x})} \frac{\delta p(\mathbf{x}, t)}{\delta x_i} = \frac{1}{\rho(\mathbf{x})} \left[F_i(\mathbf{x}, t) + \frac{\delta m_{ij}^a(\mathbf{x}, t)}{\delta x_j} \right] \quad 3.1$$

$$\frac{\delta p(\mathbf{x}, t)}{\delta t} + \kappa(\mathbf{x}) \frac{\delta v_i(\mathbf{x}, t)}{\delta x_i} = -\frac{1}{3} \frac{\delta m_{ii}^s(\mathbf{x}, t)}{\delta t} \quad 3.2$$

where $v_i(\mathbf{x}, t)$ and $p(\mathbf{x}, t)$ are the dependent variables of particle velocity (m/s) and pressure perturbations (Pa), respectively. $\rho(\mathbf{x})$ is the material density (kg/m³), and $\kappa(\mathbf{x})$ is the material bulk modulus (Pa) of the medium. The right hand terms in **3.1** and **3.2** are body source terms: $F_i(\mathbf{x}, t)$ is the force density vector (N/m³), $m_{ij}^a(\mathbf{x}, t)$ is the anti-symmetric portion of the moment density tensor and $m_{ij}^s(\mathbf{x}, t)$ is the trace of the symmetric portion of the moment density tensor (N/m²). Summation is implied by the repeated indices of the tensor. Note that these are the same velocity pressure equations as Equation **2.12** and Equation **2.13** but written in a different form that is more intuitive when considering a finite differencing scheme. A 3x3 tensor that describes various combinations of force couples applied to a point in space is known as a moment tensor. The diagonals of the moment tensor is the isotropic portion which represents a source of pressure and is proportional to the trace of the moment tensor. Various combinations of these term allows for a representation of complex sources. The body source terms are zero outside the source region and yield a homogenous system of PDEs [34].

The velocity-pressure system of Equations **3.1** and **3.2**. are solved using the finite differencing scheme with a domain defined by a regular rectangular grid. A staggered grid is utilized for variable storage and one cell of the domain with a size of $d_x \times d_y \times d_z$ is shown in Figure 3-2. The twelve edges of this cell are locations for the three components of particle velocities while the medium densities, bulk moduli and the pressure-dependent

variables are contained on the eight corner nodes. The time step is constant throughout the simulation solution. Velocity is updated on the half-integer time raster and pressure is updated every time integer. This solution-step and staggered grid configuration removes spurious oscillations within the solution. A second-order spatial accuracy is used to preserve numerical stability at locations near large gradients in medium parameters, i.e. air-water and water-earth interfaces [34].

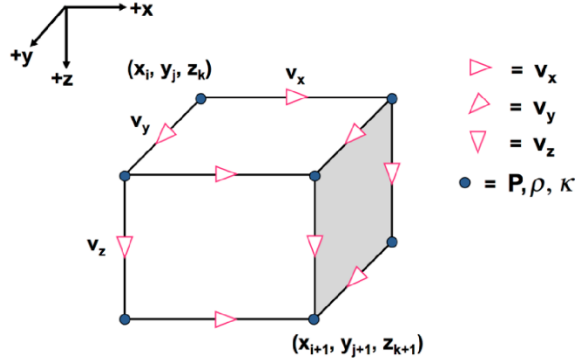


Figure 3-2: Arrangement of dependent variables and medium parameters for one cell of the standard staggered grid.

In order to obtain the desired level of accuracy, and fall within a suitable Courant-Friedrichs-Lewy (CFL) stability limit, appropriate values for grid spacing and time step are calculated as:

$$dx, dy, dz = \frac{\min(V_p)}{\max(\omega) * gnpw} \quad 3.3$$

$$dt = \frac{dx}{\max(V_p) * \sqrt{3} * \sum |fdc|} \quad 3.4$$

where V_p is the acoustical sound speed, ω is the sources' principle frequency, $gnpw$ is grid-nodes-per-wavelength, and fdc are finite difference coefficients. For a default run

using standard 4th order accurate Taylor series expansion coefficients, $gnpw$ is 10 and fdc is $9/8$ and $1/24$. There is a method available to reduce the necessary grid nodes per wavelength while still achieving a high level of accuracy. This method is based on an optimization of coefficients used in the finite difference method implemented in the Paracousti algorithm. A generic finite difference coefficient optimization was utilized for some of the simulations presented and reduces the necessary number of grid nodes per wavelength from 10 to 5.22 where the values of the coefficients are 1.1434 and -0.049046. This is extremely advantageous for large models and domains where the total number of domain grid nodes can be reduced by about a factor of 8 and run time can be reduced by 10 times.

In order to simulate an unbounded domain, we impose absorbing boundary conditions on the extents of the 3D grid in order to suppress reflected energy. The convolutional perfectly match layer (CPML) is utilized [35]. The CPML boundary acts as an energy absorber and greatly reduces boundary effects. The formulation results in only a negligible amount of energy being reflected backward into the domain. Pressure-free surfaces can be imposed at the water-air boundary to act as perfect reflectors of the energy. Due to the large gradient in properties, and therefore approximated with second-order accuracy, there is in fact a negligible amount of energy 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 above the water and earth. This latter approach must be used when there is a variation in

topography, as the CPML presently requires the air- earth and/or air-water interface to be planar.

Paracousti is capable of modeling multi-frequency monopole, dipole, and quadrupole sources. Additionally, and unlike most wave-equation solutions, this acousto-dynamic solution permits multiple source locations in a single simulation. 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 the direct pressure values. The force or force-couple is the direct pressure value 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, source that propagates equally well in all directions. A force source propagates along a single or set of orthogonal axes, which corresponds to dipoles, quadrupoles, etc. All sources for this work are based on an explosive source with a profile of

$$\sum A * (1 - \cos(2 * \pi * \omega * t)) \quad 3.5$$

where ω the frequency of the source in hertz, t is the present simulation time in seconds, and A is the desired pressure amplitude multiplied by a conversion factor of $\frac{1}{4\pi v_p^2}$ due to the definition of a source in paracousti. The profile is the summation over all relevant frequencies. This form of the profile, as opposed to a simple sinusoid, limits the amount of numerical noise that's induced by taking time-derivatives of the source due to a non-zero gradient at $t = 0$. The acoustic source is located in a relatively high-density domain (water) and when the pressure disturbances propagate to a medium with a low density

(air) most of the energy is reflected back into the water. The water current velocities are significantly smaller than the speed of sound in water and are not included.

Utilizing a delta source time function is an alternative to an explicitly defined source time function. A number of different source profiles can be solved with one delta source time function run through the use of convolution. Results from the single delta source time function run are convolved with the source profile(s) of interest to produce the correct pressure field. A large amount of computation time can be saved using this technique if multiple source profiles are to be investigated. Limitations to using this convolution method are that the location(s) of each source must be the same as the delta source time function location and the time-step and grid-size must be adequately small for the highest source frequency of interest.

Pre/Post Processing

Pre-and post-processing is required to use the Paracousti code. The pre-processing portion defines the domain grid, medium properties, boundary conditions, source properties, and receiver type and geometry and structures the input files in the correct format for use in Paracousti. Post-processing is used to visualize the output files and calculate any additional values of interest such as sound pressure level and transmission loss. Pre- and post-processing can be accomplished in Paracousti's native language, C++, however, MATLAB® is utilized for this work due to its convenience and ease of use.

Pre-processing requirements are fairly straight forward, as detailed in the Model subsection. Some additional calculation techniques used in post-processing for sound

pressure level (SPL) and transmission loss (TL) were utilized and detailed below. An accumulation of two-dimensional pressure slices taken during the last second of simulation time are used to get a “steady state” time history of pressures. We seek a solution where sound including any reflections is allowed to fully propagate throughout the domain and transients in the system have steadied. In general, the simulation time was twice the amount of time required for the sound to travel through the entire domain and is calculated based on the maximum dimension of the domain and the minimum sound speed. This time history collection of two-dimensional pressure slices are used to calculate a root mean squared (rms) pressure that in a sense averages the time-history pressure values. The rms pressure P_{rms} is calculated as,

$$P_{rms}(x, y) = \sqrt{\text{mean}_t(P(x, y, t)^2)} \quad 3.6$$

Sound pressure level (SPL) and transmission loss (TL) are acoustic solutions of interest and are calculated as:

$$SPL = 20 \log_{10} \frac{P_{rms}}{1e-6} \quad 3.7$$

$$TL = 20 \log_{10} \frac{P_{rms}}{P_{rms}(re\ 1\ m)} \quad 3.8$$

The difference between SPL and TL is the reference pressure used in the denominator of the fraction in the log scale. SPL uses a standard pressure value (1e-6 Pa) for underwater acoustics while TL uses the root mean square (rms) pressure 1 m away from the source (*re 1 m*) as a reference. While both SPL and TL have units of decibels (dB), SPL gives a sense of the magnitude of sound while TL is non-dimensionalized to its source strength.

With a TL solution any source strength can be considered and the relative drop in dB is known.

4. VERIFICATION FOR HYDRO-ACOUSTIC ENVIRONMENT

As Paracousti had already been developed for general media, the first step was to begin verification for hydro-acoustic environments. Results from Paracousti have been compared and verified against five canonical and benchmark scenarios for underwater acoustics, including monopole spherical spreading, two-layered media propagation and reflections, and a 3D sloping bottom. Analytical solutions exists for monopole spreading and numerical solutions exists for propagation within a two-layered media as well as a continuous source in a 3D sloping bottom domain [36] [37].

Case 1: Spherical Spreading of a Pulse in Unbounded Domain

Monopole spherical spreading was considered first in which energy propagates equally well in all directions. A Gaussian pulse source of 10 Hz was simulated in Paracousti with an “ideal” waveguide consisting of a constant sound speed and density of 1500 m/s and 1000 kg/m³, respectively. The CPML boundary layer was utilized in order to absorb any energy reflections from the boundary surfaces of the domain. This, in effect, produces an unbounded domain that truly represents a spherical spreading scenario as opposed to a domain where energy is reflected back into the domain, representative of cylindrical or a combination of spherical/cylindrical spreading. The solution is validated against the known analytic solution for spherical spreading loss of pressure P and given by:

$$P(r, z, t) = \frac{S\left(t + \frac{r_s}{V_p}\right)}{4 * \pi * V_p^2 * r_s} \quad 4.1$$

where S is the pressure amplitude of a source as a function of time t , V_p is the speed of sound, and r_s is the receiver distance from the source given by $\sqrt{r^2 + z^2}$. The pressure profile at any location and time is a replica of the original source, delayed by a certain amount of time $\left(\frac{r_s}{V_p}\right)$, and scaled by a spreading factor in the denominator. Note that energy density scales proportionally to $\frac{1}{r_s^2}$ for spherical spreading, and since energy is proportional to the square of the amplitude, amplitude (pressure) scales at a rate of $\frac{1}{r_s}$. A particular pressure trace (pressure at a constant location as a function of time) results from Paracousti and the analytic solution is shown in Figure 4-1. There is very good agreement between results from Paracousti and the analytic solution with a root mean square (RMS) deviation of $5.4\text{e-}7$ for all data points between the two solutions.

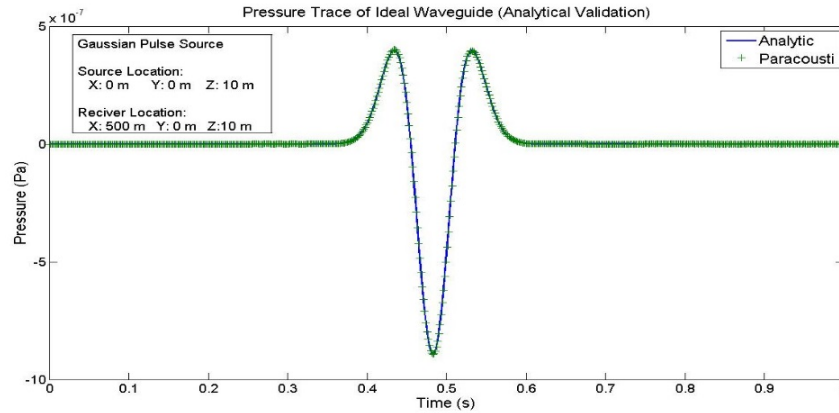


Figure 4-1: Comparison of the Paracousti solution of an ideal waveguide against the known spherical spreading relationship

Case 2: Shallow Water Two-Layered Verification Case for a Pulse

In order to demonstrate the accuracy and capability of Paracousti for shallow-water environments, a two-layered media scenario was modeled and compared against known solutions from Porter [37]. A more complex domain consisting of reflections and absorptions into a sedimentary layer is of interest. The two dimensional two layered waveguide used for this validation case is 250 m in range and consists of a 55 meter deep water domain and a flat 55 m deep sedimentary layer, resulting in a total domain depth of 110 m. The water domain has a constant sound speed of 1,500 m/s and density of 1,000 kg/m³ while the sedimentary layer has a sound speed of 2,500 m/s and density of 1,000 kg/m³. The CPML boundary condition is applied to all sides of the domain to absorb unwanted reflections back into the domain. The source profile for this case is given by the function

$$y(t) = \sin(2\pi * \omega * t) - \frac{1}{2}\sin(4\pi * \omega * t) \quad 4.2$$

Where $y(t)$ is amplitude as a function of time and ω is the source frequency, in this case equal to 100 Hz. A monopole source with a pulse duration equal to one period was used. Results from Paracousti are displayed in Figure 4-2 and represented as two dimensional “slices,” in that each slice is at a specific instance in time and displays the entire range and depth domain.

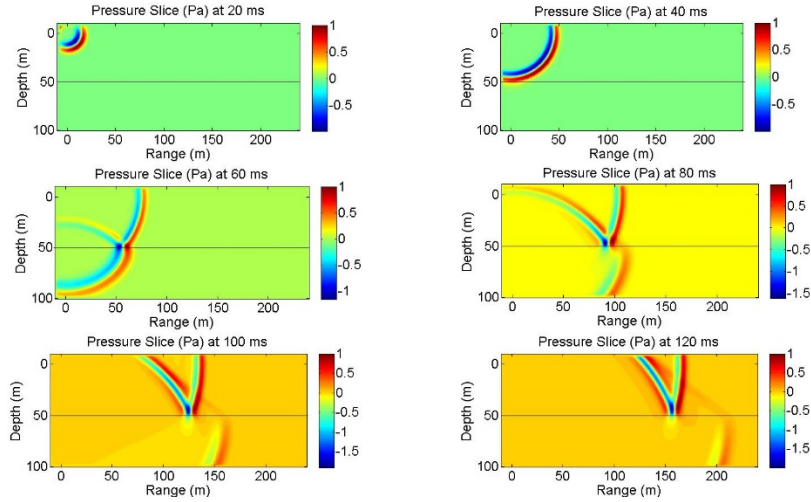


Figure 4-2: Pressure Slice Snapshots of Pulse in two layered media

Consistent with the results from Porter [37], we see in the snapshot at time 20 ms a spherical pulse wave that has not yet contacted the interface of the two layers. At time 40 ms we see the pulse has interacted with the lower half space and results in a longer wavelength pulse due to the higher sound speed. The snapshot at 60 ms shows the original head wave, transmitted wave in the sedimentary layer (lower half space), and a reflected wave due to the interaction between the two interfaces. At time 80 ms and beyond we see that the transmitted wave is now ahead of the original head wave due to the larger sound speed. Results from Porter [37] are presented in Figure 4-3.

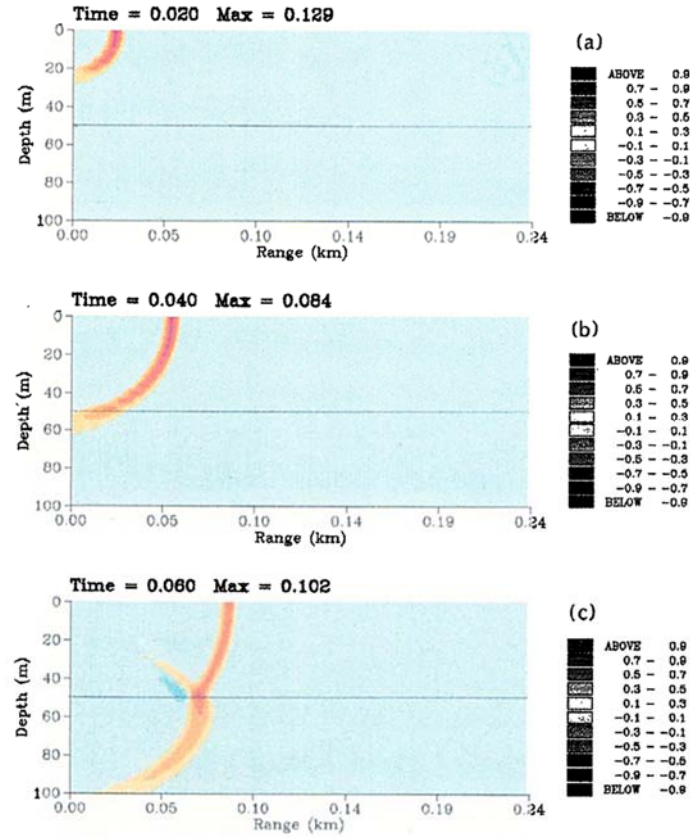


Figure 4-3: Porter results for propagation and reflection in two layered media [37]

Case 3: Two-Layered Media Verification Case with a Continuous Source

A continuous source simulation was the next verification case considered. The two-dimensional, two-layered waveguide is again utilized but this time consists of a 100 meter deep water domain and a flat 100 m deep sedimentary layer, resulting in a total domain depth of 200 m. The water domain has a constant sound speed of 1,500 m/s and density of 1,000 kg/m³ while the sedimentary layer has a sound speed of 1,800 m/s and density of 1,800 kg/m³. For this simulation and all future ones, a pressure-free, perfectly reflecting, boundary condition is used for the top air-water interface (0 m depth) while the other five boundaries (bottom and sides) of the domain utilize the CPML boundary

layer to prevent unwanted reflections back into the domain. The source is a continuous 20 Hz sinusoidal profile with an amplitude of 1, located at a depth of 36 meters. Sound pressure levels (dB re 1e-6 Pa) results from Paracousti are shown in Figure 4-4 as a function of depth and range.

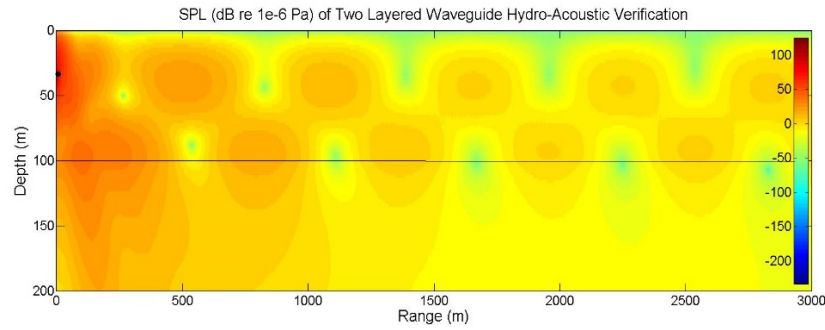


Figure 4-4: SPL (dB re 1e-6 Pa) slice of two-layered waveguide

A SPL trace at a depth of 36 m (the source depth) and 46 m are shown in comparison to analytical spreading laws, Figure 4-5. The spreading laws for this scenario begin as spherical, dropping off at a rate of $\frac{1}{r_s}$ and then transition into cylindrical spreading, reducing to a $\frac{1}{\sqrt{r_s}}$ relationship as the pressure waves become constrained by the air-water and sedimentary (earth)-water interfaces. The transition distance from spherical to cylindrical spreading is based on the relative depth of the source in the water column, and in this case is 50 m. These analytical spreading laws serve as a conservative estimate of SPLs for this scenario as some of the energy travels through and is absorbed by the sedimentary layer.

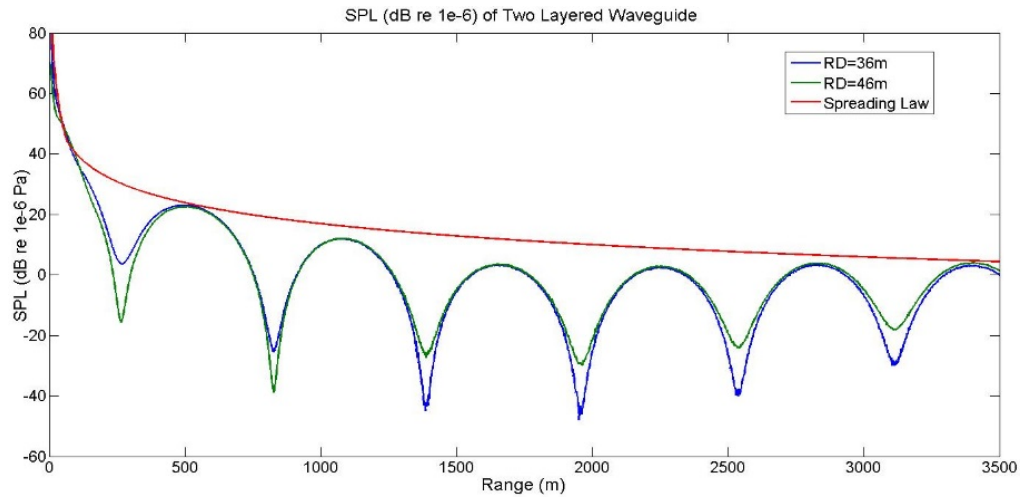


Figure 4-5: SPL (dB re 1e-6 Pa) map of two-layered waveguide at two receiver depths (36 and 46 meters) and analytic spreading solution.

As can be seen, there is a high SPL near the source that begins to decay as the distance from the source is increased and energy is spread over a larger and larger area. The rate of decay is greater in the bottom half-space than the top half-space due to the faster sound speed and absorbing bottom boundary condition. More importantly, the source is present within the water column, where all the energy is reflected from the free-surface and a significant portion of the energy is reflected back into the column from the earth-water interface between the two layers. These combined effects lead to energy dissipation, due to spreading, occurring slower than purely spherical and faster than purely cylindrical relationships. Patterns of coherency and incoherency develop from the reflections of the pressure waves on the top air-water interface and earth-water interface as a result of the additive and subtractive nature of waves. Results from Paracousti for this two-layered media case were compared to a numerical solution from [36] with good agreement. The locations and magnitudes of the coherency zones as shown in Figure 4-5

are consistent between the verification case and the compared numerical solution from [36].

Case 4: Range Independent Hyperbolic Sound Speed Profile

An additional verification case of interest is a deep water domain that contains a sound speed profile. Sound speed profiles in deep water domain can have a large influence of sound propagation. [37] provides a deep water hyperbolic sound speed profile verification case. The domain is 3 km in depth and 15 km in range with constant 1,000 kg/m³ density value and Gaussian pulse source of 20 Hz. The sound speed profile $c(z)$ in m/s is independent of range but is dependent on depth and is given by the function,

$$c(z) = 1500 * \cosh(0.0003 * (z - 1500)) \quad 4.3$$

Several pressure slice snapshots, normalized by the maximum pressure, at specific instances in time are shown in Figure 4-6. Propagation behaviors including reflection and refraction due to the sound speed profile are demonstrated and results compare well to the Porter verification case [37]. The location and shape of the pressure wave at each individual time snapshots are consistent with the verification case and capture the propagation of the pulse as it reflects from the boundaries of the domain and refract or bend towards the highest sound speed, located at a 1500 m depth.

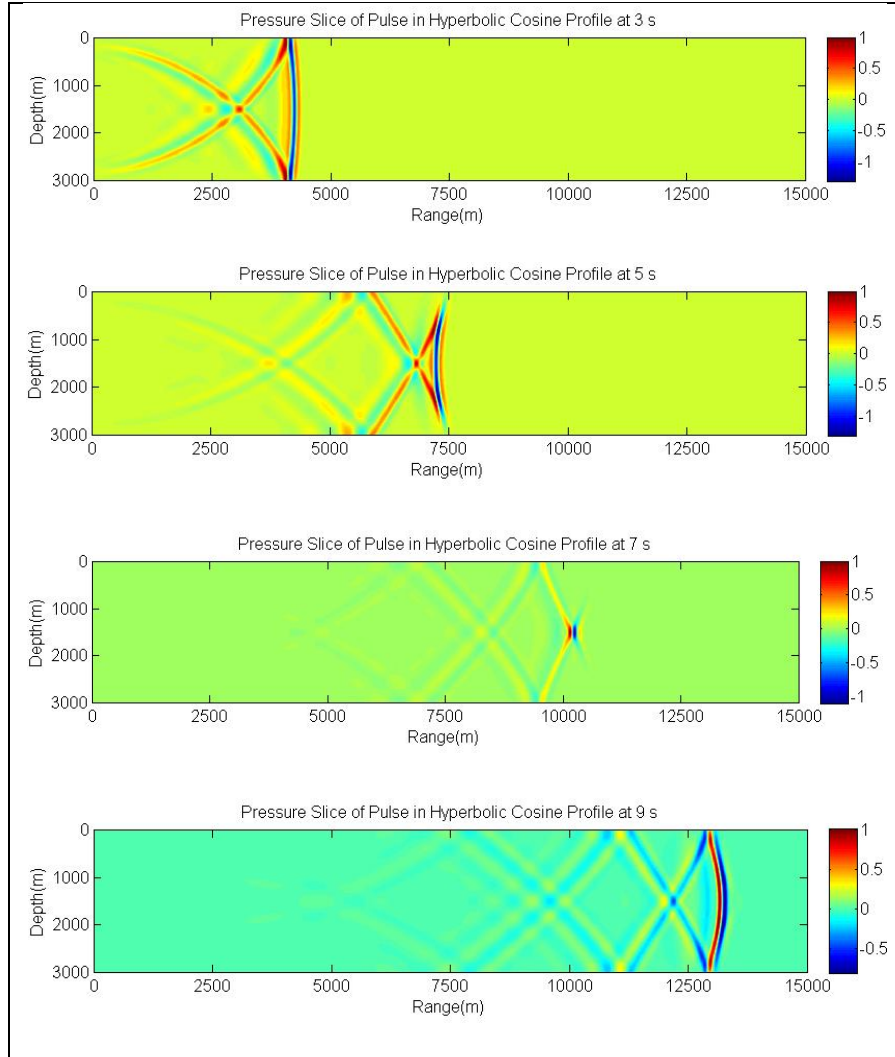


Figure 4-6: Pressure Slice of Pulse in Hyperbolic Sound Speed Profile at 3, 5, 7, & 9 seconds

Case 5: Three-Dimensional Sloping Bottom

A three dimensional sloping bottom domain is the last verification case considered. The 3D effects on sound propagation, even with a simple sloping bottom, are important and it is necessary to demonstrate the 3D capabilities of Paracousti. A continuous 25 Hz source with an amplitude of 1, at a depth of 40 meters is simulated in a domain, shown in Figure 4-7, that extends from -4 km to 4 km in the upslope x-direction,

from 0 to 25 km in the across slope y-direction, and is maximally 400 m in the depth z-direction. The water domain has a sound speed of 1500 m/s and density of 1000 kg/m^3 , while the bottom sedimentary layer has a sound speed of 1700 m/s and density of 1500 kg/m^3 .

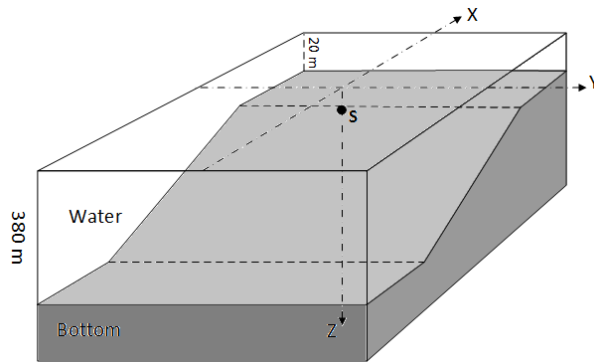


Figure 4-7: Depiction of 3D Sloping Bottom Domain

A horizontal SPL slice taken from Paracousti results in the x-y plane at a depth of 40 m is shown in Figure 4-8 and compares well against the parabolic equation solution shown in [38]. Unlike a 2D or pseudo-3D solution (the collection $n \times 2\text{D}$ azimuthal solutions), the fully 3D solution from Paracousti accounts for surface-normal reflections and refractions that affect interference structures in all directions. This has the potential to create large shadow zones, with an example seen in the large blue region beyond an across slope range of about 10 km in the top right of Figure 4-8.

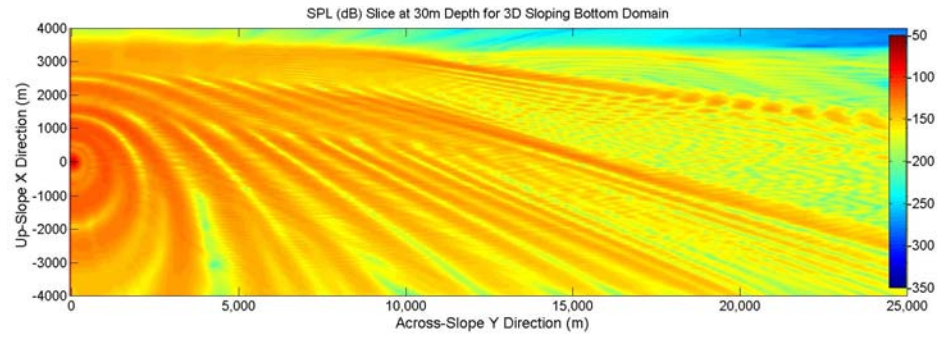


Figure 4-8: SPL Slice of 3D Sloping Bottom Domain

5. SINGLE SOURCE INVESTIGATION

Once verification was well established for Paracousti against results for canonical underwater scenarios, the next step was to investigate more complex and relevant MHK domain and sources and take advantage of Paracousti's capabilities of an implementation of complex range dependent domain with multiple frequency sources.

Multiple Frequencies

Representative of prototype deployments, a single multi-frequency source is simulated in order to understand how the combination of individual frequencies and amplitudes interact. As the sound spectra produced by any device are dependent upon the particular design and state of operation, solving an investigation of the dependence of sound pressure level on amplitude and frequency is of interest. Four source-profiles (SP) are presented and are a combination of alternating amplitudes for three frequencies, and detailed in Figure 5-1. The source is located at a range of 0 m and depth of 40 m and is given by equation 3.5. The domain is a 200 m deep two-layered waveguide consisting of a top half space of water (1,500 m/s sound speed and 1,000 kg/m³ density) and lower half space of a sedimentary bottom layer (1,800 m/s sound speed and 1,800 kg/m³ density).

	20 Hz Frequency Amplitude	40 Hz Frequency Amplitude	80 Hz Frequency Amplitude
SP 1	1	1	1
SP 2	1	0.5	0.25
SP 3	0.5	1	0.25
SP 4	0.5	0.25	1

Table 5-1: List of the source profile (SP) amplitudes (Nm)

With a sound speed of 1500 m/s, the 20, 40, and 80 Hz contributions have wavelengths of 75, 37.5, and 18.75 m, respectively. Figure 5-1 shows a 2D SPL slice as a function of depth and range for the four source-profiles.

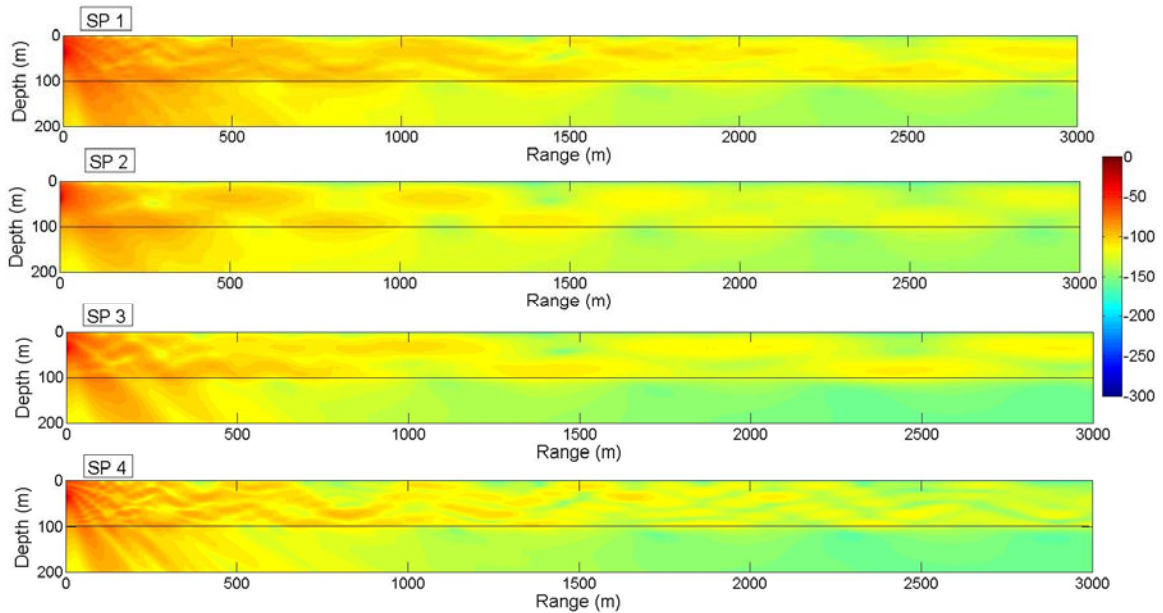


Figure 5-1: SPL (dB re 1e-6 Pa) slice comparison of amplitude and frequency dependence

As can be seen, and is expected, the particular propagation profiles are uniquely tied to the source profile. The low-frequency contribution (which also has the largest and second largest amplitudes) maintains its long-wavelength structure for the majority of the domain. However, this structure can be adversely impacted from larger amplitudes of higher frequencies, and is demonstrated well with SP4. As the power contribution shifts to higher frequencies, the bands of highest pressure become narrower. The energy of the profiles can also be seen through depth averages of SPL in the water column, which give

a better understanding of the decay of pressure levels as the waves propagate. These are shown in Figure 5-2.

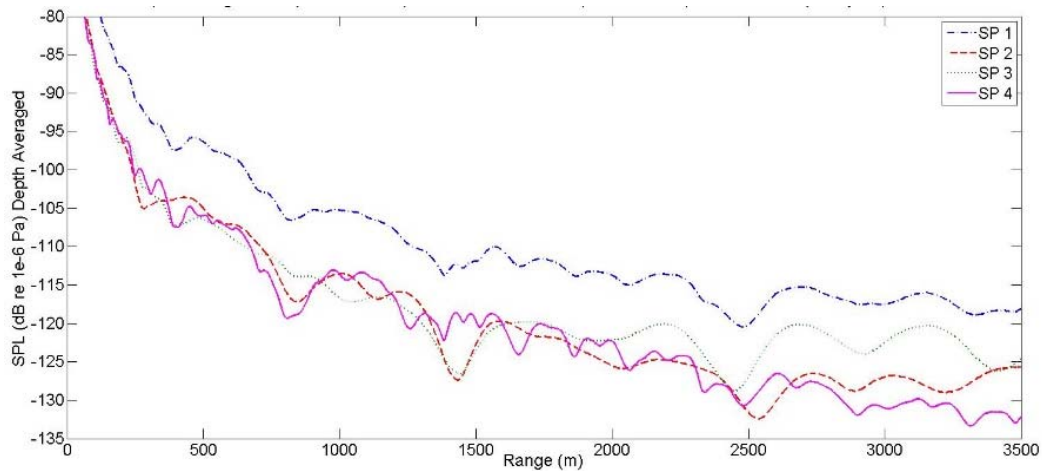


Figure 5-2: Depth Averaged SPL of water column comparison of amplitude and frequency dependence

Sound-profile 1 starts and maintains a higher SPL at all distances due to each of the three frequencies having an amplitude of 1. The remaining sound-profiles decay nearly identically until SP3 maintains a slightly elevated SPL over profiles 2 and 4, starting around 2 km. In comparison to Figure 5-2, where higher pressure levels are seen in the lower half-space for SP2 than for profiles 3 and 4, this would seem to indicate that higher-frequency energy is dissipated by the bed faster than for lower frequencies. Additionally, SP2 through SP4 demonstrate increasingly complex structures as the largest amplitude is applied to the higher frequencies. For a single, complex source there are differences between particular sound profiles, but the general trend of decay is similar for the same total sound pressure level.

MHK Source Profile

Implementation of complex sound profiles for a single simulation run is one of the main attractions to Paracousti and one of the largest gaps in many of the previously used research models. As the multi-frequency source section demonstrated, a source consisting of multiple frequencies and varying strengths in those amplitudes can create quite complex acoustic propagation patterns and needs to investigate further. In contrast to the previous section, real MHK device sources will be a complex collection of harmonic frequencies. Often times for an MHK application where the SPL, as a function of frequency, is known it is necessary to first convert the monopole contributions into a pressure profile and then take the double-integral with respect to time (and a single-integral for dipole and higher-order contributions). An example MHK spectra is shown in Figure 5-3 and adapted from predictions of noise generated from a 5 m diameter horizontal-axis turbine [39].

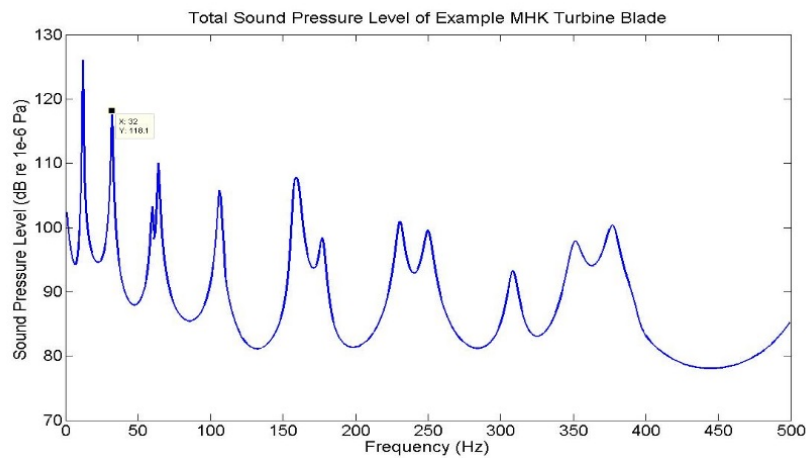


Figure 5-3: Total SPL vs. Frequency of an example MHK turbine blade

The MHK source in this chapter was initially defined by the first five principle peak frequencies of Figure 5-3, i.e. 10, 30, 62, 102, 150 Hz, and incorporate about 60% of the total energy of this MHK spectra. The resulting MHK-source pressure time-profile is shown in Figure 5-4. In reality the source spectra will be device-, operation-, and time-dependent. While the following results are representative of one source-profile, any source-profile could be modeled with appropriate grid-spacing and time-stepping.

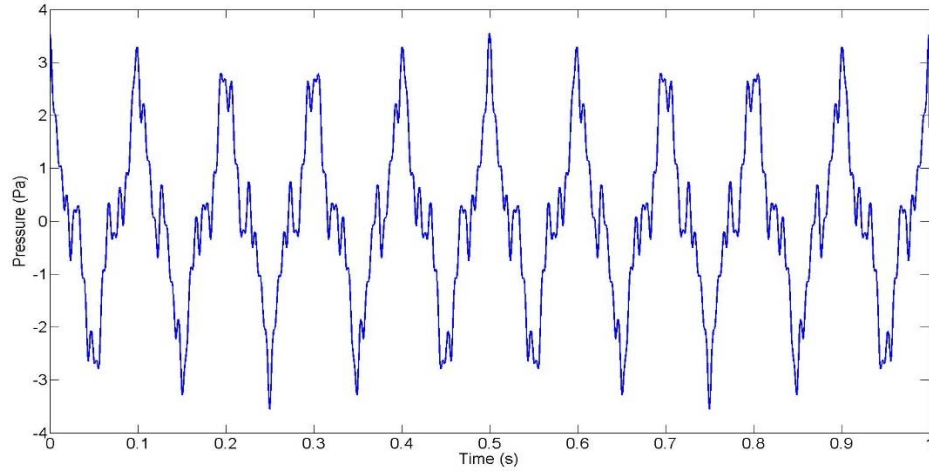


Figure 5-4: Pressure Profile of MHK example source

Converting SPL versus frequency to a source time function for use in paracousti is accomplished by the following equation,

$$STF = \sum \frac{V_p^2 * 1e - 6}{\pi * \omega^2} * 10^{\frac{SPL}{20}} * (1 - \cos(2 * \pi * \omega * t)) \quad 5.1$$

where V_p is the speed of sound, ω is the source frequency and t is time.

However, while the source profile used in the following simulations was intended to be the example MHK source as depicted in Figure 5-3 and Figure 5-4, due to an

incorrect conversion factor for amplitude, a different source profile was utilized. The source still has multiple frequency contributions. Table 5-2 lists correct (as detailed from Figure 5-4) and incorrect amplitude values corresponding to each frequency component for use in Equation 3.5. The resulting pressure profile for the incorrectly converted source used in the following simulations is shown in Figure 5-5. Despite an incorrect conversion, the following results and conclusion are still valid. The use of a complex source interpretation in Paracousti is still demonstrated. While the actual source pressure profiles are overestimate, the following study of the influence on relative overall SPL is still legitimate for the source profile used. While the localized areas of wave propagation results may differ between the two source profiles, the trends and results for a overall wave interferences and energy decay are analogous.

Frequency (Hz)	Correct Amplitude (Nm*1e4)	Incorrect Amplitude (Nm*1e7)
10	1.429	5.6415
30	0.0632	2.2459
62	0.0059	0.8941
102	0.0014	0.5641
150	0.0008	0.7102

Table 5-2: Correct vs. incorrect amplitude values for multi-frequency MHK source

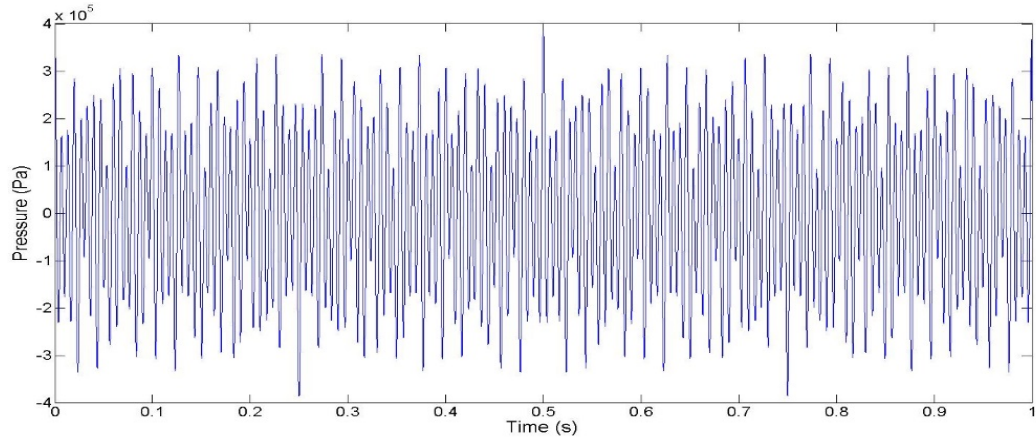


Figure 5-5: Pressure source profile with incorrect conversion

Two-Layered Waveguide

An additional incorrectly converted MHK source profile was simulated in the same shallow water two-layered waveguide as in the multiple frequency subsection. The pressure profile used is the same profile as that of Figure 5-4 but with all amplitudes multiplied by $4\pi^2$. The MHK source is located at a range of 0 m and depth of 40 m. The domain is a 200 m deep two layered waveguide consisting of a top half space of water (1,500 m/s sound speed and 1,000 kg/m³ density) and lower half space of a sedimentary bottom layer (1,800 m/s sound speed and 1,800 kg/m³ density). Figure 5-6 is a 2D SPL slice in depth and range for the MHK source in a two-layered media. Figure 5-7 is a depth averaged SPL trace of the water column compared to analytical cylindrical and spherical spreading laws which are in good agreement with each other. This demonstrates, in a simple 2D domain without medium attenuation, that less complex acoustic propagation models may be appropriate. However, as the domain increases in complexity, the approximation is likely to become quite conservative and underestimate the rate of energy decay.

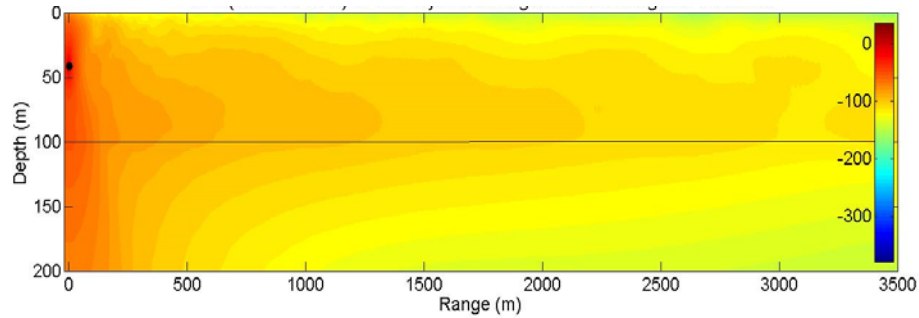


Figure 5-6: SPL (dB re 1e-6 Pa) of Two-Layered Waveguide with a Single MHK Source

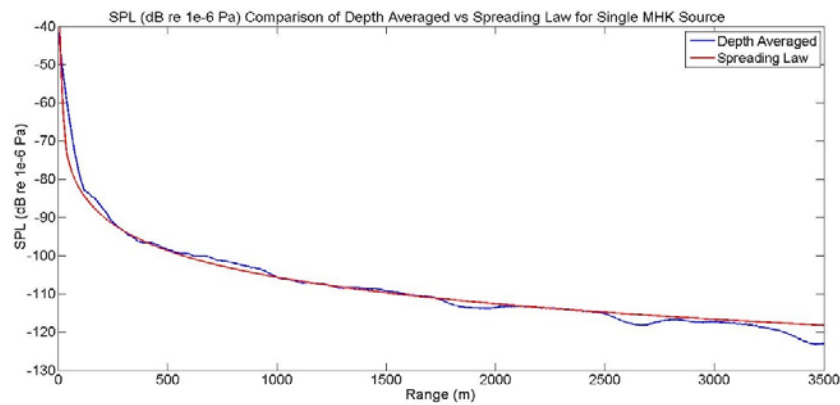


Figure 5-7: SPL trace depth averaged of a single MHK source in a two-layered waveguide vs. spreading law

Three-Dimensional Sloping Bottom

A range dependent MHK relevant domain with a complex source is of interest to show how acoustic propagation is affected. The 3D sloping bottom domain, as shown in Figure 4-7, is simulated with the incorrect MHK source profile, Figure 5-5, located in the middle of the domain at a depth of 40 meters. The domain extends from -4 km to 4 km in the upslope x-direction, from 0 to 25 km in the across slope y-direction, and is 400 m in the depth z-direction. The water domain has a sound speed of 1500 m/s and density of 1000 kg/m³ while the bottom sedimentary layer has a sound speed of 1700 m/s and density of 1500 kg/m³.

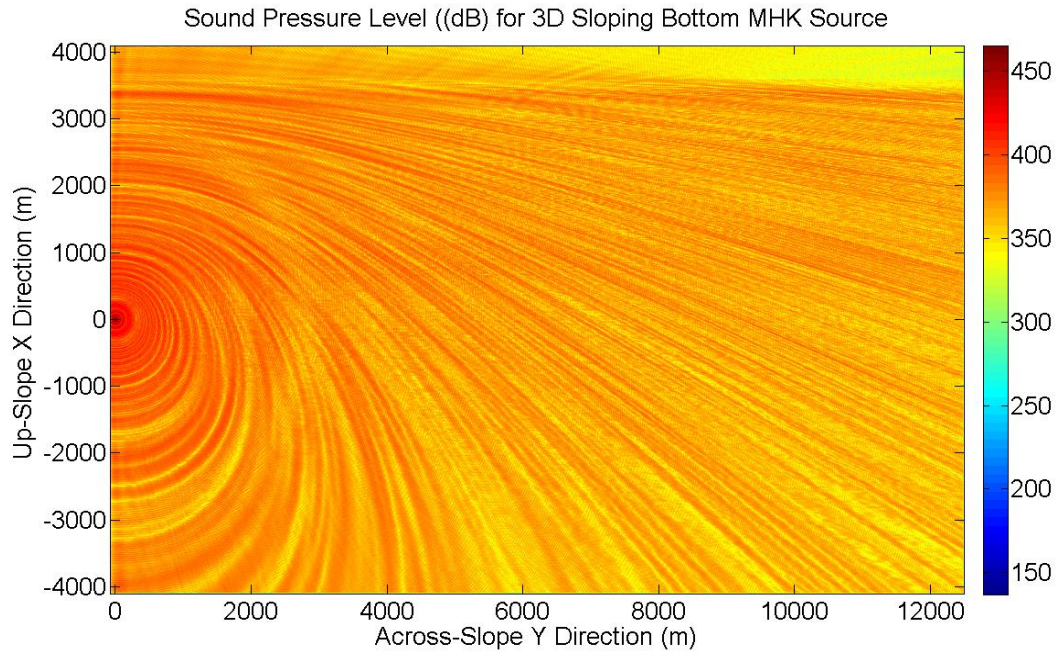


Figure 5-8: SPL Slice of 3D Sloping bottom

The 3D sloping bottom domain with an MHK source was the largest model simulated during this work. With a maximum sound speed of 1500 m/s, frequency of 150 Hz and default grid nodes per wavelength of 10, the domain is approximately 42 billion grid nodes. Roughly 40 bytes of ram per grid node is required for the Paracousti algorithm, resulting in 1.68 Tb of ram required for this model. This is a significant computational load; however, by utilizing optimized finite difference coefficients and the 5.22 grid nodes per wavelength requirement, the domain was reduced to 1.7 billion, corresponding to 0.68 Tb of required ram. This model ran on 320 Intel Xeon hyper threaded cores for a total run time of about 34 hours. Please note that an incorrect source time function based on the MHK example spectra of Figure 5-3 was used in this model. A mistake of converting SPL versus frequency to a source time function in paracousti created results of SPL in this simulation that are much larger than they should be. The

procedure and demonstration of incorporating a complex MHK source in Paracousti for a large 3D domain is still valid.

6. MULTI-SOURCE INVESTIGATION

In order to decrease the cost of energy of MHK devices, arrays of these devices will be necessary. Once the effectiveness and robustness of a single source implementation in Paracousti was established, investigation into the effects of sound propagation from multiple sources is of interest. Maximizing the power produced by an array is the principal driver in how they are located and where they are spaced. However, array spacing and depth is also important in their contribution to the sound environment. Depending on the source-profile, environment, and array spacing, noise contributions between MHK devices have the potential to be additive or subtractive to the rest of the devices in an array. This interaction of sound between devices could potentially create quite large differences in the projected sound levels when compared to a single source.

Two Device Array

The influence of two sources in a two-layered waveguide is investigated first. While an MHK array installation will likely consist of more than two devices, the interaction of sound between two devices serves as an initial investigation in understanding how multiple sources impact sound propagation through a system. Several array configurations (AC) with different device spacing and depths were considered and are listed in Table 6-1. The first nine of the twelve cases are orientated horizontally while the remaining three are vertically orientated.

Array Configuration	Depth Location (m)	Horizontal Spacing (m)
1	[25, 25]	10
2	[25, 25]	15
3	[25, 25]	12.5
4	[50, 50]	10
5	[50, 50]	15
6	[50, 50]	12.5
7	[75, 75]	10
8	[75, 75]	15
9	[75, 75]	12.5
10	[45, 55]	0
11	[42.5, 37.5]	0
12	[43.75, 56.25]	0

Table 6-1: Configurations of a two-device MHK array with specified spacing and depth

The two-layered waveguide was utilized for these simulations along with the incorrect MHK pressure profile of Figure 5-5. The device spacing was selected to be in-phase, out-of-phase, and partially in/out-of-phase by considering the peak frequency of the source (150 Hz) and the sound speed of the domain (1500 m/s). This particular frequency and sound speed results in a wavelength of 10 m. If two devices are spaced 10 m apart they will both have a positive pressure value, creating an additive contribution to each other (in-phase). In contrast, if the devices are 15 m apart the propagating source from the first device will be at a large negative value while the second source will be at its largest positive value, making a subtractive contribution (out-of-phase). The 12.5 meter spacing should result in sound interference that lie between the highly additive and subtractive device spacings (partially in/out-of-phase). The three different device spacings orientated horizontally at a depth of 50 m (AC 3,4,5) are show in Figure 6-1, Figure 6-2 and Figure 6-3 while the vertically orientated configurations (AC 10,11,12)

are shown in Figure 6-4, Figure 6-5 and Figure 6-6. A 2D sound pressure level (re $1\text{e-}6$ Pa) slice as a function of depth range are shown in these figures. It is evident that the 10 m (in-phase) device spacing (Figure 6-1) has an overall higher SPL in the water column compared to the 15 m (out-of-phase) device spacing (Figure 6-2) while the 12.5 m (partially in/out-of-phase) device spacing (Figure 6-3) falls between two. This comparison is made clearer in Figure 6-7 where the depth averaged SPL in the water column for all device configurations are shown as a function of range.

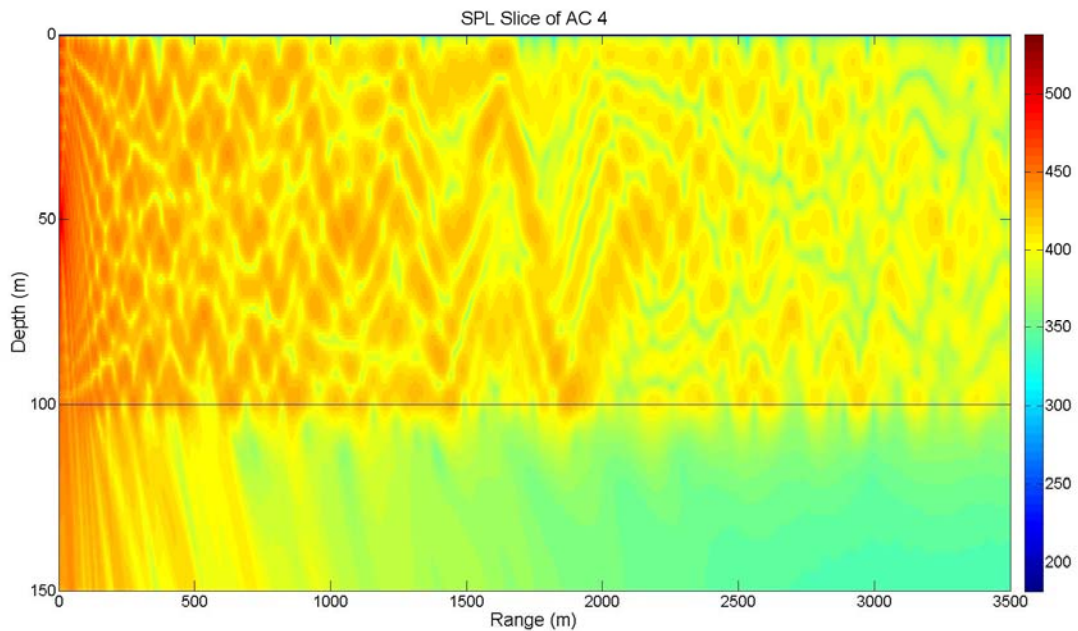


Figure 6-1: SPL (dB re $1\text{e-}6$ Pa) of MHK Array Configuration 4

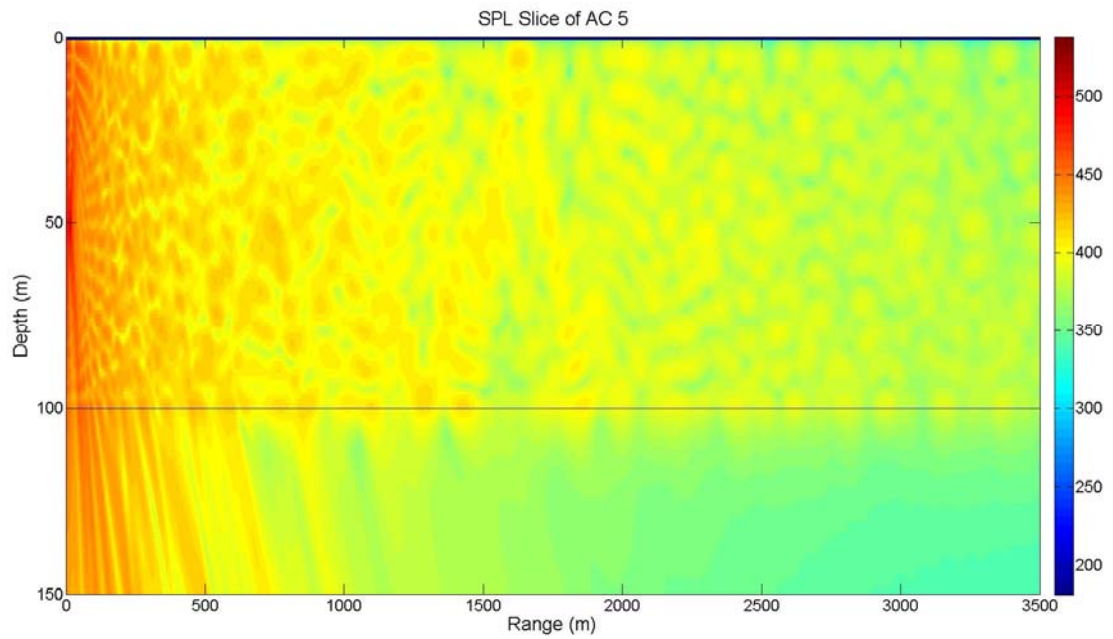


Figure 6-2: SPL (dB re 1e-6 Pa) of MHK Array Configuration 5

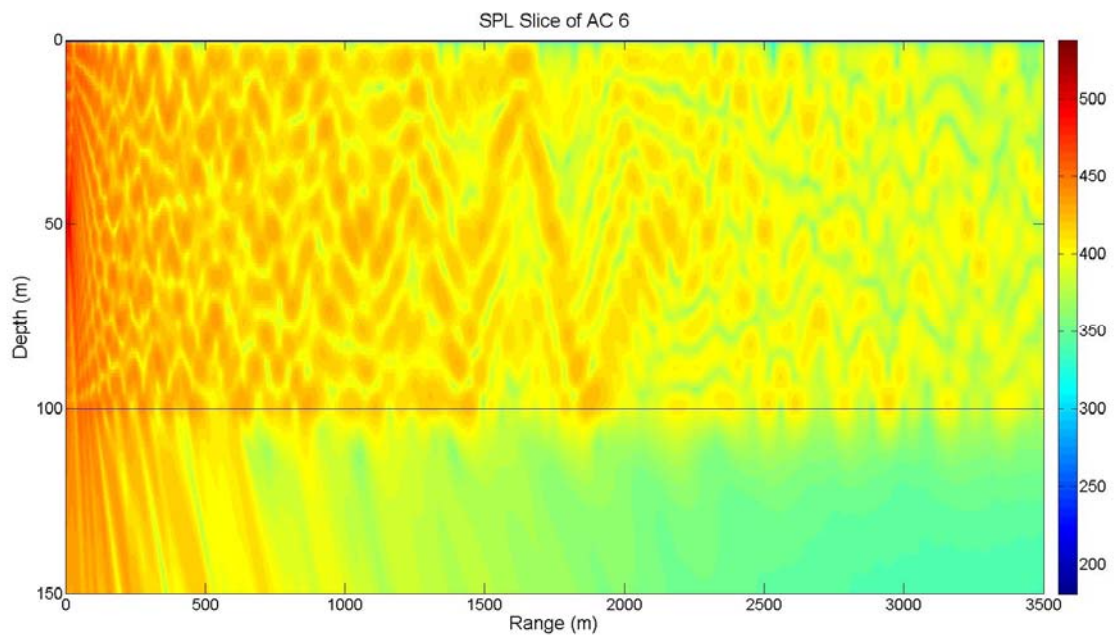


Figure 6-3: SPL (dB re 1e-6 Pa) of MHK Array Configuration 6

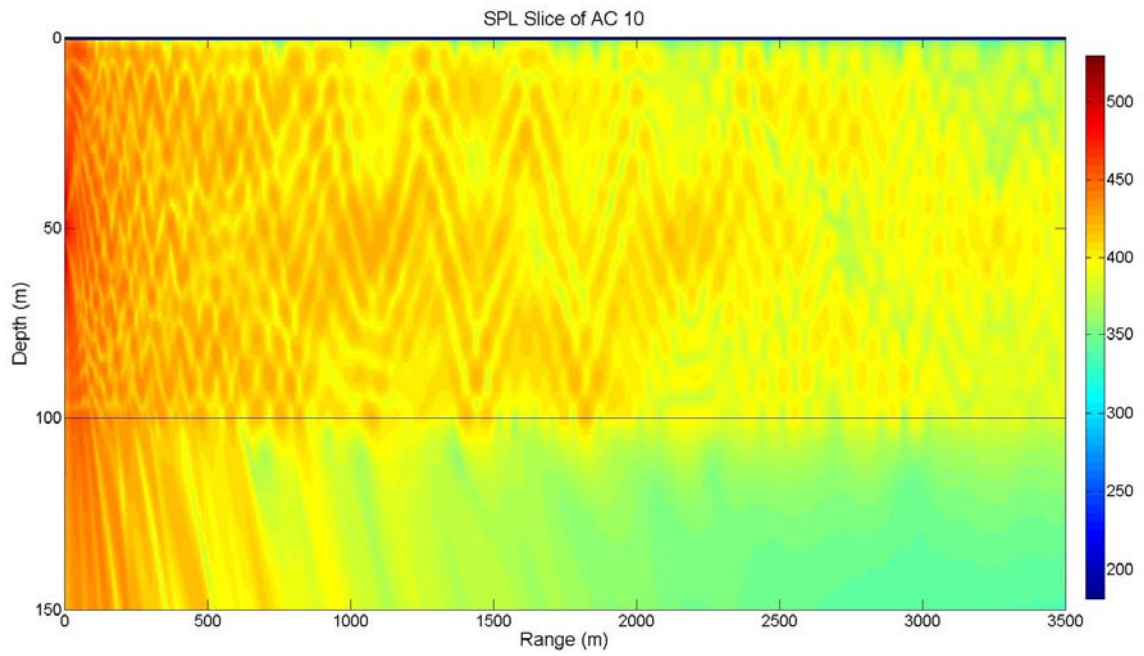


Figure 6-4: SPL (dB re 1e-6 Pa) of MHK Array Configuration 10

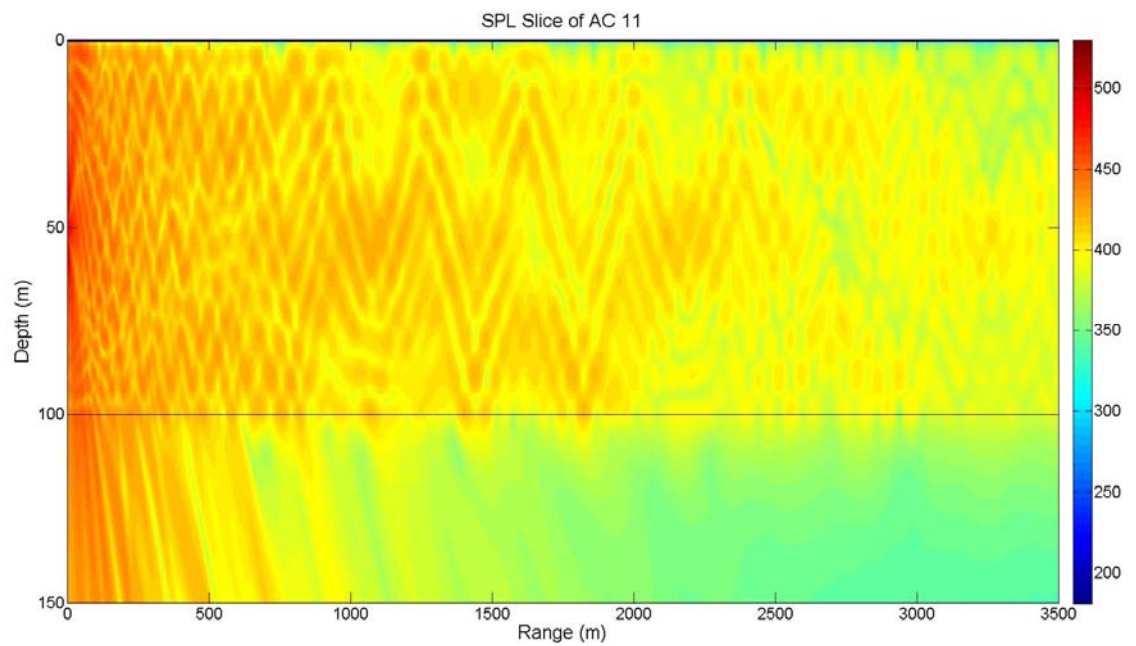


Figure 6-5: SPL (dB re 1e-6 Pa) of MHK Array Configuration 11

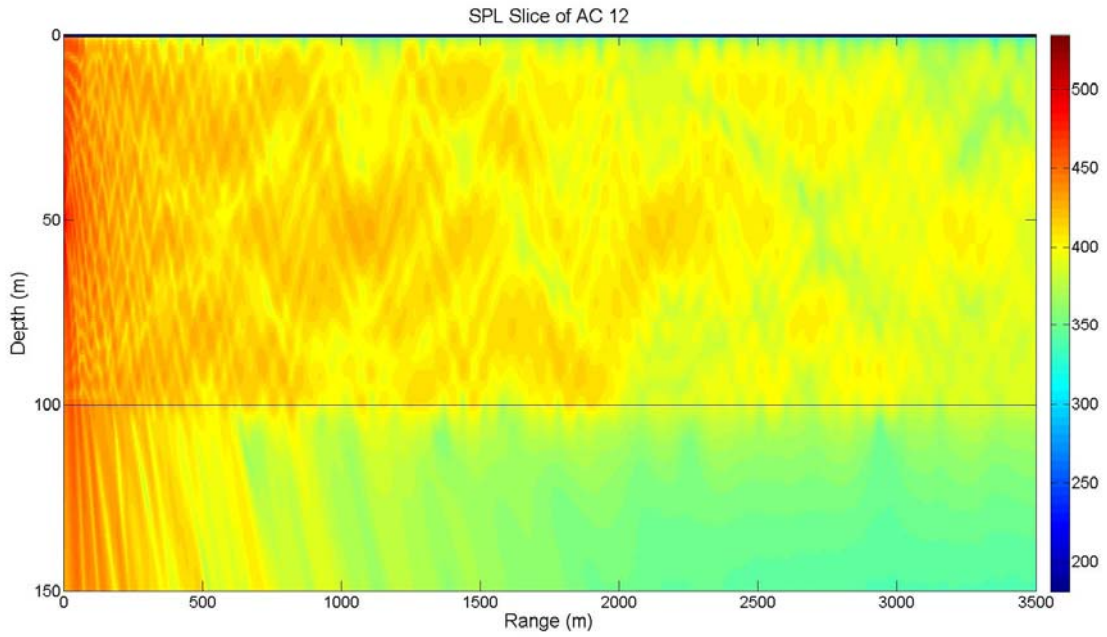


Figure 6-6: SPL (dB re 1e-6 Pa) of MHK Array Configuration 12

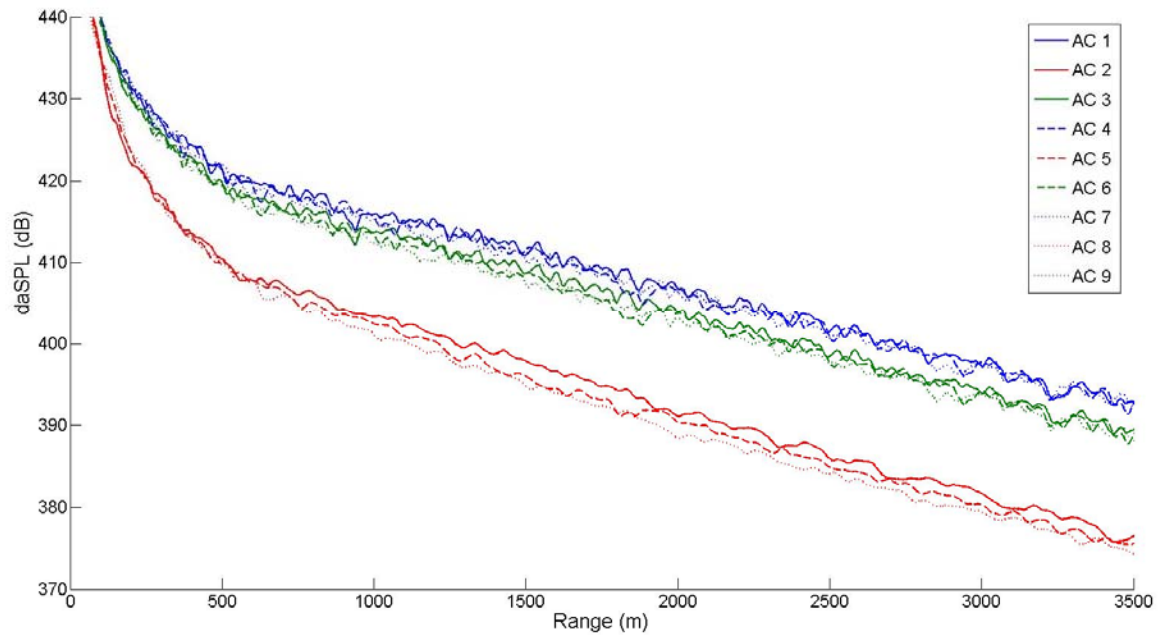


Figure 6-7: Depth averaged SPL (dB re 1e-6 Pa) of the water column for two device array configurations

As expected array configurations with a 15 m spacing have the lowest depth-averaged SPL in the domain (due to the dominant frequency of the source being 150 Hz and the sound speed of the domain as 1500 m/s) corresponding to an out-of-phase wave interaction. Similarly, the 10 m spacing should have the highest average SPL due to the MHK source locations being in-phase. The 12.5 m horizontal spacing, corresponding to a 45° phase-shift of the source for each successive MHK location, have a combination of both additive and subtractive contributions. The complexity spacing induces in SPL between two identical devices is demonstrated in the SPL slices of Figure 6-1 through Figure 6-6. Both device spacing and location in the water column impact the sound propagation. This is in contrast to the single device, where the particular placement had little overall impact.

This trend is further shown in Figure 6-7, where the depth-averaged SPL for the 9 different device configurations is shown. For all arrays having two devices, the total SPL in the water column deviated by as much as 20 dB at 1 km away from the array and continued to spread. In Figure 6-7, the blue lines correspond to 10 m device spacing (AC 1,4,7), red lines represent the 15 m device spacing (arrays 2,5,8), and the green lines are for 12.5 m horizontal spacing (arrays 3,6,9). Solid lines represent an array depth of 25 m, dashed lines represent an array depth of 50 m, and dotted lines are for an array depth of 75m. As expected, the 10 m device spacing has the largest depth-averaged SPL because of the MHK sound-profile being predominately in-phase. On the other hand, the 15 m device spacing has the lowest SPL. The 12.5 m device spacing results lie in between the 15 and 10 m device spacing and is again due to both the additive and subtractive pressure

contributions from each successive MHK device. It is also clear that the depth of each array has little impact on the depth averaged SPL compared to the device spacing. Three main groups are evident in Figure 6-7 with the device spacings being the driving factor between each group cluster while device depth creates little difference.

Square Array

Now that the in/out-of-phase interferences have been investigated for two devices, and successfully shown to create trends in propagated sound levels, an array consisting of more than two devices is of interest. While a particular deployment site will determine device placement, arrays are likely to occupy all three-dimensions. The previous section shows complexity in SPLs of a two-device array. Complexity of the SPLs with a multi-dimensional array will likely only increase. Due to the wide range of MHK designs, deployment sites, and operational conditions the array sizing, spacing, and location can be completely different between one site to the next. The ability to quickly and accurately model these different scenarios is important for developers of MHK power. As the placement and spacing between a two-device array had a significant impact on sound propagation, the effect of adding additional sources is investigated. With a four-device array, orientated in a square configuration, further complexities should arise in interference patterns due to the additional sources and geometry of the array. Spacing between each device will no longer be of equal distant to each other as is inherently the case for a two-device array but will rather be a combination of horizontal, vertical, and diagonal distances.

Square arrays are considered, with their spacing and location detailed in Table 6-2. The array spacings are again based on an in/out of phase placement of successive devices along the perimeter with 15 m being out-of-phase, 20 m being in-phase, and 12.5 m being partially in/out-of-phase (for the dominant frequency of 150 Hz and sound speed of 1500 m/s). Two depth sets were considered for each square array spacing.

Array Configuration	Depth Location (m)	Horizontal Spacing (m)
13	[15, 30]	15
14	[20, 40]	20
15	[12.5, 25]	12.5
16	[70, 85]	15
17	[60, 80]	20
18	[75, 87.5]	12.5

Table 6-2: Array Configurations for a square MHK array with specified depths and horizontal spacings

Figure 6-8, Figure 6-9, and Figure 6-10 show 2D SPL maps as a function of depth and range for array configurations 16, 17, and 18 which are the out-of-phase, in-phase, and partially in/out-of-phase array spacings, respectively. It is evident that MHK array spacing have a large influence on SPLs in the domain and clearly show complex patterns of coherency and incoherency interference zones. Similar to the two device arrays, device spacing can drastically change SPLs determined by the in-phase or out-of-phase placement of each device. Figure 6-11 further depicts this phenomena by showing the depth averaged SPL of the water column for each quad array configuration (AC 13-18). Similar to the two device array, the 20 m (in-phase) array spacing of the four devices creates the highest SPL while the 15 m (out-of-phase) array spacing results in the lowest

SPL. The 12.5 m (partially in/out of phase) SPLs lie in between the 15 m and 20 m spacings. At a range of 100 m, the difference between the in-phase 15 m spacing and out-of-phase 20 meter spacing is about 15 dB. Array depth seems to have little influence to the depth averaged SPL and rate of decay compared to array spacings.

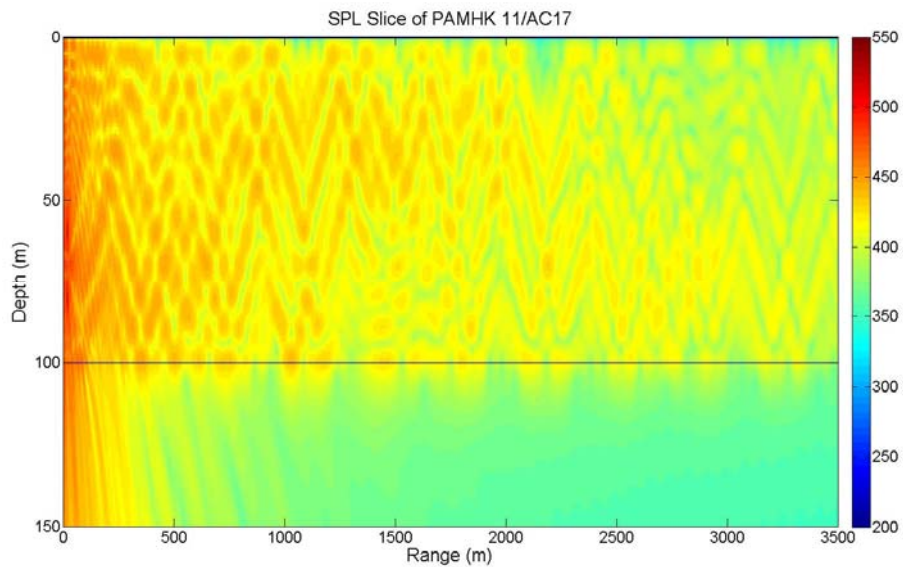


Figure 6-8: SPL (dB re 1e-6 Pa) of MHK Array Configuration 16

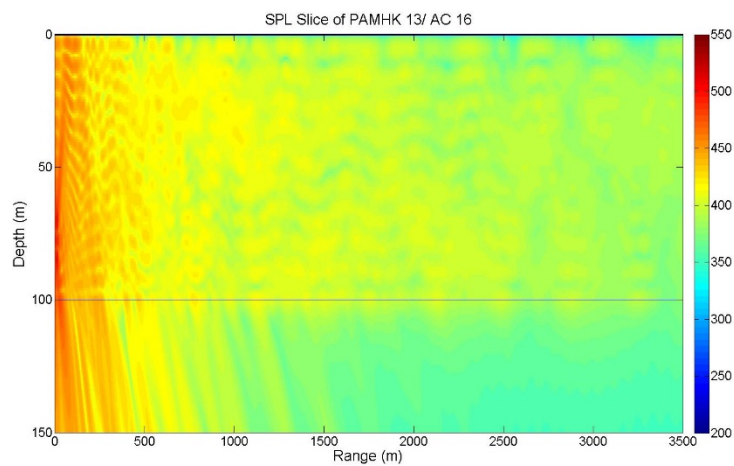


Figure 6-9: SPL (dB re 1e-6 Pa) of MHK Array Configuration 17

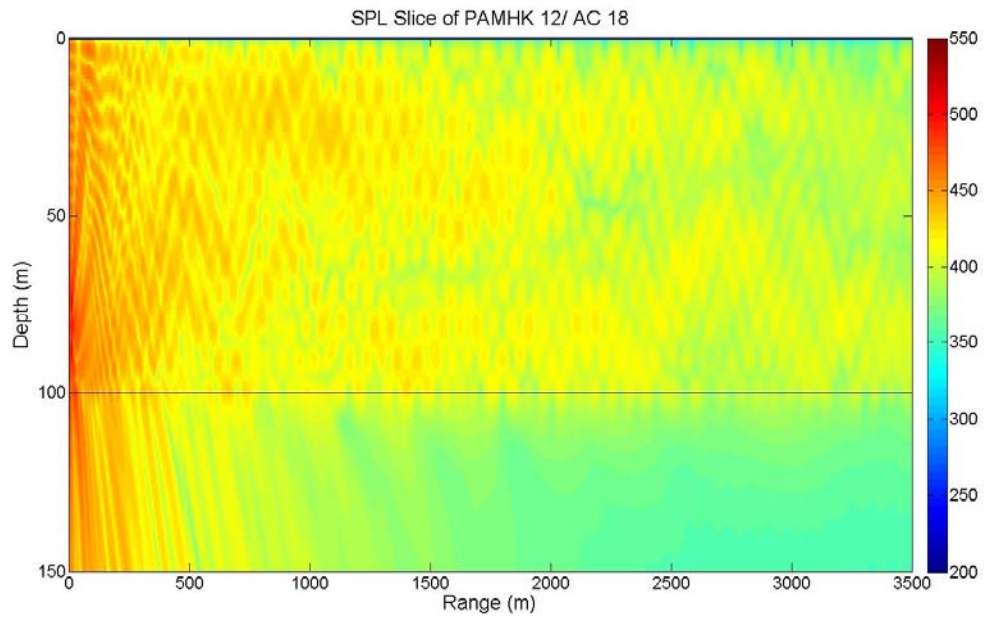


Figure 6-10: SPL (dB re 1e-6 Pa) of MHK Array Configuration 18

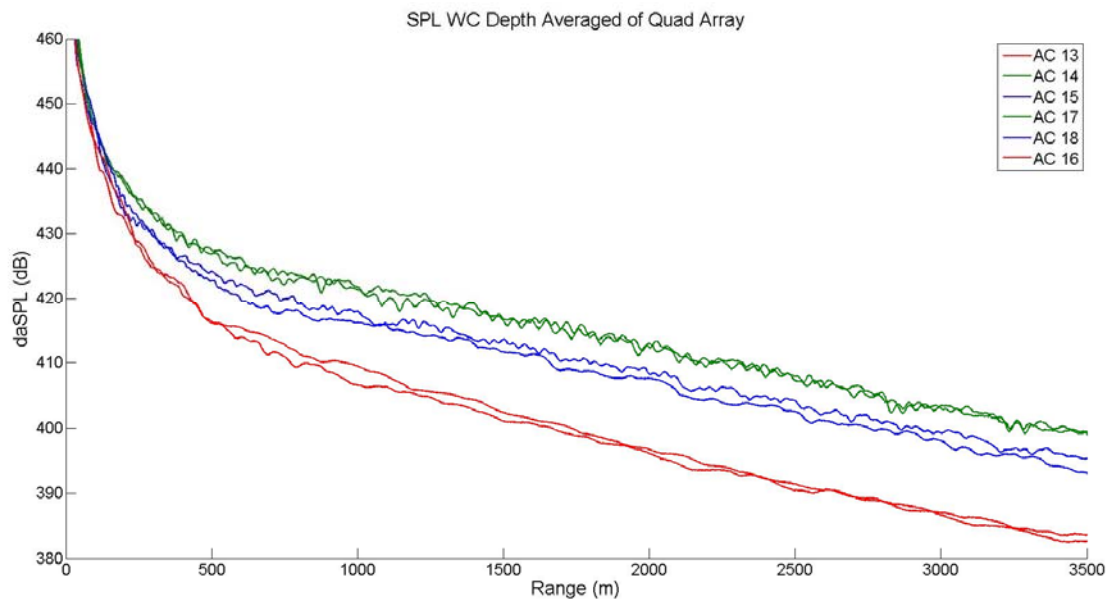


Figure 6-11: Depth averaged SPL (dB re 1e-6 Pa) of the water column for quad device array configurations

Depending on the MHK sources' dominate frequency, the domain's sound speed, and the array spacing, SPL in the domain can change. There appears to be optimal spacings that would minimize SPL when accounting for the phase shift from one device to the next and creating subtractive contributions. However, the predominate driving force behind array spacing and depth will be an optimization for power production. Nevertheless, consideration on the source and spacing to minimize SPL can be quantified. Meeting regulatory requirements on sound level will depend on a large parameter space, to include the array sizing, spacing, location, source-profile, and domain properties. It should be noted that it is unrealistic to assume that each MHK device in an array will be producing the same acoustic profile at the same time. Variations in the source profiles and phase location of each device will occur due to different operating conditions within the array. What is presented here bounds the best case and worst case scenarios of each source profile being perfectly in-phase or out-of-phase. An investigation into the effects of having variations (phase shifts) in each source is investigated in the random phase change section.

Random Phase Change

In reality MHK devices in an array will not continually produce the same sound profiles in the appropriate phase, but will vary based on operating and flow conditions. In terms of permitting and satisfying a particular sound level threshold, the varying combinations of sound profiles from successive devices in an array may be within regulation for a certain operating condition but may not satisfy the regulation for another

operating condition. The ability to identify key parameters, distribution probability, and trends in a wide range of arrays and sound profiles is critical to MHK developers in terms of satisfying federal regulations and knowing what potential sound levels are possible from an array.

In order to investigate the intricacies of having many different combinations of phase shifts, 400 trials were conducted for each of the three different array configurations and four array spacings in the two-layered waveguide. An equilateral triangular, square, and hexagonal array configuration were defined, with array spacings of 10, 15, 20, and 40 m along the dominant edges. Figure 6-12 is a diagram of the three array configurations considered with the defined array spacing (AS) dimension. Each red dot represents an acoustic source location. The array depth was kept symmetric with respect to the 100 m deep water guide so that the center of every array is at a depth of 50 m.

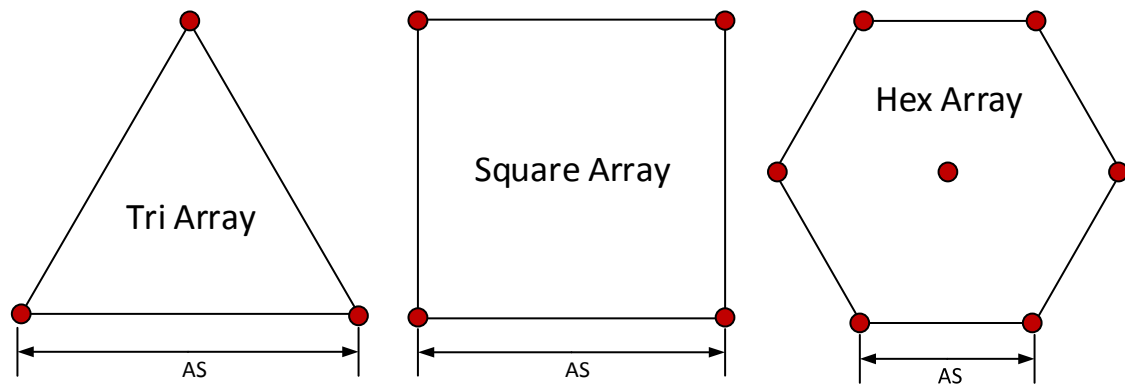


Figure 6-12: Diagram of each array configuration (Tri, Square, and Hex) with the defined array spacing (AS), red dots are sources

The source in these trials is a single frequency of 150 Hz and an amplitude of 1 based on the profile of Equation 3.5. A single frequency, as opposed to the multi-

frequency MHK source was chosen in an attempt to reduce the complexity of wave interference from a combination of multiple frequencies and reduce the number of parameters under investigation. A random phase shift between 0 and 1 wavelength, corresponding to 0-10 m, or 0-6.7 ms, for a 150 Hz source in a sound speed of 1500 m/s was applied to each source for each trial by using a uniformly distributed random number generator. A uniform distribution is the appropriate choice with the information at hand. The generated noise spectras available are approximations and lack detailed information about the phased-averaged noise generation from MHK devices that would determine the noise spectra as a function of angular rotation. There is an equal likelihood of any phase shift due to the wide range of operating conditions and flow variations. In order to reduce the chance for numerically induced noise, the random phase change was forced to correspond to a multiple of the models time step. Thus for a time step of 0.2 ms and a period of 6.7 ms, 33 different phase shifts are possible for each source. A “conservative” comparison of each array was also modeled using one source at the center of each array configuration with the source time function amplitude multiplied by the number of sources in the array. This is assumed to be the most conservative scenario or the producer of the maximum sound levels, where each array is condensed into a single source and all the sources are summed together in a perfectly constructive interference. Additionally, a comparison of a single source versus a full multi-source array is of interest to see how the two compare and understand if a single source can appropriately represent the sound levels and acoustic propagation of a more complex array.

Equilateral Triangle Array

The first array considered is an equilateral triangle configuration and was selected because each of the three sources are equal distance from each other. This equal distance configuration should allow for a perfectly constructive and perfectly deconstructive wave interference from each of the sources as opposed to a rectangular array, for example, where the geometry of the configuration means each source will not be equidistance from each other and adds complexity to the interference. Results for a depth averaged SPL in the water column of the 400 trials for the equilateral triangle are shown in Figure 6-13. Blue lines represent the 400 trials while the black line is the single source model run with the source profile amplitude multiplied by 3 in this case, for the 3 sources.

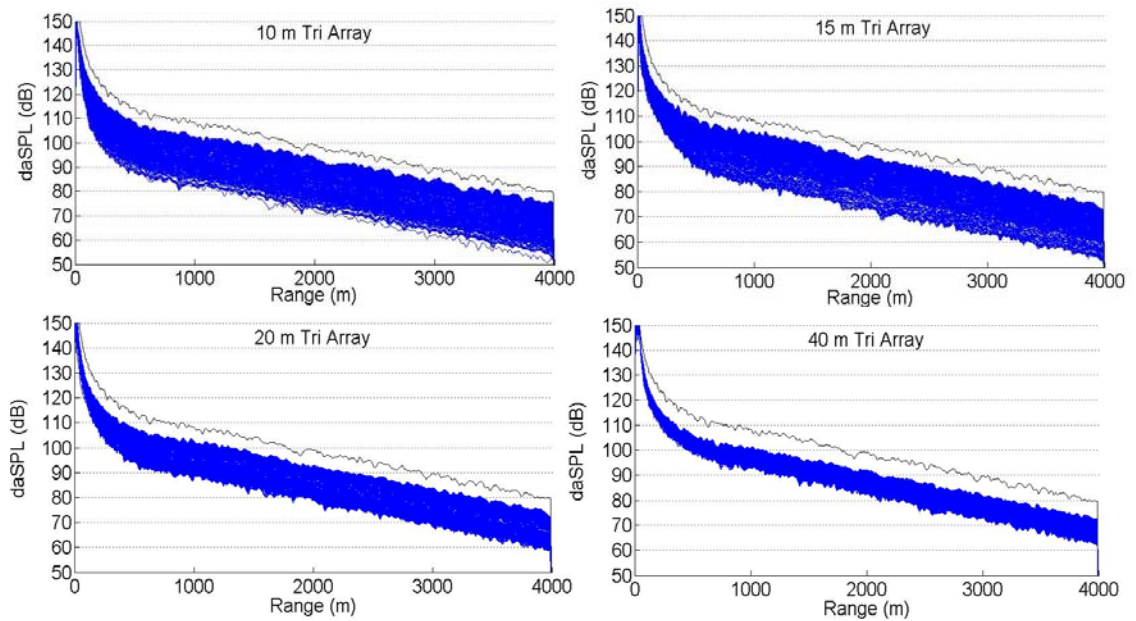


Figure 6-13: Depth Averaged SPL (dB Re 1e-6 Pa) of water column for Triangular Array with Random Phase Change

The results of SPL in Figure 6-13 for the triangular array show some initial trends. First, there appears to be a banding of SPLs for each array spacing where there is a range of SPLs, an upper and lower case, and values in-between. This indicates that for a particular array configuration and spacing, a range of SPLs are possible due to changes in the phase of each devices source profile, even though each profile is a continuous 150 Hz cosine. Secondly, this bounding, or range of SPLs, appears to decrease as array spacing increases. At a range of 3000 m, the 10 m triangular array has a SPL band of about 22.7 dB between the highest and lowest predicted SPL, the 15 m array has a spread of about 21.2 dB, the 20 m array has a spread of about 15.4 dB and the 40 m spread has a range of about 8.8 dB. The banding appears to be fairly constant after a few hundred meters where the spreading transitions from purely spherical to a partially-cylindrical spread due to energy still being lost to the sedimentary layer. Third, for all array spacings and random phase change trials, the SPL curves are substantially below the single source run. This indicates, as expected, that a single source run with an amplitude multiplier serves as the most conservative estimate of SPL for an array. Lastly, as array spacing increases, the difference between the single source amplitude multiplier and the upper band of the SPL range also increases. At a range of 3000 m the difference between the single source multiplied amplitude run and the upper bound of the full array SPL range is about 4.8 dB for the 10 m spacing, 5.3 dB for the 15 m spacing, 5.7 dB for the 20 m spacing, and 8.0 dB for the 40 m spacing. This correlation makes sense because as the array spacing increases, the strength of sound interference between successive devices decreases due to propagation loss. An array that is closely spaced will have wave interactions with higher

amplitude profiles resulting in larger contributions of coherency and incoherency than that of an array that is largely spaced where the source profile amplitude decreases more over the larger distance between devices. This also can explain why the range in SPL decreases as array spacing increases. The sound sources at the larger spaced arrays have decayed more or lost more of its amplitude than that for the closely spaced arrays resulting in a wider range of SPL for the close spaced array than the large spaced array.

The trial mean of depth averaged SPL for all triangular trials is shown in Figure 6-14. The four blue curves are for each of the array spacings while the black curve is again the conservative estimate of the combined, single source located at the array center. Despite the different bounds and ranges of SPL and difference between the upper bound and conservative estimate for the different array spacing's, the mean SPL of the random phase change trials for each spacing is very similar.

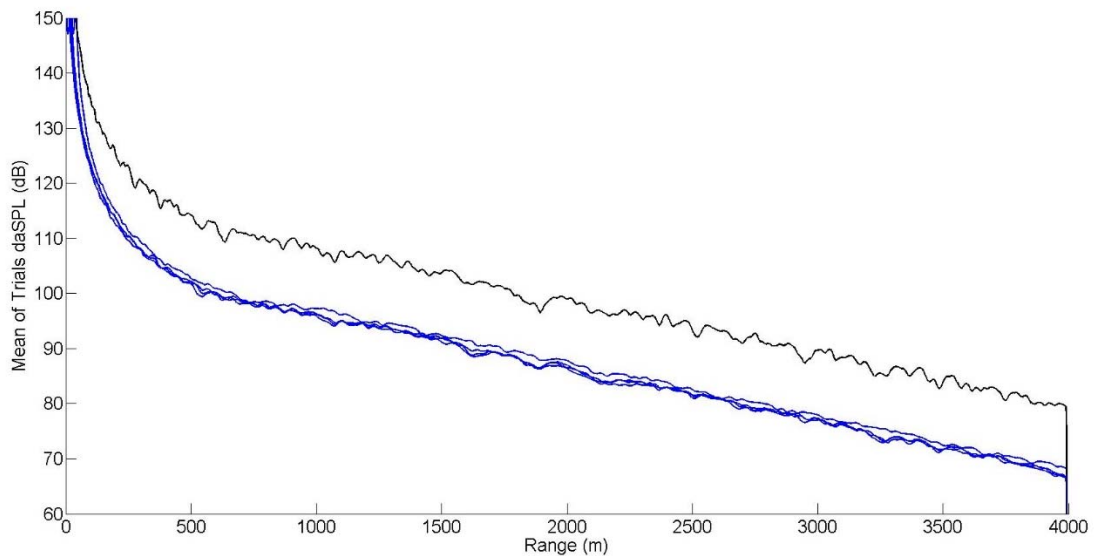


Figure 6-14: Mean depth averaged SPL (dB re 1e-6 Pa) of all triangular arrays

In order to get a better sense of the distribution of SPLs in the random phase change study, a statistical analysis is required. A probability density function is created from the trial data at a specified range and describes the relative likelihood or probability of being at a particular SPL. In this case, a discrete probability density function is created at a specific range for each trial data set. The data is counted and binned for each SPL level, then divided by the total number of samples to create probability density. The appropriate bin width and location is determined by the Freedman-Diaconis rule which factors in sample size and spread of the data [40]. Once the discrete and binned probability density function is known, a continuous probability distribution function can be created. The continuous distribution function uses the discrete density function by prescribing predefined distribution curves to the data, e.g. normal, Weibull, etc. After consideration of different distributions available, the kernel distribution was selected for use in the random phase change study. A kernel distribution is used when assumptions about the distribution of the data is not desired and when a parametric distribution cannot properly fit the data [41]. It is a non-parametric way to estimate probability distributions. The kernel density estimator $\hat{f}_h$ is the estimated probability density function of the random variable and given by the equation,

$$\hat{f}_h(x) = \frac{1}{nh} \sum_{i=1}^n K\left(\frac{x - x_i}{h}\right) \quad 6.1$$

Where K is the kernel smoothing function, n is the sampling size, and h is the bandwidth. A binned probability density function for the 400 trials of the triangular array spacing 10 m at a range of 3000 m with a comparison of a Kernel distribution and normal

distribution is shown in Figure 6-15. As can be seen the kernel distribution is a much better fit to the trial data and does not include slowly decaying tails at the upper bounds of SPL.

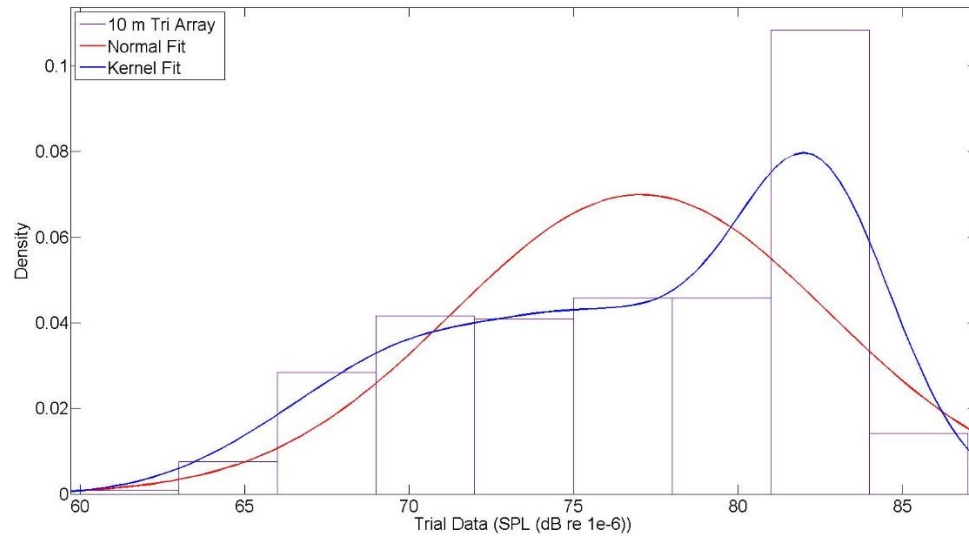


Figure 6-15: Example probability density function and comparison of normal vs. kernel distribution fit

The probability density function and corresponding probability distribution function at a range of 3000 m is show in Figure 6-16 for the four different array spacing's of the triangular array. The probability density function is depicted by binned data while the probability distribution function is a continuous curve. The 10 m spacing is show in blue, the 15 m spacing in green, the 20 m spacing in red, and the 40 m spacing in black. The kernel distribution is utilized to obtain the continuous probability distribution function from the binned probability density data.

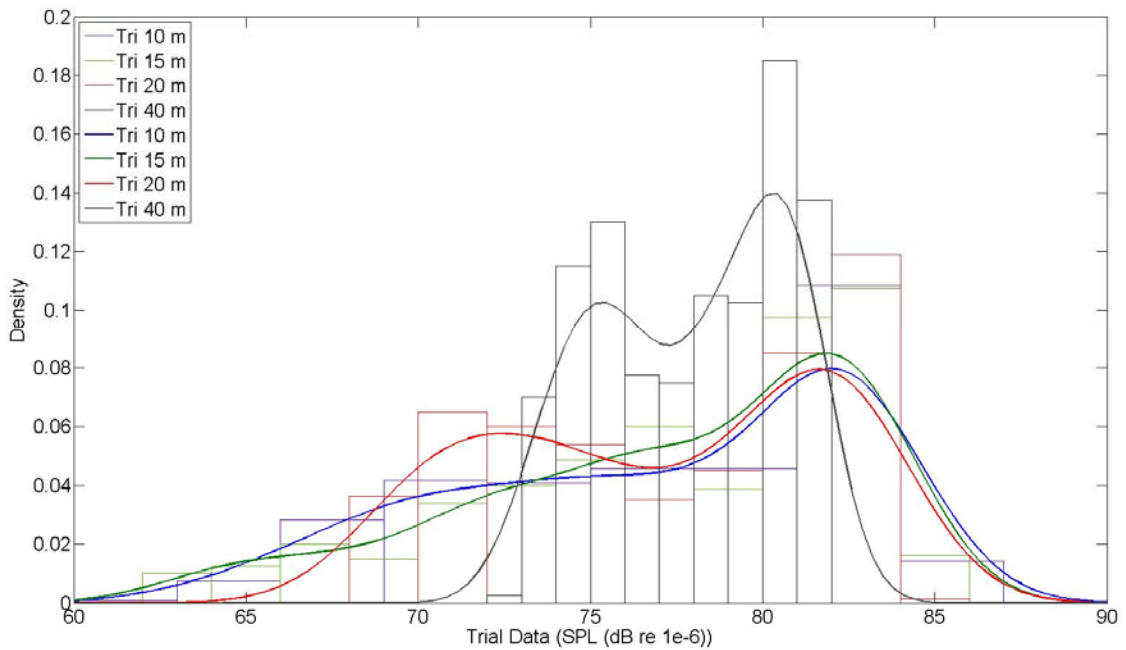


Figure 6-16: Probability density/distribution function for the four triangular array spacings at a range of 3000 m

From the probability density/distribution results of Figure 6-16 it is evident that for the 400 different trails for each array spacing there is a probability distribution of being at a certain value of SPL. It appears that this distribution is more heavily weighted towards a higher SPL than a lower SPL and is not a normal Gaussian distribution. The trends previously described are also depicted here. As the array spacing increases, the range in possible SPLs as shown by the width of the continuous PDF curve narrows.

Square Array

The next array configuration is a square array and seemed to be the logical next step comparison to the equilateral triangular array. With the addition of a fourth source and the geometry of the square quad array, each device is equal distance to each other

around the perimeter of the array but the cross diagonals are not the same distance as the defined array spacing. This will add complexity to the wave interactions and results.

Results of the 400 trials for the square array are shown in Figure 6-17.

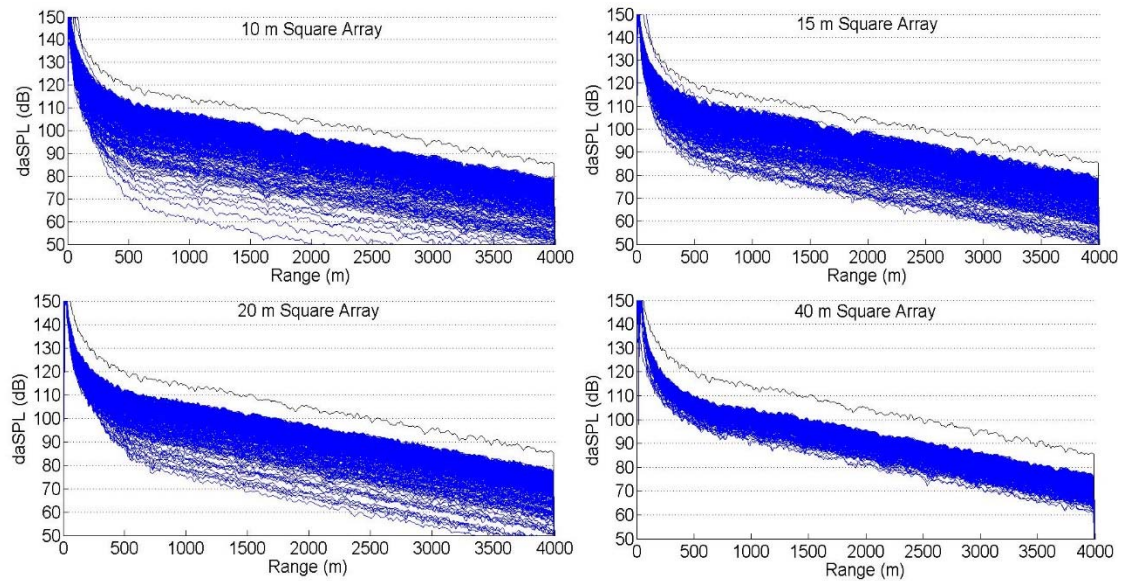


Figure 6-17: Depth Averaged SPL (dB Re 1e-6 Pa) of water column for Square Array with Random Phase Change

Similar trends are seen in the square array as in the triangular array. First, for every array spacing, the upper bound of SPL band is below the conservative single source multiplied amplitude run (multiplied by four in this case for a four source array). Second, the difference between the conservative run and the upper bound of the SPL band increases as array spacing increases, at a range of 3000 m the difference is about 6.5 dB for the 10 meter array spacing, 5.9 dB for the 15 meter array spacing, 7.7 dB for the 20 m array spacing, and 9.3 dB for the 20 meter array spacing. Lastly, overall there appears to be a narrowing of the SPL band as array spacing is increased however there is an

exception to this with the 15 m case. At 3000 m the SPL band between the upper and lower bound has a range of about 49.2 dB for the 10 m spacing, 30.4 dB for the 15 m spacings, 33.4 dB for the 20 m spacing, and 14.8 dB for the 20 meter spacing. It is possible that this discrepancy in the trend is due to the limited number of trials conducted and the additional complexity to the wave interferences from this type of array.

Even though the band size doesn't follow the continually decreasing trend as seen in the triangular array, the mean SPL for all square trials still collapse on top of each other. This is shown in Figure 6-18 with the blue lines representing the mean of all trials for each array spacing and the black line is the conservative estimate of a single source located at the center of the array with a source profile amplitude multiplied by 4.

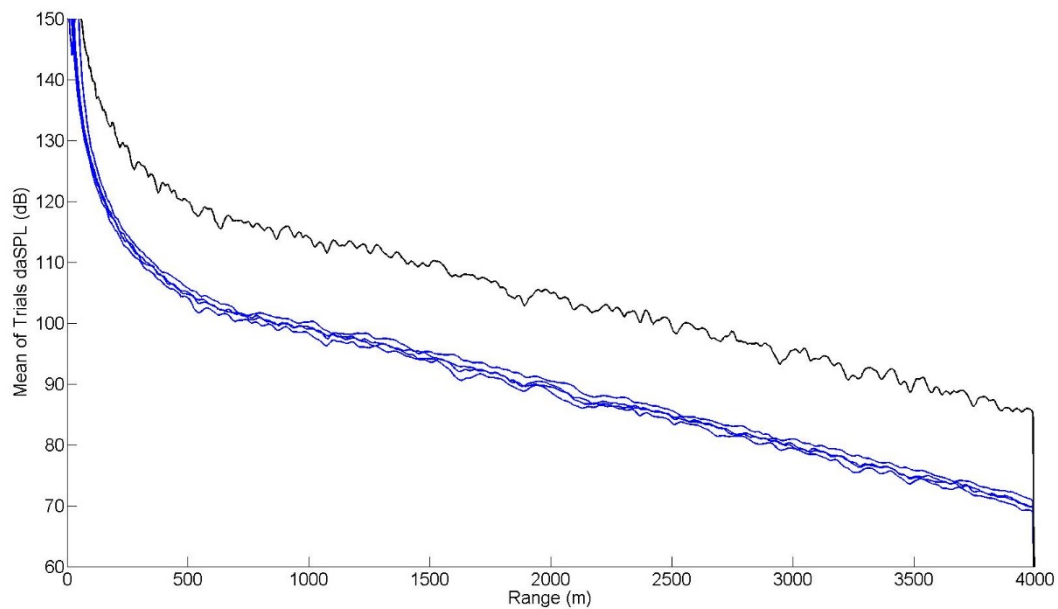


Figure 6-18: Mean depth averaged SPL (dB re 1e-6 Pa) of all square arrays

The probability density function and corresponding probability distribution function at a range of 3000 m is show in Figure 6-19 for the square array spacings. The probability density function is depicted by binned data while the probability distribution function is a continuous curve. The 10 m spacing is show in blue, the 15 m spacing in green, the 20 m spacing in red, and the 40 m spacing in black. The generalized extreme value distribution is utilized to obtain the continuous probability distribution function from the binned probability density data.

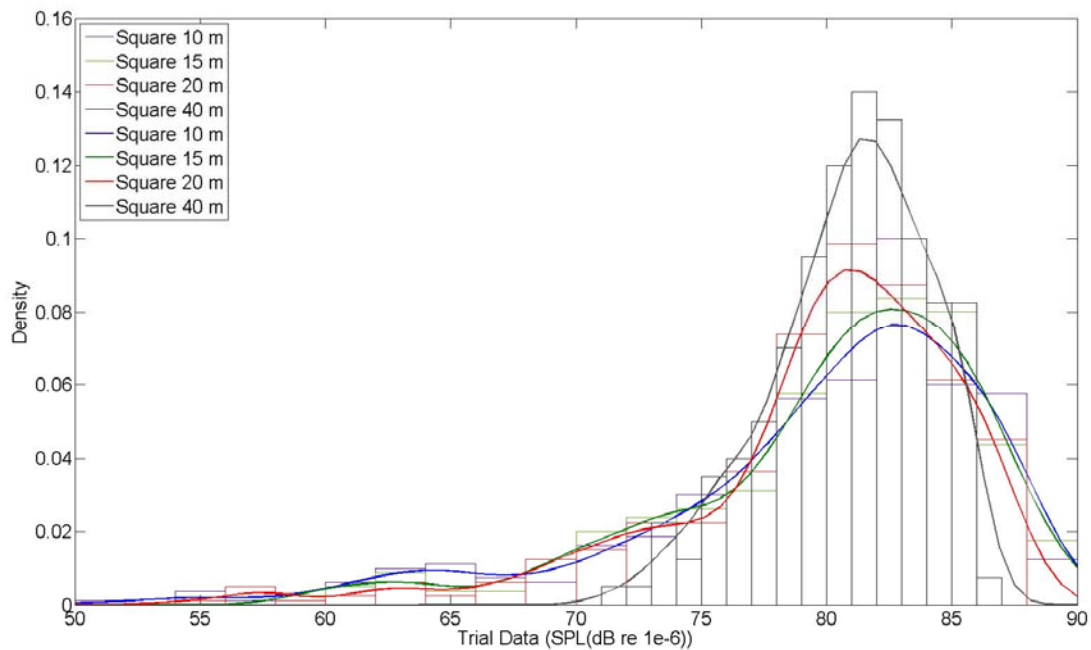


Figure 6-19: Probability density/distribution function for the four square array spacings at a range of 3000 m

The trends in distributions seen here are similar to that of the triangular array. Based on the 400 random phase change trials, there is a higher probability of seeing a larger SPL compared to a lower one. Also, the probability distribution functions narrow

as array spacings increase implying that the likelihood of having a wider range of SPL is higher for a square array that is more closely spaced than one that is spaced further apart.

Hexahedral Array

A hex array configuration with a seventh source in the middle is the next configuration considered. This configuration is similar to a staggered grid arrangement that many wind turbine arrays utilize. Results of the 400 trials for the hex array are shown in Figure 6-20.

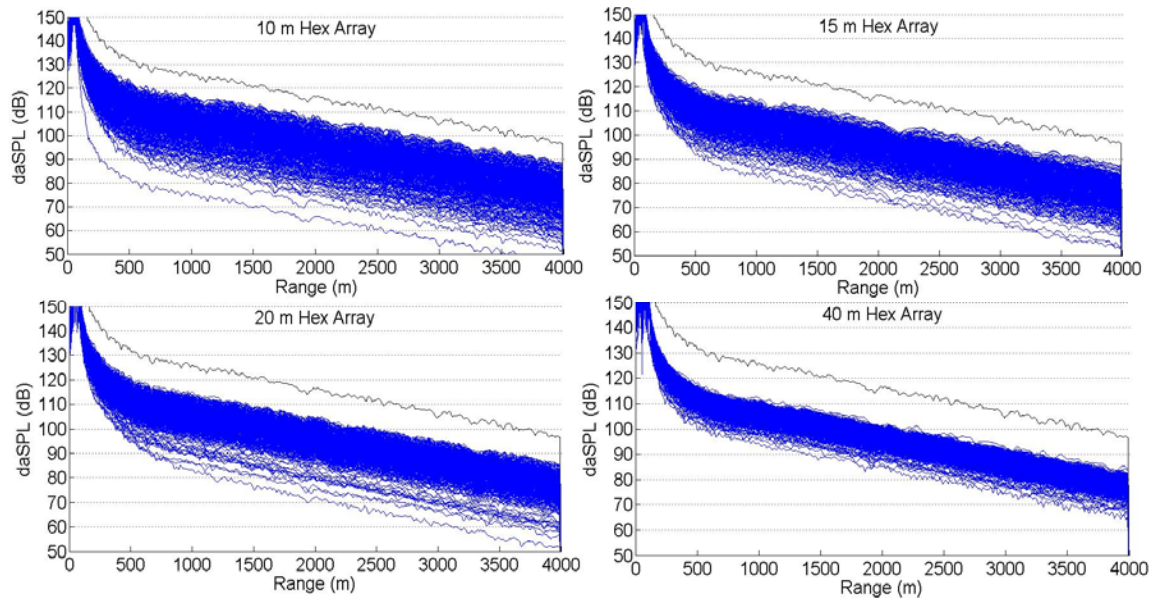


Figure 6-20: Depth Averaged SPL (dB Re 1e-6 Pa) of water column for hex Array with Random Phase Change

The difference between the conservative single source at the array center with a source amplitude multiplied by 7 and the upper bound of the band of SPLs for a random phase change is about 7.4 dB for a 10 m spacing, 9.4 dB for a 15 m spacing, 9.7 dB for a

20 m spacing, and 12 dB for a 40 m spacing. The banding of SPL has a range of about 44.0 dB for 10 m spacing, 31.9 dB for 15 m spacing, 33.5 dB for 20 m spacing, and 18.5 dB range for a 40 m spacing. The mean SPL for all of the hex trials is shown in Figure 6-21 and the means are close to the same. Despite the banding of SPL and trends described about, the average of each trial for each array spacings appear to be very similar.

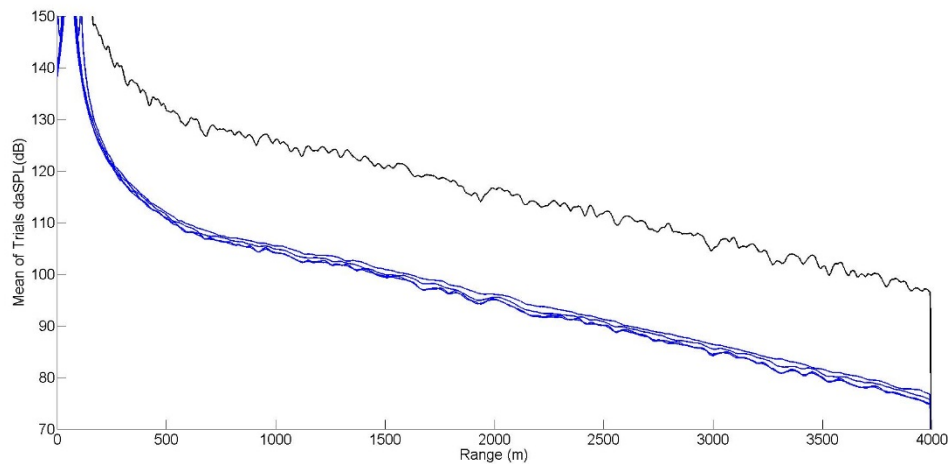


Figure 6-21: Mean depth averaged SPL (dB re 1e-6 Pa) of all hex arrays

The probability density function and corresponding probability distribution function at a range of 3000 m is shown in Figure 6-22. Like previously seen, the distributions show the trend of a narrowing SPL band (depicted as a narrowing of the distribution curves) as array spacing increases. Additionally, there is a sharply decreasing tail of the probability distribution function of higher SPL compared to a shallow decaying tail of lower SPLs.

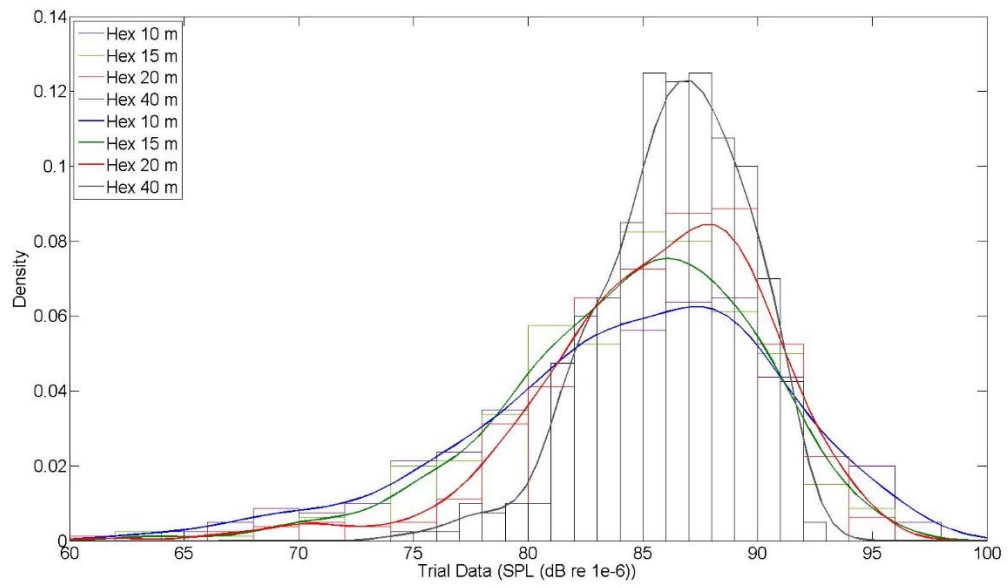


Figure 6-22: Probability density/distribution function for the four hex array spacings at a range of 3000 m

7. HYDRO-ACOUSTIC INTERFACE

With the overall goal of developing a tool and framework for developers and regulators of MHK energy in mind, progress was made to incorporate a hydrodynamic model with the Paracousti acoustic propagation model in order to simulate real world locations with more realistic property values. The hydrodynamic model provides bathymetric information, as well as density, temperature, and salinity values of the water domain that are used to set up an appropriate grid and property values for the acoustic propagation code. While the present work details integration with Sandia National Labs Environmental Fluid Dynamics Code (SNL-EFDC) [42], these tools are model agnostic and require only a new interpretation module to read the outputs from other hydrodynamic codes, such as Delft-3D [43].

An interface code between SNL-EFDC and Paracousti was developed within MATLAB®. Dependent upon the sound frequencies desired for investigation, the cell sizes for Paracousti may be orders of magnitude smaller than those used to calculate the hydrodynamic response of a system. This code takes SNL-EFDC model input data (cell center locations and depths) and interpolates these values onto an appropriately smaller space grid for use in Paracousti. As the hydrodynamic models are geographically large, the entire domain may not be necessary to efficiently compute sound propagation to answer regulatory questions. Based upon the source location and strength, and desired sound level threshold, conservative spreading laws can be used to estimate the required domain size necessary for sufficient acoustic propagation estimates. There is an initial spherically spreading that occurs as the sound waves are unconstrained, as the energy

becomes constrained by the top air-water interface and reflects off the sedimentary layer the spreading becomes cylindrical. The distance that spherical spreading occurs is related to the relative distance of the source from the top air-water interface and sedimentary layer. A domain of interest for acoustic modeling can be formulated from this estimated propagation range. A general schematic of this interface process is shown in Figure 7-1.

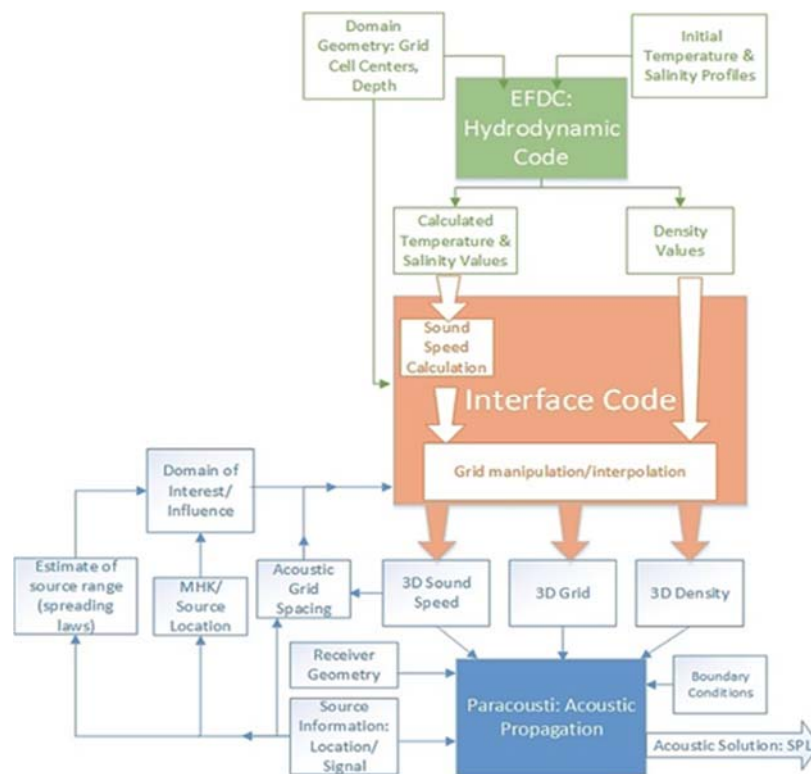


Figure 7-1: General schematic and flow diagram of interface code

A two-dimensional cubic interpolation scheme is utilized to construct the bottom bathymetry of the acoustic domain from information provided by the SNL-EFDC model (cells' center location and depth). Acoustic grid property values (sound speed) can be calculated using temperature and salinity values from SNL-EFDC. Sound speed can be

calculated based on a number of different analytical approximations each with its own level of complexity and range of validity, including one known as the Mackenzie equation [44]:

$$\begin{aligned}
 c(D, S, T) = & 1448.96 + 4.591T - 5.304 \times 10^{-2} T^2 + 2.374 \times 10^{-4} T^3 \\
 & + 1.340(S - 35) + 1.630 \times 10^{-2} D + 1.675 \times 10^{-7} D^2 \\
 & - 1.025 \times 10^{-2} T(S - 35) - 7.139 \times 10^{-13} T D^3
 \end{aligned} \tag{7.1}$$

where D [kg/m³], S [parts per thousand], and T [°C] are the density, salinity, and temperature at a particular (x,y,z) grid location, respectively. The above equation indicates that for a 1°C change in temperature or a 3.5 ppt change in salinity the sound speed changes by about 4 m/s.

Cobscook Bay

To demonstrate the application of the interface code, two acoustic simulations were performed using the Cartesian hydrodynamic grid of Cobscook Bay, Maine. Two different source locations ([10, 10] km & [13, 11] km in [x,y]), an arbitrary range, and continuous 25 Hz source was used. The imported SNL-EFDC grid cell centers and depths of the bay are shown in Figure 7-2. The rectangles represent the bounds of the two different simulations and the interpolated bathymetry for the two different simulations are shown in Figure 7-3 and Figure 7-4. The sound pressure levels in a 2D slice for the x-z and y-z planes located at the source, as well as a depth averaged SPL of the water column are shown in Figure 7-5 and Figure 7-6 for both simulations. It appears that due to the shallow water environment the 25 Hz structure is lost and becomes a smooth profile in range; whereas the sound levels in the sediment layer retain their distinct structure.

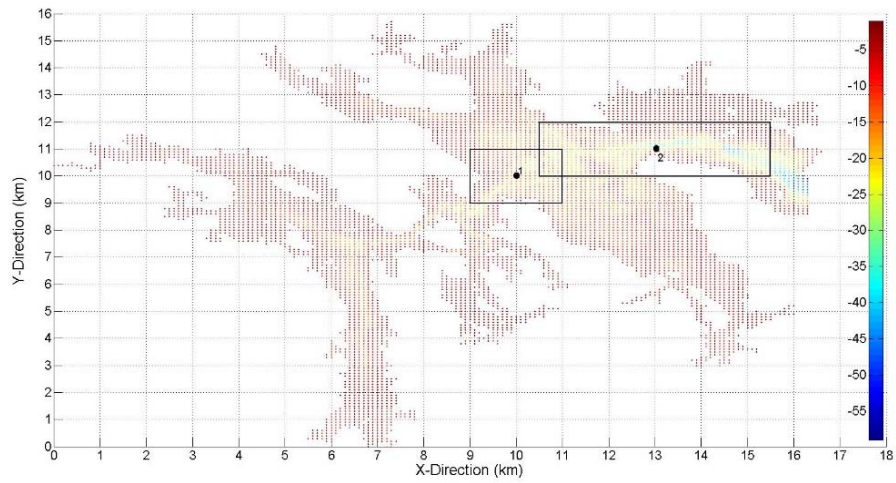


Figure 7-2: Imported EFDC grid cell centers and depths

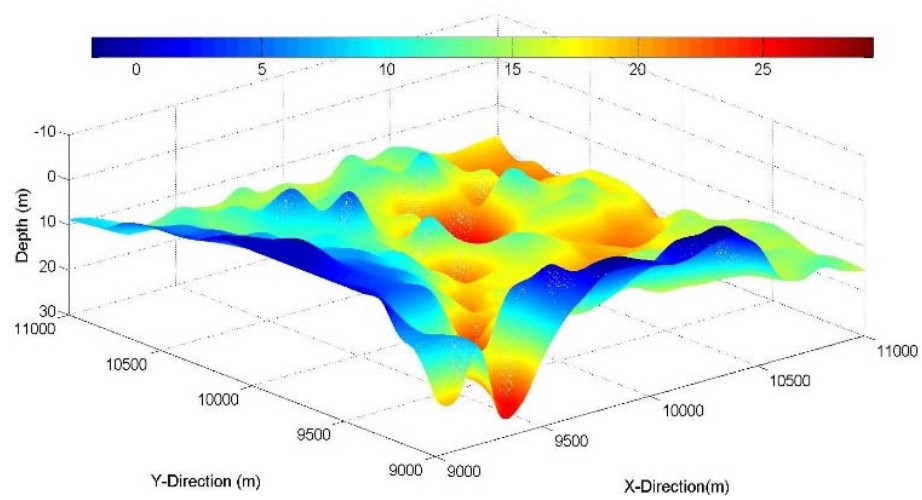


Figure 7-3: Interpolated bathymetry of acoustic domain 1

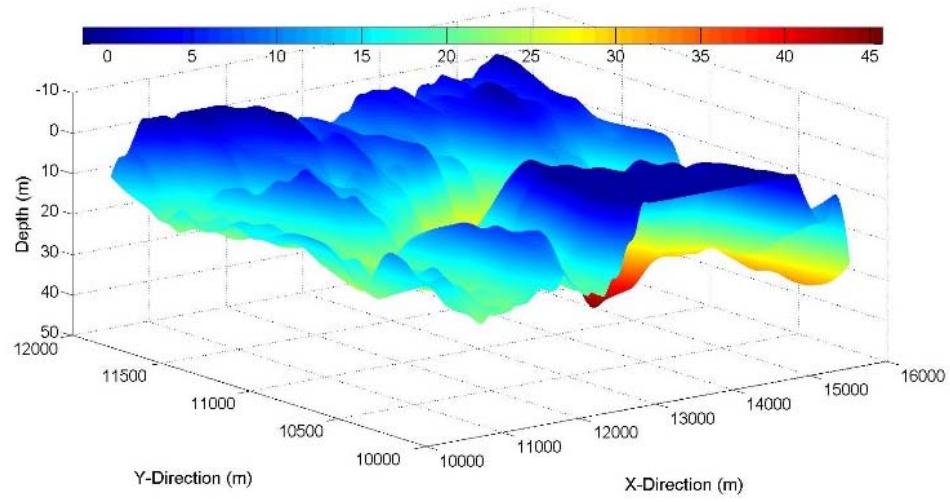


Figure 7-4: Interpolated bathymetry of acoustic domain 2

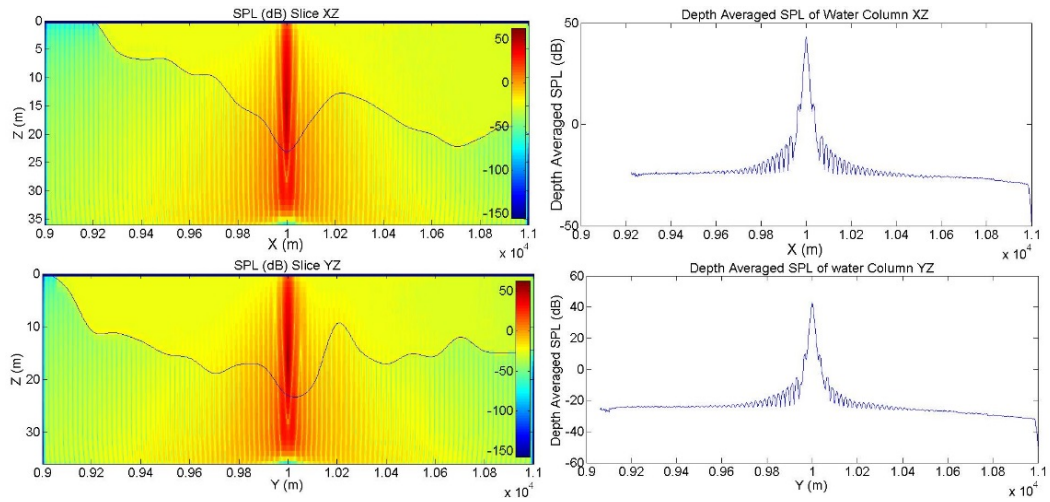


Figure 7-5: SPL Slices and depth averaged SPL of water column in XZ and YZ planes for acoustic domain 1

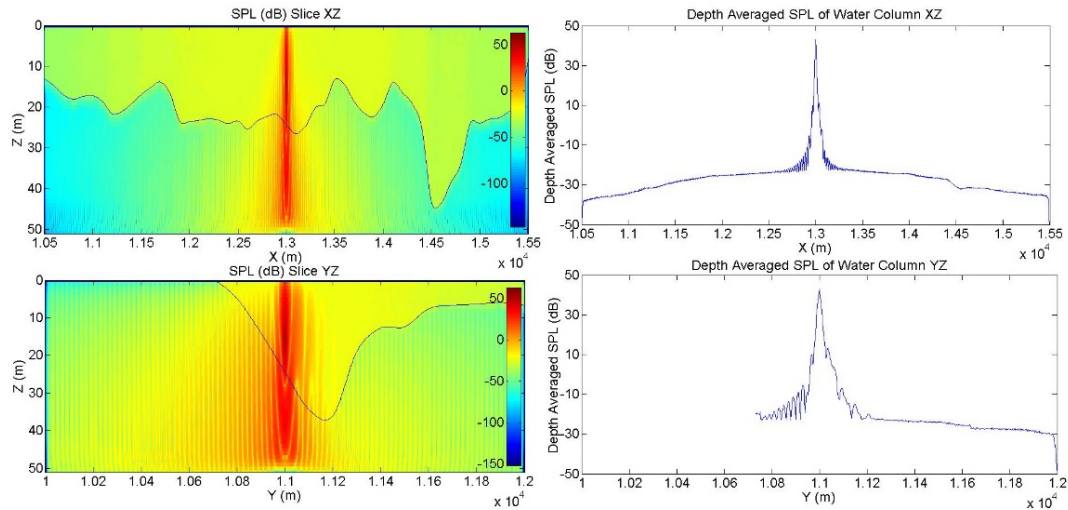


Figure 7-6: SPL Slices and depth averaged SPL of water column in XZ and YZ planes for acoustic domain 2

Comparison with Parabolic Equation

A comparative simulation was performed to show how a 3D solution from Paracousti differs from a 2D range dependent Parabolic equation code (RAM). The objective of this comparison is to demonstrate the importance of a 3D solution to accurately quantify the acoustic propagation through a complex MHK relevant domain. The domain, separate from Domains 1 and 2 above, is taken from the Cobscook Bay model and the bathymetry is shown in Figure 7-7. The domain is 4 km in the x-direction and 2 km in the y-direction with the domain center located in the Cobscook Bay model (Figure 7-2) at 14 km in the x-direction and 11 km in the y-direction. The 3D bathymetry file for use in Paracousti was reduced to a 2D range dependent domain for use in RAM by taking a 2D slice at a y-location of 11 km. This 2D bathymetry profile is shown in Figure 7-8. The source is a continuous sinusoid of 300 Hz located at 12 km in the x-direction and 11 km in the y-direction.

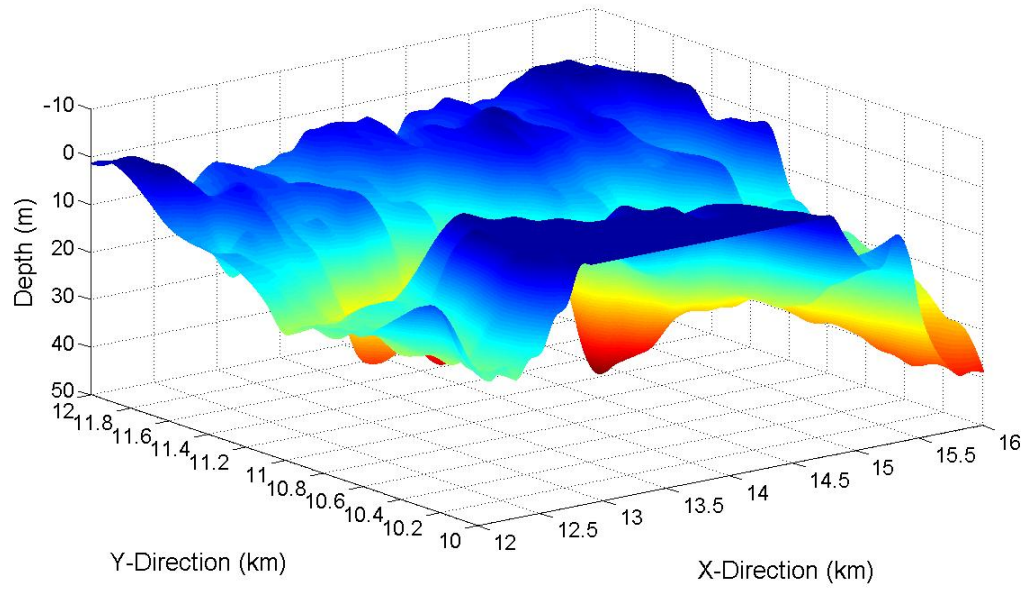


Figure 7-7: Bathymetry of Cobscook Bay Domain for 3D Paracousti vs 2D ram

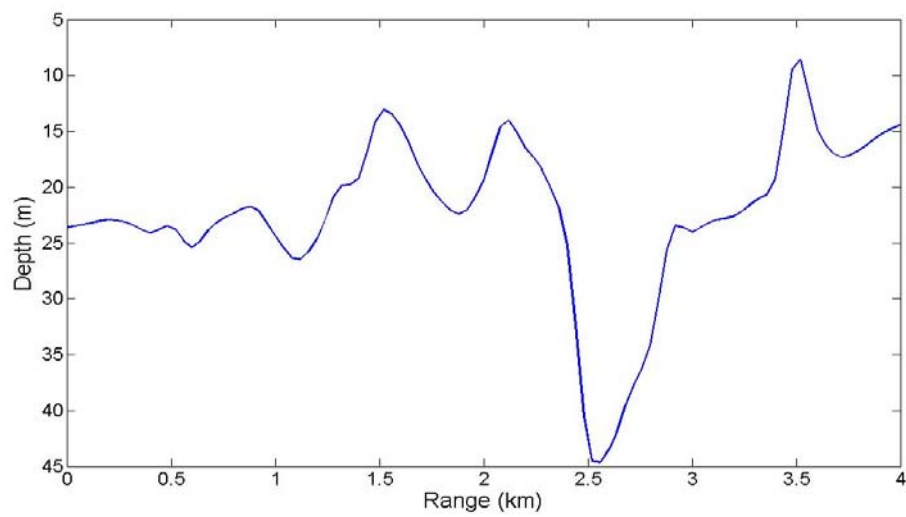


Figure 7-8: 2D Bathymetry taken at $y=11$ km for use in RAM

A transmission loss comparison plot is shown in Figure 7-9. As can be seen, and is expected, there is a difference between the 3D paracousti solution and the 2D RAM PE solution. While the two solutions have relatively similar magnitudes of TL, the patterns of decay are quite different. These differences are most notable at a range of 1000, 1500, and 2000 m where the two solutions deviate by as much as 30 dB. The divergence of the two solutions come from the inherent difference in a 2D versus 3D model. The 2D solution lacks additional reflections and interference that occur from the additional bathymetry and seabed geometry that is included in a 3D model.

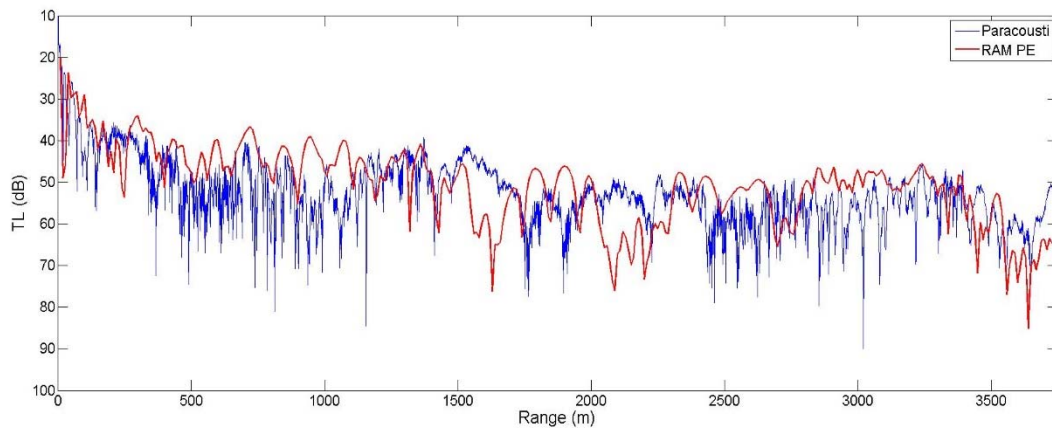


Figure 7-9: Comparison of Transmission Loss dB (re 1 m) results from Paracousti with Ram PE

8. FUTURE WORK

The work presented here is only a start in the development of an acoustical and ecological tool specific towards the field of MHK technology and has shown some interesting trends and correlations. There is a large potential for future work. This chapter outlines some recommendations for future work both involving the acoustic propagation algorithm Paracousti and the overall modeling tool/framework.

Improvements to Paracousti Algorithm

Attenuation

Some of the energy in propagating sound is transformed into heat through molecular absorption and additional losses come from the scattering of sound by different kinds of inhomogeneities. Both of these losses are included in attenuation, a gradual loss in intensity of energy flux, and can have quite a large impact on energy transmission and acoustic propagation in a marine environment especially at long ranges and for high frequencies. This is an important loss mechanism that should be included when considering acoustic propagation for MHK applications. Until recently, the paracousti algorithm did not include attenuation including molecular absorption (loss of energy in the form of heat) and inhomogeneous scattering in its calculations. A computationally efficient means of modeling attenuation has sense been added to the model. The attenuation calculations model the fluid as being a grid of many springs and dampers and is a technique borrowed from seismology. It allows fitting a fairly arbitrary loss versus. frequency curve into parameters that characterize standard linear fluid mechanics. 3D

variations in attenuation can be implemented into the model. Verification and validation of the attenuation calculations in Paracousti is necessary first but should provide accurate representation and calculations of attenuation.

Variable Grid Spacing and Non-Rectangular Domains

Currently Paracousti model grids and finite difference calculations are limited to a uniform grid ($dx=const_1$, $dy=const_2$, $dz=const_3$). It is advantageous to allow for a non-uniform grid spacing were the spacing between grid nodes is allowed to vary in all three directions based on the localized sound speed. For a medium that has a higher sound speed, a larger grid spacing is possible while still achieving the required grid nodes per wavelength. This has the potential to reduce the number of grid nodes in the model and thus reduce computational time.

The CPML boundary condition implemented at the boundaries of the computational domain are used to damp out unwanted reflections back into the domain and are critical to the accuracy of the solution. The current implementation of this boundary in Paracousti is limited to the 6 flat sides of the 3D domain and thus can create quite a large number of unnecessary grid nodes in a model. For example, in the hydro acoustic interface section, Figure 7-5 and Figure 7-6, show a large amount of sea bed material that was included in the model due to the current limitation of the strictly 6-sided domain. Because there is a deep valley in the bathymetry a large number of unnecessary sea bed grid nodes for the rest of the shallower bathymetry points is required. A domain that is not limited to be strictly a 3D rectangle and that can include a sloped side would be advantageous. It would allow the domain and boundary conditions to better follow

bathymetry and reduced the number of unneeded grid nodes in the sea bed material thus reducing overall domain size and computation run time.

Finite Difference Coefficients

Work from others on optimizing finite difference coefficients for Paracousti has resulted in a technique to minimize the required number of grid nodes per wavelength given a certain maximum error bound and minimization criteria [45]. Since computational cost and runtime is proportional to node spacing to the fourth power, even a relatively small decrease in the required number of grid-nodes-per-wavelength can have a large impact on runtime and computational requirements. A nearly tenfold reduction in run time has been reported for several different test cases. This is extremely advantageous when dealing with a large domain that is most likely required in these MHK applications. While this work utilized a generic finite difference coefficient optimization, further reduction in the necessary grid-nodes-per-wavelength and time step can be achieved when considering the source profile.

Additions/Improvements to the MHK Tool/Framework

Hydro-Acoustic Interface

Further development and applicability of the hydro-acoustic interface is advantageous. The importation of non-rectangular hydrodynamic grids is an important and necessary step to be able to take pre build hydrodynamic models and make them work for the acoustic propagation algorithm. Furthermore, obtaining accurate values of temperature and salinity values from the hydrodynamic model together with appropriate

equations for sound speed and density input to the acoustic code will increase the accuracy and reliability of the acoustic model to real world developments.

Ecological Response Model

An ecological response model is an advantageous addition to the MHK acoustic tool. While quantifying sound pressure levels in a domain is important to regulator threshold laws, the ability to predict a fish or marine mammal's response to noise is very important. Results from the acoustic model serve as inputs to an ecological response model where certain behavioral patterns are characterized as logical coded statements and a statistical probability can be obtained. Similar to the work done by [33] an hydrodynamic model would provide realistic bathymetric and medium property data to the acoustic propagation code which would in turn provide acoustical sound data to the ecological response model.

Common Language Programming and All-Encompassing Executable

While MATLAB® is a user friendly and relatively easy to use software package for pre- and post-processing of inputs and outputs to and from Paracousti; however, for large models it becomes computational inefficient. Development of an all-encompassing executable that builds the necessary input files and evaluates the output data from Paracousti would be advantageous. The executable would allow arbitrary domains to be built with included inputs for sound speed and density profiles and would allow for an importation of a hydrodynamic model. Also, the executable would automatically

calculate the necessary grid spacing and time step based on the user defined source and inputted sound speed.

9. CONCLUSION

Progress has been made in the overall goal of developing a tool/model/framework for a developer or regulator of MHK technology. After careful consideration of the acoustic propagation techniques and algorithms available, the velocity-pressure (VP) solution based on conservation of linear momentum and Cauchy's equations was selected as the most appropriate technique available for an MHK application. The inherent assumptions and limitations involved with the derivation of the VP system compared to conventional wave and Helmholtz equation based techniques is quite small and allows for a fully 3D solution. While other acoustic propagation techniques are only valid for a specific range of solutions, the VP system works equally well in all applications (provided there is enough computational resources available) and therefore most suitable for the range of MHK devices and deployment locations. The accuracy, robustness, and wide range of applicability makes the VP system a clear choice.

The VP system based acoustic propagation code Paracousti was leveraged for use in this research project. Paracousti was developed for general media and validated for a number of geophysical activities included seismology. The first steps for using this code for an MHK application was to verify results for a hydroacoustic environment for a range of canonical and benchmark scenarios from underwater acoustics. This was accomplished using known analytical spreading law equations as well as results from other established numerical acoustic propagation codes. A spherically spreading pulse in an unbounded domain, a pulse in a 2D shallow water domain, a continuous source in a 2D shallow

water domain, a range independent hyperbolic sound speed profile, and a 3D range dependent sloping bottom case were verified.

Once confidence in the accuracy of Paracousti results in a hydroacoustic environment was established. Research and investigation of MHK relevant scenarios was performed. First, a single source investigation was conducted to better understand the dependence of acoustic propagation and sound levels on a source that is composed of a combination of different frequencies and amplitudes. This was extended into modeling an example MHK source in both a shallow water two-layered media and a large 3D sloping bottom domain. Next, the investigation was extended into multiple sources to help understand the wave interactions and interferences from multiple sources. Multiple two and four source arrays were modeled in paracousti with careful consideration of the device spacing, source frequency and domains sound speed (which determines the sources wavelength) in order to understand how these parameters interact to create constructive and destructive interferences between successive devices. Quite a large difference in sound levels can be obtained by simply changing the device spacing due to sound wave interactions. Next, an investigation of a randomized phase change for each device in an array was performed. Several different array configurations and spacing's lead to initial trends and correlations that will be useful in terms of characterizing the probability of being at a certain sound level and for regulation. Finally, an integration of the acoustic propagation model with a hydrodynamic model to better represent real life scenarios and potential development sites was performed.

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