Environmental Communication Optimization in Underwater Acoustic Sensor Networks

by

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Abstract

In **Underwater Acoustic Sensor Networks (UASNs)** maintaining communication integrity is a significant challenge. This is largely due to the adverse physical properties of the medium of communication. The acoustic properties of an underwater environment change significantly with variations in weather. Despite these variations, the typical environment of an **UASN** remains highly reverberant and prone to multipath propagation.

In order to reduce the negative impact on communication integrity in **UASNs** it is necessary to evaluate the impact of different types of communication devices, and determine if there are ways to minimize the detrimental effects of the medium on communication by taking advantage of the same physical properties that reduce communication integrity.

Herein, several types acoustic transducers are evaluated over a range of simulated transmission distances. The results of this heuristic analysis lead to the formulation of a methodology by which communication can be optimized by using a change in depth. This methodology is heuristically verified using a combination of empirically gathered and simulated data.

To my mother and father, for giving me life; a love of science; and an ample supply
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Contents

Abstract	ii
Table of Contents	iv
List of Tables	vii
List of Figures	viii
1 Introduction	1
1.1 Communicating Underwater	2
1.2 Objectives	3
1.3 Contributions	4
1.4 Thesis Organization	5
2 Communicating at Great Distances	7
2.1 Device Beam Patterns	8
2.1.1 Parameters of The Thin Cylindrical Line Transducer	8
2.1.2 Beam Pattern Derivation of a Circular Piston Transducer	11
2.1.3 Beam Pattern Analysis	14
2.2 Waveguide Model of the Underwatere Acoustic Medium	16
2.2.1 Boundary Conditions	17

2.3	Medium-Advantageous Optimization	17
2.3.1	Beam Focus Signal Coupling	18
2.3.2	Spatially Displaced Signal Coupling	19
3	Communicating at Great Distances	20
3.1	Key Concepts	21
3.2	Simulation Design	22
3.2.1	Environmental parameters	23
3.2.2	Types of Transmitters	25
3.2.3	Determining Positive Results	27
3.3	Simulation Evaluation	27
3.4	Conclusion	30
4	Formulating a Better Approach	31
4.1	Developing the Effective Projector	32
4.2	Defining the Effective Projector	35
4.2.1	Adding a Window of Opportunity	39
4.2.2	Considering a Source Beam Pattern	43
4.3	Effective Projector & Signal Modulation	45
4.4	Conclusion	46
5	Node Depth Optimization	47
5.1	A Methodology for Node Depth Optimization	47
5.2	Depth Precision	48
5.3	Test One: Ideal Conditions	49
5.4	Test Two: Summer in The Bedford Basin	54
5.5	Test Three: The Bedford Basin with Ice	58

5.6	Test Four: Bedford Basin Winter	60
5.7	Test Five: Simulated Winter with 80 % Ice	63
5.8	Conclusion	63
6	Concluding Remarks	66
6.1	Optimization Through Beam Focusing	66
6.2	Node Depth Optimization	67
6.3	Future Work	67
6.4	Final Words	68
	List of References	72

List of Tables

4.1	Vertical cuts made by reflections through the medium.	35
5.1	Relationship Between Depth and Measurement	49
5.2	Arrival metrics for a source and receiver depth of 10 m.	52
5.3	Arrival metrics for a source at 200 m and receiver at 10 m.	53

List of Figures

1.1	Types of Rays.	3
2.1	Formulating the beam-pattern of a line transducer.	9
2.2	Formulating the beam-pattern of a circular piston transducer.	12
2.3	Beam Patterns for Thin Cylindrical Transducers of Varying Length.	15
2.4	Beam Patterns for Circular Piston Transducers of Varying Length.	15
3.2	Upward Refracting Sound Speed Profile (SSP)	25
3.3	Downward Refracting SSP	25
3.4	Isovelocity SSP	26
4.1	An Arbitrary Waveguide with Source and Receiver at Equal Depth.	32
4.2	Source and Receiver Interval Movement Toward Receiver.	33
4.3	Source and Receiver Interval Movement Toward Source.	34
4.4	Multiple Reflections for Source and Receiver at Equal Depth.	35
4.5	General Case of a Ray Approaching R from Below.	36
4.6	General Case of a Ray Approaching R from Above.	37
4.7	General Case of a Ray Approaching R from Above with an Error Window.	39
4.8	General Case of a Ray Approaching R from Above with an Error Window.	39
4.9	Possible Cases for a ray Arriving at a Receiver with an Error Window.	40
4.10	Defining the departure angle.	44
4.11	Two possible beam patterns.	45

5.1	Eigenrays between a source and receiver at extremes in an idealized environment.	50
5.2	BER heat-map of an ideal environment.	51
5.3	Raw BER data Corresponding to Figure 5.1a and Figure 5.1d, respectively.	55
5.4	SSP of the Bedford Basin.	56
5.5	Eigenrays between a source and receiver at extremes in the Bedford Basin, summer environment.	57
5.6	BER heat-map of the Bedford Basin environment.	58
5.7	Eigenrays between a source and receiver at extremes in the Bedford Basin, summer environment with 80% ice cover.	59
5.8	BER heat-map of the Bedford Basin environment with ice cover. . . .	60
5.9	Eigenrays between a source and receiver at extremes in the Bedford Basin, winter environment.	61
5.10	BER heat-map of the Bedford Basin environment with winter conditions.	62
5.11	Eigenrays between a source and receiver at extremes in the Bedford Basin, winter environment with ice cover.	64
5.12	BER heat-map of the Bedford Basin environment with winter conditions & ice cover.	65

Chapter 1

Introduction

Canada, by total area, is the second largest country in the world, and is bordered on three sides by oceans. Traditionally, the massive bodies of water surrounding the nation have provided some level of natural border protection. In part, the oceanic borders have contributed to the young age of the country; the result of impeded travels through arduous conditions. However, the improvement of marine technology has reduced the level of security provided by the oceanic waters, and their presence is rapidly becoming a security encumbrance. Indeed, the fractal nature of Canadian shorelines, their vast lengths, and in some regions, inhospitable weather conditions have begun to pose a threat as marine technology improves. No longer do these oceanic borders provide Canada with a suitable level of security against possible threats. This reality is becoming increasingly obvious with the introduction of cruises through the Canadian arctic [14].

The insecurity of Canadian oceanic borders leads to the requirement of new technologies to monitor and protect these vast borders. A lack of reliable satellite coverage, in the arctic region of Canada poses a communication difficulty which is compounded by the harsh climate. This leads to the requirement of technologies which are capable of providing a boundary topology with a great deal of distance between mobile

agents, that can only communicate using underwater acoustics [12]. The requirement for acoustic signal transduction is the result of the high relative permittivity of water, a physical phenomenon, which causes electromagnetic transmissions to attenuate at distances which would render electromagnetic wireless communication implausible. As such one must define what underwater communication requires.

1.1 Communicating Underwater

In order to communicate underwater there must be some device which converts a digital signal to an analog electrical output which in turn drives a device that transduces the electrical potential energy into mechanical potential energy. The mechanical potential energy being considered is a pressure wave which propagates through the water, eventually arriving at the receiver. The receiver then converts the mechanical potential energy back to electrical potential energy and eventually back to a digital signal which contains the sent information. The device that performs this task is the hydro-acoustic modem. The component in the modem which is responsible for sending the acoustic pressure wave is the hydro-acoustic projector, herein referred to as a projector, and the component which receives the pressure wave is the hydrophone. In many cases, a hydro-acoustic modem utilizes the same transduction device to operate as a projector and hydrophone, much like a radio transceiver.

Unlike electromagnetic waves, acoustic waves require a medium to propagate, leaving a projector and hydrophone at the mercy of the environment in which they are submerged. In the case of arctic ocean waters, the propagation medium is relatively shallow, and prone to reflection/refraction. The speed at which sound travels through the medium is also nonconstant, and as such the sound wave is subject to bend towards either the surface or towards the bottom, as illustrated in Figure 1.1. The

effects of the environment are discussed in further detail in subsequent chapters.

Figure 1.1: Types of Rays.

- (a) A reflected ray, a ray where the incident angle is equal to the angle of reflection.
- (b) An eigenray. A type of ray where there are no reflections/refractions.
- (c) A refracted ray, a ray where the incident angle is not equal to the angle of refraction.

1.2 Objectives

The goal of the work herein is to determine if it is possible to improve communication between sensors in an Underwater Acoustic Sensor Network by analyzing two techniques to reduce losses through the acoustic channel. One technique regards the use of projector properties to determine if it is possible to reduce loss by reducing signal dispersion, as seen in Chapter 3. The other technique seeks to take advantage of the waveguide properties of the Underwater Acoustic Medium (UAM) to reduce loss, as follows in Chapter 5.

Testing the operation of various directional transducers under experimental conditions provides a clear understanding of the effect of directivity on signal transmission and reception in underwater acoustic communication networks, a topic which is

difficult to find information on due to the proprietary nature of projector design. Furthermore, testing these conditions on horizontally separated communications offers a new perspective on the efficacy of directional signal transmission, since much of the available research focuses on vertically separated devices. A common case in existing practical environments such as military applications and offshore oil platforms.

In Chapter 3, the projector and hydrophone beam-patterns will be considered more closely to determine how projector design can be used to improve signal transmission in long-range hydro-acoustic communication. The efficacy of the devices under test conditions is determined by the **Bit Error Rate (BER)** with respect to the **Energy per Bit to Noise Power Spectral Density (E_b/N_0)**. This metric is used because it relates the **BER** to the amount of energy put into each bit of a transmission. Other metrics, such as the number of arrivals produced by a ray-trace, discussed in Chapter 2, are not definitive.

In Chapter 5, an alternative approach to improving communication is evaluated by taking advantage of the waveguide properties of **UAMs**. In this technique the depth of a transmitting node is varied to determine the set of depths corresponding to optimized communication. The concept hinges on the idea that the signal spreading and multipath propagation effects can, to some extent, be leveraged to improve communication, as seen from the analysis of ideal waveguides in Chapter 4.

1.3 Contributions

A comparative evaluation of the effectiveness of different types of transducers in a simulated arctic environment is conducted under various experimental conditions, detailed in Chapter 3, to the affect of showing that a projector with a directional flextensional beam-pattern, provides a marginal reduction in **BER** with respect to

E_b/N_0 , regardless of horizontal separation in an environment, with a downward refracting sound speed profile. This indicates that a directional transducer is less likely to create the destructive phase-delays that increase BER when using Binary Phase Shift Keying (BPSK), or any type of phase-shift keying. This is a surprising result because one would expect that as the separation between the projector and hydrophone increased, then the projector Beam Pattern (BP) would approach an isotropic BP, much in the way that a beam of light from a flashlight appears as a dot from a distance.

Of the various projector designs considered in environments with upward refracting and isovelocity SSPs, the directional flextensional and four-wavelength long Thin Cylindrical Line Transducer (TCL) operate in a manner which is statistically similar to an isotropic source, as discussed in Chapter 3.

The effects of directional devices are limited in their ability to improve communication in any of the tested environments, as seen in Chapter 3. As such a methodology to optimize communication through manipulating the node depth is designed to provide meaningful improvements in the quality of communication, as conceptualized in Chapter 4 and discussed in Chapter 5. Statistical interpolation is used to reduce the measurement complexity of this methodology to reduce the number of measurements in exchange for precision.

1.4 Thesis Organization

The organization of the chapters herein will be presented in terms of the practical and theoretic background of underwater communication, succeeded by the experimental model used to determine the efficacy of varying levels of directivity in order to improve the transmission quality along an acoustic channel and the types of hydro-acoustic

projection devices capable of producing the desired effect. This experimental model is followed by an analysis of waveguide properties and their effects on the range of angles for successfully transmitted beams. Finally, an approach to optimize transmission through an acoustic medium by taking advantage of the waveguide properties is presented, analyzed, and evaluated.

Specifically, Chapter 2 explores the mathematical background required to understand operation of the devices and waveguide modes under consideration. Chapter 3 details the methods used to generate experimental models, and explores those models; explaining the usage of tools, and metrics for simulation, which are used to evaluate results. Chapter 4 explores the principles of waveguide operation and explains some reasons for the results observed in Chapter 3 while discussing the first principles required to understand the technique formulated in Chapter 5. Chapter 5 formulates a methodology to optimize sensor performance by using operating depths that take advantage of the physical phenomenon responsible for the acoustic channel. The later portion of this chapter evaluates the technique and exemplifies how resilient the methodology is to high noise environments. Finally, concluding with Chapter 6 where the possibility of future works in investigating algorithms and other methods to achieve optimal communication.

Chapter 2

Communicating at Great Distances

Due to the communication-opaque and highly variable nature of an aquatic transmission channel **UASNs** are unable to transmit data as rapidly as their wireless-radio counterparts. The aquatic medium is highly reflective, causing destructive alterations to signals being transmitted. Additionally, sound in water is able to travel hundreds, sometimes thousands, of kilometers which means the noise from vessels, or cracking ice, can cause perturbations in a communication system from afar. Unfortunately, the extent of problems in underwater acoustics is not limited to a highly variable environment. Even if the medium was perfectly calm there are still large latencies in communication; a result of the slow speed of sound in water, approximately only 1500 m/s [18]. The result being an environment in which typical wireless-communication protocols are not possible as of yet.

There has been a great deal of scientific endeavor around modeling the **UAM** as a waveguide, which is necessary for signal processing applications [17]. The physical design parameters of hydroacoustic devices have also seen decades of research for the purposes of military telemetry, marine biology, oil platforms, and early detection and warning systems for natural disasters [4]. The fundamental concepts of device design are discussed in Section 2.1. The fundamental concepts regarding the parametric

analysis of the **UAM** are discussed in Section 2.2.

2.1 Device Beam Patterns

To compute the **BP** of a hydroacoustic projector, one must consider each point on the transducer as a single isotropic radiator; in other words, each point of the transducer is considered to be a source of wave-radiation in a uniform sphere. The next step is to select some point at a distance far away enough that it can be considered to be in the *Fraunhofer Region*, which is also referred to as the far-field region [18]. This will simplify the calculation, and produce a **BP** that will be useful, since normal operation will often take place in the far-field. Once this point, P , is selected one must integrate the effective pressure at P from every point on the transducer. The pressure, and transducer surface, being vector quantities it follows that the integrand is the dot product of the pressure and unit surface. Specifically, the integrand is, for all cases herein, $\vec{p} \cdot d\vec{S}$.

This section considers the derivation of the **BP** of two transducers, for the purpose of clarifying the fundamental principles of designing a transducer. The transducers discussed in this section are the **TCL** and the **Circular Piston Transducer (CPT)**.

2.1.1 Parameters of The Thin Cylindrical Line Transducer

The simple **TCL** is the first geometric shape being considered, since it can be modelled in only two dimensions, which is simple in comparison with the **CPT**. The geometric set up of the **TCL** is as follows in Figure 1, where:

- P is the point where the pressure is being detected.
- θ is the angle from the centre of the transducer.

- r is the distance from the centre of the transducer to the point P .
- $d\delta$ is the area of the infinitesimal isotropic point source.
- r' is the distance from $d\delta$ on the transducer to the point P .
- δ is the distance of the point source from the centre of the **TCL**.

Figure 2.1: Formulating the beam-pattern of a line transducer.

Thus, the differential pressure, $dp(\theta, r')$, as a function of the angle, θ , and the distance from the point source to the point of measurement, r' , is as seen in equation (2.1).

$$dp(\theta, r') = \frac{2\pi A d\delta}{r'} e^{j(\omega t - kr')} \quad (2.1)$$

Where:

- A is the signal amplitude.

- k is the wavenumber.

This equation can be simplified to be in terms of only θ by making an approximation for r' which works under the assumption that the point of measurement is in the Fraunhofer Region, in other words $r \gg L$. Thus $r' \approx r - \delta \sin \theta$, then the differential pressure becomes a function of θ alone as seen in equation (2.2), and the error caused by the approximation is small enough to be insignificant.

$$dp(\theta) = \frac{2\pi A d \delta}{r'} e^{j(\omega t - kr + \delta \sin \theta)} \quad (2.2)$$

It is now possible to solve the integral of (2.2) and arrive at an expression for the pressure as a function of θ .

$$p(\theta) = \frac{2\pi AL}{r} \left[\frac{\sin(\frac{kL}{2} \sin \theta)}{\frac{kL}{2} \sin \theta} \right] e^{j(\omega t - kr)} \quad (2.3)$$

Now that the equation for pressure has been established it can be intuitively understood that, if one were able to remove the effect from physical pressure, all that would be left is the BP. Equation (2.4) shows the derivation for the BP of TCL transducers.

$$bp(\theta) = \left(\frac{p(\theta)}{p_0} \right)^2 = \left[\frac{\sin(\frac{kL}{2} \sin \theta)}{\frac{kL}{2} \sin \theta} \right]^2 \quad (2.4)$$

Where:

- bp is the BP.
- p_0 is the pressure evaluated at $\theta = 0$.

From equation (2.4) the half power beam width can be computed by solving for θ when $bp(\theta) = 0.5$. By methods of a look-up table the value of x is observed in (2.6) and

used to compute the value of θ corresponding to the half power beam width. Recalling that the wavelength, λ , is related to the wavenumber, k , by a proportionality constant of $\frac{1}{2\pi}$ (2.7) is rearranged to compute the half power beam width in terms of the wave length (2.8) with some exhaustive operations shown in between.

$$bp(\theta) = \left(\frac{p(\theta)}{p_0} \right)^2 = \left[\frac{\sin(\frac{kL}{2} \sin \theta)}{\frac{kL}{2} \sin \theta} \right]^2 \quad (2.5)$$

$$x = \frac{\pi}{2.26} \quad (2.6)$$

$$\sin \theta = \frac{2\pi}{(2.26)kL} \quad (2.7)$$

$$\theta = \arcsin \frac{0.443}{L/\lambda} \quad (2.8)$$

2.1.2 Beam Pattern Derivation of a Circular Piston Transducer

The method for finding parameters such as pressure, BP, and half power beam width of a TCL is no different than what must be done to find those parameters with a CPT. In order to compute the pressure output by a CPT, first one must observe the geometric set up required to compute the $dp(\theta)$ integrals as follows in Figure 2.2. Where:

- P is the point where the pressure is being detected.
- θ is the angle from the centre of the transducer to r along the horizontal axis.
- ϕ is the angle from the centre of the transducer to dS along the vertical axis.
- r is the distance from the centre of the transducer to the point P .
- dS is the surface area of the infinitesimal isotropic source ($dS = \rho d\rho d\phi$).

Figure 2.2: Formulating the beam-pattern of a circular piston transducer.

- r' is the distance from dS on the transducer to the point P .
- ρ is the distance from the centre to dS along the disk.

From the geometric interpretation of the pressure exerted on a point of measurement, P , the integrand of the pressure function takes the same form as that of equation (2.1). Under the assumption that P lies somewhere in the Fraunhofer Region one may assert that the radius of the CPT is much less than that of the distance to the point of measurement, P , namely one may use the assumption that $r \gg a$, equivalently $r' \gg a$. This allows the approximation $r' \approx r - \rho \cos \phi \sin \theta$. It becomes obvious that solving for pressure, p , requires more advanced techniques than that of the pressure of the TCL. The first step is to recognize a separation of the integrand to make clear a relationship with the Bessel function of the first kind, as seen in equation (2.10) it becomes obvious that the function of pressure simplifies to equation (2.11),

finally resulting in the function of pressure of a **CPT** in equation (2.12).

$$dp(\theta, r') = \frac{2\pi AdS}{r'} e^{j(\omega t - kr')} \quad (2.9)$$

$$dp(\theta) = \frac{A}{r} e^{j(\omega t - kr + k\rho \sin \theta \cos \phi)} \rho d\rho d\phi \quad (2.9)$$

$$p(\theta) = \frac{A}{r} e^{j(\omega t - kr)} \int_0^a \rho \left\{ \int_0^{2\pi} e^{jk\rho \cos \phi \sin \theta} d\phi \right\} d\rho \quad (2.10)$$

$$p(\theta) = \frac{A}{r} e^{j(\omega t - kr)} \int_0^a \mathbf{J}_0(k\rho \sin \theta) \rho d\rho \quad (2.11)$$

$$p(\theta) = \frac{A}{r} e^{j(\omega t - kr)} \left[\frac{\mathbf{J}_1(ka \sin \theta)}{ka \sin \theta} \right] \quad (2.12)$$

Where:

- A is the signal amplitude.
- k is the wavenumber.

Applying the relationship between pressure and **BP** as seen in equation (2.4). The **BP**, bp , is as follows in equation (2.13).

$$bp(\theta) = \left(2 \frac{\mathbf{J}_1(ka \sin \theta)}{ka \sin \theta} \right)^2 \quad (2.13)$$

Recalling that the half power beam width is computed by solving for the value of θ where $bp(\theta) = 0.5$. Through the use of look up tables for $\mathbf{J}_1(x)$ one identifies that $bp(\theta) = 0.5$ when $ka \sin \theta = 1.6$ as seen in terms of wavelength, λ in equation (2.14)

and in terms of wavelength and diameter, d , in equation (2.15).

$$\left(2 \frac{J_1(ka \sin \theta)}{ka \sin \theta}\right)^2 = 0.5$$

$$ka \sin \theta = 1.6$$

$$\theta = \arcsin \frac{1.6}{ka}$$

$$\theta = \arcsin \frac{0.255}{a/\lambda} \quad (2.14)$$

$$\theta = \arcsin \frac{0.509}{d/\lambda} \quad (2.15)$$

2.1.3 Beam Pattern Analysis

The **BPs** which have been analyzed thus far correspond to the **TCL**, **CPT** and cardioid transducers. Starting with the simplest transducer, the **TCL**, the **BPs**, directivity index, and half-power beam widths corresponding to three common transducer lengths (L) are as follows in the **BP** plots of Figure 1. The **BP**, Equation (2.16), is used to compute the half-power beam width by finding values of θ where the beam pattern is half the maximum, Equation (2.17), and doubling that angle. The same technique is used for the other arrays discussed herein.

$$bp(\theta) = \left[\frac{\sin\left(\frac{kL}{2} \sin(\theta)\right)}{\frac{kL}{2} \sin(\theta)} \right]^2 \quad (2.16)$$

$$\theta = \arcsin \left(\frac{0.443}{L/\lambda} \right) \quad (2.17)$$

The **CPT BP** is considerably more complex and relies on a Bessel function of the first kind, as seen in equation (2.17). Instead, the focus will be on the **BPs** which can

(a) Beam pattern where:
 $L/\lambda = 1$
 $DI = 39.34dB$
 $BW_{3dB} = 52.59^\circ$

(b) Beam pattern where:
 $L/\lambda = 2$
 $DI = 50.25dB$
 $BW_{3dB} = 25.59^\circ$

(c) Beam pattern where:
 $L/\lambda = 4$
 $DI = 62.62dB$
 $BW_{3dB} = 12.7^\circ$

Figure 2.3: Beam Patterns for Thin Cylindrical Transducers of Varying Length: it is important to pay special attention to figure (c) since the large DI and narrow BW will be useful for testing the benefits of directional transducers.

be seen in Figure 2.

$$bp(\theta) = \left(\frac{2J_1(ka \sin \theta)}{ka \sin \theta} \right)^2$$

Analyzing these transducer **BPs** in simulated environments show a reduction of

(a) Beam pattern where:
 $2a/\lambda = 1$
 $DI = 167.52$
 $BW_{3dB} = 61.24^\circ$

(b) Beam pattern where:
 $2a/\lambda = 2$
 $DI = 161.43$
 $BW_{3dB} = 29.51^\circ$

(c) Beam pattern where:
 $2a/\lambda = 4$
 $DI = 155.09$
 $BW_{3dB} = 14.63^\circ$

Figure 2.4: Beam Patterns for Circular Piston Transducers of Varying Length: where a is the radius of the transducer.

total arrivals at the receiver. However, the understanding provided by simulations is limited, which leads for the desire to design and test a prototype in lab environments for the collection of data regarding noise and signal profiles. The collection of noise and signal patterns is especially useful for calculating the device gain, a more general case of the DI, which is a much better metric for understanding how the transducer will operate in field conditions.

2.2 Waveguide Model of the Underwatere Acoustic Medium

There are two main types of operation in an UAM, and both are concerned with making reasonable assumptions regarding the speed of sound in the medium. Generally, one distinguishes between shallow-water and deep-water operation. In shallow-water the depth is approximately the same length as one wavelength and as a result the speed of sound can be assumed to be constant. Unlike shallow-water, deep-water is often many wavelengths in depth and as such the variations in sound speed must be considered. There are general metrics used to determine if a communication system is operating in shallow-water mode [17]. Communication systems typically employ high frequencies such that one can often make the generalization that the system operates in deep-water. In fact, there is no exact measure to determine whether shallow or deep water operation assumptions are required [17]. Due to this fact, analysis from a priori principles will assume shallow-water, constant speed, approximations, whereas heuristic analysis will assume deep-water conditions.

2.2.1 Boundary Conditions

There are other features of the **UAM** that need to be considered when modeling the **UAM** as a waveguide. The boundary conditions determine how a wave interacts with a boundary. There are many types of boundaries, however, those considered herein are vacuum, and attenuative. The vacuum boundary is a simple boundary that perfectly reflects an incoming wave without any loss of force where the angle of reflection is equal and opposite to the angle of incidence. This type of boundary is analogous to the perfect mirror described in optical studies. This type of boundary is useful when modeling an interface between mediums with very different **SSPs**. The attenuative boundary is complex, when compared to the vacuum. It is useful for situations where a ray of sound will penetrate into an absorbing medium where a portion of the force of the incident ray before reflecting the remainder. The angle of reflection is determined by the rate of change of the speed of sound in the medium. Attenuative boundaries are useful to describe a wide variety of interfaces. The attenuative boundaries used herein describe interfaces between water and the seabed, and water and ice.

2.3 Medium-Advantageous Optimization

Understanding the waveguide behavior of an **UAM** is important because it allows an opportunity to expand research into techniques to improve the quality of communication between sensors in an **UASN** by taking advantage of environmental properties to improve communication coupling. In Chapter 3, a comparison between the coupling of directional and non-directional **BPs** is compared to determine the effectiveness of beam focusing on a communication across different distances. In Chapter 5 spatial techniques are used to determine the effectiveness of coupling at different depths. These techniques expand upon existing knowledge of **BPs**, directivity, and waveguide

properties to estimate the set of optimal operating depths for sensors in an **UASN** by bridging the study of **BPs** with the study of the waveguide model. By bringing these concepts together, one may focus on how a signal escaping a projector can be optimally coupled to the **UAM**. Allowing two approaches, coupling using a focused beam, or coupling by means of spatial displacement of the transmitter and receiver, and as a posteriori each technique must be analyzed.

2.3.1 Beam Focus Signal Coupling

One possible way to couple a signal is by using a highly focused transmitting **BP**. Although this technique is common in optic communication systems [2], it is not obvious from first principles in underwater acoustics. Generally, the benefits from a focused beam in underwater acoustics tend to be a result of sending more total output power towards a known target, with the same amount of input power. It is not obvious whether or not a highly focused beam can survive the signal degrading the effects of dispersion. In general, dispersion leading towards interactions between boundaries tend to be the greatest contributor to signal degradation, and as a result the effects of a focused beam are not immediately apparent. It is important to note that the analysis assumes long-range communication, and as such the results do not infer the effectiveness of focused beams for short ranges. It is interesting to note that the height of the underwater waveguide is generally much larger than that of the projector, otherwise the projector would not be underwater. An observation arises from the obvious fact that the ocean is, generally, much deeper than the size of a hydroacoustic projector. Namely, focusing the beam will not increase the effective signal power being coupled to the **UAM** since the entire signal originates within the waveguide. However, it does not imply that it will not increase the signal strength at the receiver, as is discussed in full detail in Chapter 3.

2.3.2 Spatially Displaced Signal Coupling

Considering the substantial size of **UAMs** used herein, it is interesting to determine the set of depths for which communication is optimal. Dissimilar to a focused beam, spatial displacement of communication devices along the depth of the medium can be shown to change the region of transmission of rays which arrive at a receiver from a priori analysis. A first principles analysis requires several assumptions regarding the behaviours a waveguide must exhibit. The properties of shallow-water operation, and vacuum interfaces at both the sea surface and seabed are required to delineate the range of departure angles, as seen in Chapter 4.

Showing that a change in the depth of either the signal source or receiver corresponds to a change in the range of angles which arrive at the receiver in an idealized environment is somewhat conjectural. Recall that shallow-water operation assumptions are incomplete and insufficient when analyzing deep-water systems, but this is not the only limitation with the ideal model. Having a vacuum at the sea surface is generally acceptable; however, having a vacuum at the seabed is not. The ideal model is also insufficient to discuss the effects of ice coverage or other realistic obstacles. In order to cast away the shadows of conjectural doubt an empirical analysis is required. This is achieved through the use of a simulated environment, constructed from data collected in the Bedford Basin, Halifax Canada, by **Defense Research and Development Canada (DRDC)** [3]. The complete analysis follows in Chapter 5.

Chapter 3

Communicating at Great Distances

In acoustic communication theory one is often concerned with one of two modes of operation namely, waveguide mode, or anti-waveguide mode [16]. These names make a great deal of sense when operating on the surface of Earth. When operating in waveguide mode, sound will travel towards the ground, where most people spend their time. Conversely, operation in anti-waveguide mode sends the sound upward towards the bounds of the troposphere.

In underwater communication, waveguide and anti-waveguide modes are not so manageable. This is especially true in shallow waters, where reflection, refraction, and boundary absorption dominate [16]. As such, sending a transmission in shallow, or near-shallow, water can be viewed as a similar practice to coupling an electromagnetic wave to a waveguide. During coupling there is inevitably some transmission loss as a result of how the wave has been coupled. It follows that different beam dispersion patterns may couple differently in the underwater acoustic waveguide, as a result of the different shape of their dominant lobes. Thus, a change in the environmental parameters leading to a change in **Signal to Noise Ratio (SNR)** as well as horizontal separation between source and sink nodes may change the optimal **BP** for coupling to the underwater acoustic waveguide [16, 18].

Herein, the design of the simulation is discussed, explained, and followed by a comparative evaluation of the **BPs** with the highest transmission efficacy over a range of distances and **SNRs**. However, first one must briefly review some of the key concepts pertaining to the analysis of a source and sink node which are horizontally separated by a great distance.

3.1 Key Concepts

When evaluating a **BP** one must ensure that the receiver is in the far-field, which can be estimated with Equation (3.1). This condition is met in the simulated environment, since the device parameters can be arbitrarily defined to fit simulation requirements.

$$R \approx \frac{D^2}{4\lambda} \quad (3.1)$$

- Where R is the distance away from the device determining the beginning of the far-field region.
- D is the width of the aperture.
- λ is the wavelength.

Having satisfied that operation is in the far-field, one must now justify the topology which will be used for altimetry and bathymetry in any experimental simulation modelling a large horizontal separation, namely a flat surface and bottom. This justification is much more intuitive. When the point of observation of any wave reflected or refracted from a surface becomes sufficiently distant, then the surface appears smooth [17, 18]. Consider observing a field of grass, if one is sufficiently close, then the topology becomes rough and each blade of grass in small area is visible, as the point of observation becomes further from the surface, it is more difficult to see each

blade of grass, and instead the surface begins to appear smooth in texture. This effect is a product of the refraction and reflection of light waves as they depart the grassy surface and approach the observer. At a large enough distance any medium can be assumed to be smooth at its boundaries [15].

In summary, the operation of two nodes, source and sink, separated by a large horizontal distance and operating in the far-field with smooth boundaries. Such assumptions not only simplify the complexity of the problem, but also allow one to maintain focus on the purpose of such a simulation, namely the evaluation of different types of sources, in various environments, discussed herein.

3.2 Simulation Design

Having discussed the environmental parameters, the device simulation parameters begin by defining the transmitter. Several types of transmitting BPs are considered, but all devices share the following common operating parameters:

- All devices use BPSK.
- All devices use an operation frequency of 14 kHz.
- Unity gain. The intensity of the same maximum value of 1 dB/mPa.
- Transmitter and Receiver share the same BP.

These parameters are not chosen arbitrarily. An operation frequency of 14 kHz is representative of a common operation frequency of Off The Shelf Acoustic Modem (OTSAM) and is roughly in the middle of the typical underwater acoustic communication band [7]. BPSK is chosen because it is a common implementation of phase shift keying, which is a common modulation scheme used in wireless communication.[11]

The final constant operating parameter requires some explanation. Different devices require different input power to produce the same output intensity, and as such the benefit in power consumption is not analytically valuable, since specifics regarding efficiency are not relevant to this analysis in particular. The purpose of this analysis is to observe any benefits arising from the coupling of different **BPs** of equivalent output intensity to the environment. Therefore, unity gain allows the focus to remain on communication efficacy over the environment as a function of the source **BP**.

3.2.1 Environmental parameters

The simulated environment is representative of an idealized two-dimensional rectangular cross section of a shallow water ocean. It has parameters which remain constant over the course of the simulation as well as parameters which are variable. The constant parameters are seen in Figure 3.1 and as follows:

- Depth of 200 m.
- Seabed depth of 10 m.
- Attenuation of 1.8 dB/km in the seabed.
- Sound Speed (SS) of 1500 m/s in the seabed.
- Thorp Volume Absorption Model [13].
- Vacuum at Surface.
- Vacuum at left and right vertical boundaries.
- Source and receiver depths of 100 m.

Figure 3.1: Environmental Parameters

The variable parameters are the **SNR**, horizontal separation of the source and receiver, and the **SSP**. The simulation is divided into three categories, one for each **SSP** under consideration. Doing so allows the **SNR** and horizontal separation to be incremented uniformly while maintaining a constant **SSP** throughout each of the simulated environments. The considered **SSPs** are linear upward refracting in Figure 3.2, linear downward refracting in Figure 3.3, and isovelocity 3.4.

Using each **SSP** as a unique category allows the statistical analysis to focus on **SNR** changes with distance, while providing meaningful information about the impact of **SSP** on the operation of devices with different **BPs**. By varying these features it becomes possible to determine the performance of different types of transmitters with respect to horizontal distance between the source and receiver nodes.

Figure 3.2: Upward Refracting SSP

Figure 3.3: Downward Refracting SSP

3.2.2 Types of Transmitters

The types of transmitter BPs considered in the simulations exhibit a range of directionality in the elevation plane. Since the simulation environment is two-dimensional,

Figure 3.4: Isovelocity SSP

the azimuth plane is assumed to be isotropic, which is an idealization. The families of transducer which have been considered are: **TCL**, **CPT**, and **Flextensional "dogbone" Array (FTA)**. From each family several **BPs** have been considered, and the best characteristics are compared relative to the performance of an isotropic, omnidirectional, radiator.

In order to determine optimal beam patterns a methodology for selecting transmitters is developed in the following manner. A transmitter is considered for analysis if it performs in a manner which is similar to or better than the performance of an isotropic radiator. A transmitter is rejected from analysis if it is out performed by a similar transmitter in the same family. A family of transmitters is rejected from analysis if it is out performed by at least two other families of transmitting devices.

3.2.3 Determining Positive Results

The metric used to establish the performance of a transmitter is the E_b/N_0 . This metric is used to measure the performance of an isotropic radiator, and other transmitters relative to the isotropic radiator. If a transmitter is better than, or similar to, the isotropic radiator with a confidence interval of 95%, then it is considered for comparative analysis.

There are two types of possible desirable results which may arise from such a simulation. The first kind of positive result shows that one specific transmitter outperforms all other transmitters under the majority of test conditions, with high confidence. The other possible positive result is less obvious, it is representative of a situation where a transmitter outperforms other devices under a specific SSP , or a range of $SNRs$, but is out performed otherwise.

The other type of beneficial result occurs when a transmitter outperforms all others over a certain interval. This indicates that one transmitter is best used in low noise situations, whereas the other is best used in high noise environments. Having been exposed to a discussion of what desirable results are, it becomes prudent to discuss the actual results of the simulation conducted.

3.3 Simulation Evaluation

Initially, several device dimension to wavelength ratios were tested for the CPT and TCL families. The wavelength was incremented in integer intervals between one wavelength and eight wavelengths. BPs corresponding to classes five and seven flex-tensional arrays operating in dipole and cardioid modes were analysed [5, 19]. The BPs were then applied to the acoustic channel and the $BERs$ were compared to determine the top three device types.

The result of this analysis showed that the only devices worth considering for any further analysis, relative to an isotropic radiator, are the 4-wavelength (4λ) **TCL** and either class of **FTA** operating in cardioid mode.

After a complete analysis and full normalization of output intensities over a wide scale of **SNRs** the refined **BER** Vs. E_b/N_0 curves for downward refracting, isovelocity, and upward refracting **SSPs** are as follows in Figures 3.5-3.7. Where each curve is enveloped by its respective confidence interval in the same color. Figure 3.5 shows

Figure 3.5: Positive Result where BER curves intersect

the most interesting case where the range of E_b/N_0 values on the interval of [25 dB, 45 dB] show the flextensional array outperforming the isotropic radiator and the 4λ -**TCL** with a 95% confidence interval. However, this benefit is marginal and only observed on a narrow interval. Observe the results for the isovelocity **SSP** case where all devices have overlapping confidence intervals. This suggests that for an isovelocity

Figure 3.6: Positive Result where BER curves intersect

Figure 3.7: Positive Result where BER curves intersect

SSP it is not possible to determine a statistically meaningful difference in performance. For the test environment, with isovelocity **SSP** it would appear that the flextensional array operating in cardioid mode and the 4λ -**TCL** operate in a manner which is statistically similar to an isotropic radiator. The same analysis follows for Figure 3.7, where the confidence intervals overlap for almost all values of E_b/N_0 suggesting that all devices operate in a statistically similar manner in an environment with an upward refracting **SSP**.

3.4 Conclusion

What can be seen from the results of the analysis of this simulated environment is that there exists a specific type of transmission device that is best suited to all simulated ranges and **SSPs**. Specifically, any class V flextensional hydroacoustic projector which is capable of operating in cardioid mode is best suited to long range communication in a highly reflective environment. This is especially true for a highly reflective environment with an upward refracting **SSP**. However, very little difference exists between tested devices, which is somewhat counter-intuitive for an observer with experience in wireless radio. The results of this simulation offer new questions, particularly, what are the reasons why the devices operated so similarly despite their drastically different designs. It also leads to wondering if changing the device design does not improve communication, then is there a way to take advantage of other physical characteristics to improve arbitrary communication, perhaps by modulating the operation depths.

Chapter 4

Formulating a Better Approach

In the previous chapter, the effect of BP on the efficacy of communication was explored. Despite the simple attenuative environments used in Chapter 3 it was observed that regardless of the projector aperture there did not appear to be a definitive benefit to altering the BP. This is not to imply that it is impossible to use BP to produce a favorable aperture. However, it does not appear to have an obvious benefit to long distance communication over a general communication channel. The corollary of such an observation is the well-known fact that the communication channel that UASNs are subject to operation within can be modeled as waveguides [17]. As a result, the idea of treating a transmitter and receiver as devices which can be coupled to an acoustic waveguide in much the same way as one does with electromagnetic antennae.

In antenna theory a concept known as the effective aperture is used to describe how well an antenna can receive a radio signal [1]. It also describes the regions of an antenna that are best at receiving a radio signal. A similar concept can be applied to an underwater acoustic system, where it can be determined what departure angle a ray originating from a projector will have for a given number of reflections in an ideal environment.

Knowing the number of reflections a ray will encounter as it travels to the receiver is important for understanding phase delay, a form of noise caused by reflection, which effects **Phase Modulation (PM)** and **Frequency Modulation (FM)** schemes [1, 10]. A consequence of phase delay is the ability determine what departure angle corresponds to a specific number of reflections, relative to the environmental dimensions. In other words, the phase delay can be used to identify the number of times a ray has reflected between a source and sink.

4.1 Developing the Effective Projector

To better understand why the different **BPs** in Chapter 3 provided such similar results this analysis begins with a simple geometric analog of an ideal waveguide, Figure 4.1. This is the simplest case, source and receiver at the depth midpoint, equally dividing

Figure 4.1: An Arbitrary Waveguide with Source and Receiver at Equal Depth.

the waveguide. Figure 4.1 shows the division of the waveguide for one reflection. Defining the two triangles is as follows, both have a height of h , and both have horizontal distances of d and d' for the left and right triangle, respectively. It is known that the sum of both lengths of bases are equal to the total distance, $d + d' = D$.

Though not explicitly labelled, it can be seen that the angle of inclination from the horizontal of the ray departing from S , θ , is equal to the angle of inclination from the horizontal of ray entering R , where S and R are the source and receiver, respectively.

Equation (4.1) relates the height and base to the departure angle. What follows is an exhaustive example that $d = d'$ in (4.2).

$$\tan \theta = \frac{h}{d} \quad (4.1)$$

$$\frac{d'}{h} = \frac{D - d'}{h} \quad (4.2)$$

Of course this example, considers only the most simple scenario. There is still the consideration of what happens when the source and receiver depths change, and how that would effect the location at the surface where a ray reflects. Intuitively, this question can be answered by extending the ray beyond the boundary prior to vertically translating the source and receiver, as follows in Figures 4.2 and 4.3.

Figure 4.2: Source and Receiver Interval Movement Toward Receiver.

It is apparent, from this geometric approach, how the position of the point of

Figure 4.3: Source and Receiver Interval Movement Toward Source.

reflection translates across the surface of the waveguide, but it also gives an idea about how the departure angle changes as the depth of the source and receiver change. However, none of these examples have yet to consider what happens when the ray reflects more than once. Indeed, the geometric discussion is approaching the end of its use. A momentary return to the single reflection case will conclude this geometric discussion and begin a more analytic approach.

With the source and receiver both at the midpoint-depth it can be observed, either with the Snell-Descartes Law [15] or through the geometric symmetry of the environment, that the environment is divided by the number of reflections as seen in Figure 4.4 and listed in Table 4.1.

At this point in the analysis, the intuitive-geometric approach has been exhausted. Some key features have been observed which will be helpful for a formalized analysis, including how the number of reflections effect the location where a ray reflects from the surface or bottom. It has also shown how that location can move as the source and receiver move. This is the intuitive basis for the formal analysis that follows.

Figure 4.4: Multiple Reflections for Source and Receiver at Equal Depth.

Table 4.1: Vertical cuts made by reflections through the medium.

n	<i>Location of Reflection</i>
1	$\frac{D}{H}$
2	$\frac{D}{2H}$
3	$\frac{D}{3H}$
4	$\frac{D}{4H}$
$\vdots$	$\vdots$
n	$\frac{D}{nH}$

4.2 Defining the Effective Projector

Let one consider an arbitrary perfect acoustic waveguide with: isovelocity sound speed; source and receiver at arbitrary depths; some horizontal separation between the source and receiver; and some ray travelling from the source to the receiver. There are two possible cases for how the ray arrives at the receiver. Either it arrives after reflecting from the bottom, as in Figure 4.5, or it arrives after reflecting from the surface, as in Figure 4.6.

Figure 4.5: General Case of a Ray Approaching R from Below.

Where, in the case of a ray arriving from below:

- S is the source.
- R is the receiver.
- n is the number of reflections along the top of the waveguide of a ray sent from S approaching R with an ultimate reflection from the bottom of the waveguide.
- h_m is the vertical height of S from the bottom of the waveguide.
- d_m is the distance from S to the angle bisector of the first reflection.
- α_m is angle from the ray to the interior bisector of the reflected ray from S .
- h'_m is the vertical height of R from the bottom of the waveguide.
- d'_m is the distance from R to the angle bisector of the last reflection.
- δ_m is the distance along the surface between reflections.
- H is the total internal height of the waveguide.

Where, in the case of a ray arriving from above:

- S is the source.

Figure 4.6: General Case of a Ray Approaching R from Above.

- R is the receiver.
- n is the number of reflections along the top of the waveguide of a ray sent from S approaching R with an ultimate reflection from the top of the waveguide.
- h_n is the vertical height of S from the bottom of the waveguide.
- d_n is the distance from S to the angle bisector of the first reflection.
- α_n is angle from the ray to the interior bisector of the reflected ray from S .
- h'_n is the vertical height of R from the bottom of the waveguide.
- d'_n is the distance from R to the angle bisector of the last reflection.
- δ_n is the distance along the surface between reflections.
- H is the total internal height of the waveguide.

First, consider the case where a ray approaches from the bottom, Figure 4.5. The distance between S and R is defined as in Eq. (4.3).

$$D := \text{dist}(S, R) \quad (4.3)$$

$$D = ((m-1)2H + H - h_m + 2H - 2h'_m) \tan \alpha_m \quad (4.4)$$

$$\tan \alpha_m = \frac{D}{(2m+1)H - h_m - 2h'_m} \quad (4.5)$$

This case is the more difficult of the two to visualize. To find D , one must add all distances, that includes some multiple of δ_m added to d_m and some multiple of d'_m . In this approach, one counts all δ_m between the first and last reflections, and adds d_m and twice d'_m . In such a manner one arrives at Eq. (4.4). The value of $2d'_m$ comes from the smaller isosceles, a byproduct of the symmetry of reflection in a perfect waveguide. The result is a quantification of α_m as seen in Eq. (4.5). This value will change when the ray approaches from above.

In the case when the ray approaches the receiver from above, the distance is described as in Eq. (4.6). This results in an angle, α_n , which is distinct from α_m , and is seen in Eq. (4.7).

$$D = (n-1)\delta_n + d_n + d'_n \quad (4.6)$$

$$\tan \alpha_n = \frac{D}{2nH - h_n - h'_n} \quad (4.7)$$

From this formal definition, it can be clearly understood what happens if the source or receiver move, but this model is limited to a point. What would happen if the source or receiver were not points, or if they existed within a range, is yet to be explored.

4.2.1 Adding a Window of Opportunity

Instead of treating the receiver and source as just points, they can be seen as existing in a range of possible depths. In other words, the number of rays that would approach the receiver in a fixed number of reflections is no longer coming from a single departure angle, but instead comes from a range of possible departure angles. This will serve as the foundation for defining the effective projector, which exists in a window of opportunity as seen in Figure 4.7 and Figure 4.8.

Figure 4.7: General Case of a Ray Approaching R from Above with an Error Window.

Figure 4.8: General Case of a Ray Approaching R from Above with an Error Window.

In this case, it is not good enough to just apply the previously discussed model in Section 4.2, now one must consider four possible cases for how the ray hits the error

window, as follows in Figure 4.9.

Figure 4.9: Possible Cases for a ray Arriving at a Receiver with an Error Window.

In order to analyze these cases the values h_n , h_m , h'_n , and h'_m must be redefined to include the height of the source h_s , receiver h_r and their respective error windows ϵ_s and ϵ_r , as follows in Equations (4.8) - (4.11).

$$h_n = h_s \pm \epsilon_s \quad (4.8)$$

$$h'_n = h_r \pm \epsilon_r \quad (4.9)$$

$$h_m = h_s \pm \epsilon_s \quad (4.10)$$

$$h'_m = h_r \pm \epsilon_r \quad (4.11)$$

These four cases must be tested as each of the adjusted source and receiver heights approach the surface and the bottom of the ideal arbitrary waveguide. Such a test corresponds to eight possible limits which will reduce to an upper bound and lower bound, resulting in only two of the four possible cases being required considerations for determining the range of α_m and α_n which define the range of departure angles which will arrive at the receiver.

Consider the extreme case for m and n respectively, where the source and receiver approach the top of the waveguide in Equation (4.12) and Equation (4.13).

$$\lim_{(h_m, h'_m) \rightarrow H} \frac{D}{(2m+1)H - h_m - 2h'_m} = \frac{D}{2(m-1)H} \quad (4.12)$$

$$\lim_{h_n, h'_n \rightarrow H} \frac{D}{2nH - h_n - h'_n} = \frac{D}{2(n-1)H} \quad (4.13)$$

One could continue in this way for all eight possible limits, but a pattern exists in the limits. The tangent of an angle approaches infinity as the angle approaches $\pi/2$. Conversely, the tangent of an angle of 0 radians is 0. In this way, the limits that produces the smallest and largest denominator that are desired. The case for which the largest value of α_m has already been observed for both m and n in Equation (4.12) and Equation (4.13). The largest denominator occurs when the source and receiver depth approaches the bottom of the waveguide, as follows in Equation (4.14) and Equation (4.15).

$$\lim_{(h_m, h'_m) \rightarrow 0} \frac{D}{(2m+1)H - h_m - 2h'_m} = \frac{D}{(2m+1)H} \quad (4.14)$$

$$\lim_{h_n, h'_n \rightarrow 0} \frac{D}{2nH - h_n - h'_n} = \frac{D}{2nH} \quad (4.15)$$

Currently, the extremes for Figure 4.9a and Figure 4.9c have been analyzed. Now, consider the inclusion of cases where the source and receiver approach the surface and bottom for which a ray reflects k times. For such a case $m = n = k$, and what follows

is an interval for α_k that describes the possibility of including rays where the ultimate reflection is from the top or bottom the waveguide. To observe this one must compare the smallest α_k and the largest α_k respectively.

$$\tan \alpha_{below} = \tan \alpha_{above} \quad (4.16)$$

From Eq. (4.16) it can be seen that the largest angle of a ray hitting from above or below, at their respective limit is equal for the same number of reflections. However, this is not the case for the smallest angle, as seen in Eq. (4.17), where only one or more reflections is considered.

$$\begin{aligned} \tan \alpha_{below} &\geq \tan \alpha_{above} \\ \frac{D}{(2k+1)H} &\geq \frac{D}{2kH}, k \geq 1 \end{aligned} \quad (4.17)$$

In the case of the smallest α_k , for at least one reflection, the ray must approach from below corresponding to the smallest possible value of h_m and h'_m . Thus, this ray must approach from the bottom of the waveguide and must be incident on the bottom of the interval. For the case of the largest possible α_k the ray can arrive after reflecting off the top or bottom of the waveguide, but must be incident on the top of the interval. In other words, the only cases which need to be considered are those of Figure 4.9b and Figure 4.9c.

The range of angles which represent the possible rays for k reflections creates a special case of the effective projector with an error window such that $0 \leq h_k \leq H$ and $0 \leq h'_k \leq H$ is defined as α_{k*} as follows in Eq. 4.18.

$$\alpha_{k*} \in \left[\arctan \frac{D}{(2k+1)H}, \arctan \frac{D}{2(k-1)H} \right] \quad (4.18)$$

When the error window is narrow such that $0 < h_k < H$ and $0 < h'_k < H$ then the interval for α_k is seen in Eq. (4.19). Applying this constraint makes the general case for the effective projector where both rays must approach from the bottom, since $(2k+1)H > 2kH$ for all values of k and it is unclear if h_k and h'_k are at the extremes of the waveguide.

$$\alpha_k \in \left[\arctan \frac{D}{(2m+1)H - (h_s + \epsilon_s) - 2(h_r + \epsilon_r)}, \arctan \frac{D}{(2k+1)H - (h_s - \epsilon_s) - (h_r - \epsilon_r)} \right] \quad (4.19)$$

The reason for the distinction between α_{k*} and α_k is made because $\alpha_k \subseteq \alpha_{k*}$. It is also useful to define α_{k*} as a special case that shows the complete range of angles that are possible for rays that will reflect k times a ray with a reflection angle outside of α_{k*} will certainly never arrive at the receiver.

Shifting the focus towards α_k , it becomes clear that the range of angles changes as the depth of the source and receiver changes. This will become interesting when discussing the effect of aiming a directional projector.

4.2.2 Considering a Source Beam Pattern

What happens to the effective projector of a source for a **BP** is really quite clear when one considers α_{k*} . If one desires the range of rays that will arrive at the receiver then those rays will be at most α_{k*} . Consider a departure angle, θ , such that $\theta = \frac{\pi}{2} - \alpha_k$ as in Figure 4.10.

Figure 4.10: Defining the departure angle.

As long as the maximum power region of the **BP** contains θ then the **BP** has no impact on the desired ray. The **BP** could be isotropic, or extremely directional. The only effect that a **BP** could have is to change the likelihood that θ will be within the maximum power region. To illustrate this concept observe the **BPs** of Figure 4.11, where the **BPs** are in red. Surely, it is less likely that **BP** (a) will contain θ after it has been rotated, or if the source depth changes, than **BP** (b). In fact, since pattern (b) is isotropic it will contain θ for all possible source and receiver depths, and all possible rotations of the source **BP**. Such a phenomenon may explain why the **BPs** analyzed in Chapter 3 yielded such similar results. It is likely that whatever contributing angles, angles that would correspond to the effective projector, lie in the primary lobe the of the isotropic and **FTA** sources. These angles were less likely to be in the highly directional piston projector.

One may wonder why the analysis of source **BPs** begins considering rotations and changes in depth. To answer that question one must consider any modulation scheme where phase delay causes signal degradation.

Figure 4.11: Two possible beam patterns.

4.3 Effective Projector & Signal Modulation

In any modulation scheme that depends on frequency or phase it is desirable to have no phase delay. However, since phase delay is periodic. The encoded data would not be effected by a phase delay which is an even-integer multiple of π . Consider the following sinusoidal wave $S(t)$, in Eq. (4.20), where data can be encoded on to $\Theta_i(t)$ [6].

$$S(t) = \sin \Theta_i(t) \quad (4.20)$$

$\Theta_i(t)$ can represent a FM signal or a PM [10, 6]. The difference between the two being mathematically subtle, does not preclude either from being obscured by phase delay. In FM schemes a phase delay may correspond to a frequency difference that is too large. In PM a phase delay may obscure the carrier. In either case a phase delay that causes the signal to lag or lead by even-integer multiples of π is desirable. Considering the Snell-Descartes' Law that states a reflection causes a phase delay of

π one would wish a ray to traverse the waveguide in a number of reflections that is an even-integer number of reflections [15]. Of course, for a large number of reflections this corresponds to an effective projector, α_k , that eventually includes all angles $[-\frac{\pi}{2}, \frac{\pi}{2}]$, but such a large number of reflections is not practically possible.

4.4 Conclusion

An optimal configuration may exist in a practical environment by attempting to take advantage of environmental factors. Considering Section 4.2.2, it is reasonable that rotating the beam, or using a different beam, would provide little to no benefit. However, changing the depth of the source and receiver such that they maximize even-integer reflections through the waveguide have a theoretical benefit. Essentially, this is a practice of tuning the source and receiver depths as to produce the lowest possible noise scenario. Such an approach would have to be heuristic, since environmental factors readily change in a practical environment and the upper bound on the number of reflections is not a priori.

Chapter 5

Node Depth Optimization

Chapter 4 concluded by stating the theoretic evidence that changing the depth of a source, receiver, or both had the effect of changing the position of the range of rays leaving the source that would arrive at the receiver. This analysis was conducted using an idealized boundary conditions and an assumption of shallow-water operation. Recall the difference between shallow-water and deep-water modes of operation discussed in Section 2.2. As a result, it is not obvious, if the conclusions regarding shallow-water analysis follows with deep-water operation.

5.1 A Methodology for Node Depth Optimization

A methodology for node-depth optimization in deep-water operation is developed with depth aware sensors, using omnidirectional projectors, that divide the height of the water column into an ascending ordered set of depths which equally divide the depth of the environment, h , and are real numbers on the interval $[0, h]$. The number of depths in the set is dependant on the desired precision. A task which is commonly achieved with an on board pressure sensor.

The sensors begin at the lowest point of pressure, the sea surface, and the BER

of a test message sent using **BPSK** is measured. The receiver then dives to the next depth increment and a new test message is sent. When the receiver reaches the last depth, the source dives to the next depth increment, and the process is repeated until both sensors have measured the BER of messages between each depth. This is a costly procedure in two regards. Sensors in an **UASN**, have a finite amount of battery life available, which must be maximized. A procedure which requires the device to dive and ascend repeatedly would certainly hinder the longevity of the sensors. It is also costly from a computational standpoint, since transmitting a signal is another high battery cost procedure. A technique to reduce the number of measurements is required in order for node depth optimization to be efficacious. There must be a reasonable trade between precision and number of measurements in order to reduce the operational overhead.

5.2 Depth Precision

Consider the following arbitrary set of depths, d , as follows in (5.1).

$$d = d_1, d_2, d_3, \dots, d_n \quad n \in \mathbb{Z}_+ \quad (5.1)$$

It is fairly obvious that the size of d is n . Consider two sensors, implementing the same depth measurement set such as d . The following table, Table 5.1, compares the size of d for a source and receiver to the number of measurements.

From the table, a source and receiver in a **Point to Point (PTP)** link, the number of measurements is exactly $O(n^2)$. However, with a reduced precision for the depths along the interval between measurements can be inferred from statistical techniques.

Table 5.1: Relationship Between Depth and Measurement

Number of Depths	Number of Measurements
1	1
2	4
3	9
4	16
$\vdots$	$\vdots$
n	n^2

It follows that depths which are near a depth with a high **BER** will also have a high **BER**, and vice versa.

Using techniques of statistical interpolation with MATLAB a piece-wise linear surface is used to generate a heat-map of areas with high **BER**. In this way the number of measurements can be kept constant while maintaining the ability to generate a meaningful set of optimal depths. Of course this solves the intractability of a continuous interval, but one must remain aware that the precision of measurement is directly limited by discrete set of measurement depths. In this way there is a trade between the longevity of the battery and the number of measurements. Fewer measurements reduces the strain on the battery. However, it also reduces the precision of the measurement of the optimal depth.

5.3 Test One: Ideal Conditions

Testing the methodology begins with a near-ideal environment. The first test involves an environmental model, built using the BELLHOP acoustic medium simulator, with a constant speed of sound of 1500 m/s. The sea surface and bottom are modelled with a vacuum. The separation between the source and receiver is set to 1000 m, and

Figure 5.1: Eigenrays between a source and receiver at extremes in an idealized environment.

the depth of the medium is 200 m. The following are ray traces corresponding to the extreme source and receiver depths showing the effect of changing the device depths on the rays which arrive at the receiver, known as eigenrays, as follows in Figure 5.1.

For this simulation, the depth increments are 10 m, equivalently there are 20 points of measurement for each sensor. The corresponding heat-map indicating the optimal regions in deep blue, and the worst regions in yellow. Each point of measurement is indicated with black discs and forms a locus of points such that the x-axis corresponds

to receiver depths and the y-axis corresponds to source depths, as follows in Figure 5.2.

Figure 5.2: BER heat-map of an ideal environment.

The results of this simulation are rather promising. From the heat-map it can be seen that the majority of regions produce optimal depths, and only the region surrounding the point of measurement where the receiver depth is 90 m and the source depth is 180 m. These results are as expected. An ideal environment should produce nearly ideal results. To verify that the methodology is working correctly consider Figure 5.2, which shows the arrivals corresponding to the ray trace in Figure 5.1a. Now consider Figure 5.3 which corresponds to the ray trace of Figure 5.1d. The extreme differences indicates the capability of the methodology to change the range of beams that arrive at the receiver.

Table 5.2: Arrival metrics for a source and receiver depth of 10 m.

1	14000.000000000000		1	1	1		
2	10.00000000						
3	10.00000000						
4	1000.00000						
5	8						
6	8						
7	4.29455482E-04	378.066559	0.723076403	-22.9591827	22.9591827	2	1
8	4.79027134E-04	201.157623	0.718019903	-21.9387760	-21.9387760	1	1
9	7.90377017E-05	205.061905	0.717936695	-20.9183674	-20.9183674	1	1
10	6.22675580E-04	180.000000	0.666784942	-1.53061223	1.53061223	1	0
11	9.99973621E-04	0.00000000	0.666640222	0.510204077	0.510204077	0	0
12	6.79688019E-05	29.7512264	0.713087857	19.8979588	-19.8979588	0	1
13	5.24933450E-04	25.0619259	0.713176191	20.9183674	-20.9183674	0	1
14	4.79027134E-04	201.157623	0.718019903	21.9387760	21.9387760	1	1

Table 5.3: Arrival metrics for a source at 200 m and receiver at 10 m.

1	14000.000000000000		1	1	1		
2	199.998474						
3	10.0000000						
4	1000.00000						
5	6						
6	6						
7	1.19619835E-04	180.000000	0.681124687	-12.7551022	12.7551022	1	0
8	8.58963816E-04	180.000000	0.681206226	-11.7346935	-11.7346935	1	0
9	9.40518570E-05	0.00000000	0.678592920	-10.7142859	-10.7142859	0	0
10	7.54584034E-04	85.8306808	0.678593338	10.7142859	-10.7142859	0	1
11	6.80713449E-04	258.684601	0.681206644	11.7346935	11.7346935	1	1
12	9.37798031E-05	251.822205	0.681125104	12.7551022	12.7551022	1	1

Observe the beam width of the case where the source and receiver depths are 10 m, as in Figure 5.1a. From Figure 5.2 the largest departure angle is approximately 21.94° as seen on line 14, column 4. The smallest departure angle is approximately -22.96° . This corresponds to a beam width of about 45° . This beam width is much larger than that of the environment corresponding Figure 5.1d and Figure 5.3, which has a beam width of approximately 25° . One may abduct from the two cases discussed that since they both have beam widths which very nearly share a midpoint at 0° , they must have similar BERs. Unfortunately, the heat-map is not very clear for the locations corresponding to Figure 5.1a and Figure 5.1d. Instead, consider the raw data of Figure 5.3.

The raw data is comprised of two columns. The left column is the BER, and the right column is the signal to noise ratio. Both values are in Decibels. Each row corresponds to a unique simulation. Notice that the mode of Figure 5.3a and Figure 5.3b are the same and the mean BER of Figure 5.3a is small.

In conclusion, the data collected is consistent with the a priori predictions of 4, supporting the validity of the methodology. Having satisfied that the empirical data supports the methodology in this ideal environment, it becomes relevant to determine if is possible to find optimal depths in realistic environments.

5.4 Test Two: Summer in The Bedford Basin

Consider the environmental data collected in the Bedford Basin by Defense Research and Development Canada [3]. This data is representative of environmental conditions typical to normal operation for UASNs. Unlike the environment of Section 5.3, the Bedford Basin environment has a transitional SSP that is downward refracting along the thermocline, and isovelocity at depths greater than 30 m, as seen in Figure 5.4.

0.03809523809520	-25
0.0	-20
0.00884955752212	-15
0.0	-10
0.0	-5
0.0	0
0.0	5
0.00884955752212	10

(a) Raw BER for source, receiver at 10 m.

0.0	-25
0.0	-20
0.0	-15
0.0	-10
0.0	-5
0.0	0
0.0	5
0.0	10

(b) Raw BER for source at 200 m, receiver at 10 m.

Figure 5.3: Raw BER data Corresponding to Figure 5.1a and Figure 5.1d, respectively.

The Bedford Basin also has a nonlinear bottom, and can be seen in the ray trace figures depicted in brown, as follows in Figure 5.5.

Figure 5.4: SSP of the Bedford Basin.

From the ray traces of Figure 5.5 the effects of changing source and receiver depths is visibly obvious. However, it is not obvious how the ray trace corresponds to the quality of communication. In order to determine what locations work, and what needs to be avoided, one must observe the heat-map, as follows in Figure 5.6. From both the ray-trace figures and the heat-map it is apparent that a change in source and receiver depths has a direct impact on the quality of communication in the channel. It

Figure 5.5: Eigenrays between a source and receiver at extremes in the Bedford Basin, summer environment.

becomes apparent to determine what the limitations to this methodology are. Clearly, the multipath propagation and signal dissipation effects are not as significant as the waveguide effects, even in a practical environment. Revisiting the ray-traces of Figure 5.5 one may notice that very few rays which arrive at the transmitter reflect off the surface. The majority of rays refract downwards before reaching the surface of the water column. This could suggest that the surface effects are responsible for the lack of eigenrays which reflect off of the surface. This could in part be a product of either the surface parameters, or the downward refracting sound speed near the surface.

Figure 5.6: BER heat-map of the Bedford Basin environment.

5.5 Test Three: The Bedford Basin with Ice

Before exploring the efficacy of node depth optimization in an upward refracting environment it is interesting to determine if adding simulated ice cover would produce an environment which is chaotic enough to cause the methodology to fail.

Simulated ice is provided in accordance with a stochastic model [9]. The goal of this test is to determine the efficacy of the model when the sea surface and seabed are defined by attenuative acoustic mediums with nonlinear altimetry and bathymetry, respectively.

From the ray traces of Figure 5.7 it is observed that the surface ice changes the number of eigenrays. This is seen regardless of the depth. The addition of ice can actually prevent the sound from moving towards the receiver in the channel.

The addition of ice, generally, results in additional signal degradation [17]. This effect can be observed when comparing the heat-map of Figure 5.6 with the heat-map of the ice-covered environment in Figure 5.8. As the environment begins

Figure 5.7: Eigenrays between a source and receiver at extremes in the Bedford Basin, summer environment with 80% ice cover.

to include additional nonlinear attenuative bathymetric and altimetric features the signal degradation begins to increase. The methodology has proven to withstand the effects of both ice-cover, and nonlinear seabed features, but it is important to observe

Figure 5.8: BER heat-map of the Bedford Basin environment with ice cover.

that despite these features most of the eigenrays are reflecting from the bottom. Only a small number of eigenrays ever reflect from the surface. It is necessary to determine if an upward refracting **SSP** would produce meaningful results.

5.6 Test Four: Bedford Basin Winter

Having observed that the majority of eigenrays reflect from the bottom it becomes important to test the methodology against an upward refracting **SSP**. The **SSP** of 5.3

is replaced with an **SSP** that is consistent with arctic conditions [8]. What results are ray traces that contain an exceedingly large number of reflections, as follows in 5.9.

Figure 5.9: Eigenrays between a source and receiver at extremes in the Bedford Basin, winter environment.

From the ray traces of Figure 5.9 it is difficult to making a meaningful observation. What is apparent is the fact that each depth is indistinguishable from one another with the naked eye. However, it is still possible that an optimal depth set may exist. The heat-map in Figure 5.10 the optimal depths can be observed. These

results are consistent with existing empirical observations regarding upward refracting sound speed profiles which indicate that upward refracting **SSPs** hinder communication [17]. It is necessary to note that even in such arduous environmental conditions the methodology is able to determine optimal depths of operation.

Figure 5.10: BER heat-map of the Bedford Basin environment with winter conditions.

5.7 Test Five: Simulated Winter with 80 % Ice

An upward refracting **SSP** combined with a large amount of ice-cover is one of the most communication adverse underwater environments possible, and the methodology has yet to be applied to such an environment. The ray traces of Figure 5.11 show the eigenrays for the Bedford Basin environment with an upward refracting **SSP** and simulated ice. Despite appearing sparse when compared to Figure 5.9, it produces a much less desirable heat-map, as seen in Figure 5.12.

The high **BER** in the heat-map is consistent with environmental expectations [17]. Not only, does it indicate the resilience of the optimal node depth finding methodology, it also delineates the impossibility to infer the quality of a transmission from the ray trace alone.

5.8 Conclusion

It is possible to optimize the environmental interaction of a transmission between two nodes forming a link in an **UASN** by changing operating depths. Using omnidirectional projectors shows that this effect is predominantly caused by the characteristic behaviour of the underwater acoustic medium. The methodology is shown to be resilient to communication adverse environments, and despite environments which cause high **BERs**, the optimal depths are discoverable using this methodology.

Despite the increased **BER** as the environment takes on additional communication hindering features one may abduct a conclusion that this methodology produces diminishing returns. However, in challenging environments which prove to hinder communication any improvement to the quality of a transmission is beneficial. Especially, when considering the inherent latency of a slow medium such as water, where

Figure 5.11: Eigenrays between a source and receiver at extremes in the Bedford Basin, winter environment with ice cover.

the propagation delay is on the order of minutes.

Figure 5.12: BER heat-map of the Bedford Basin environment with winter conditions & ice cover.

Chapter 6

Concluding Remarks

Within this work, the use of directional transmission and depth sensitive transmission are evaluated for optimizing a transmission between sensors forming a **PTP** link in a typical **UASN**. These methodologies are evaluated based on their efficacy in improving communication. Both techniques treat the transmission of a signal as an exercise in signal coupling. The goal is to develop a protocol for either technique to optimize transmission.

6.1 Optimization Through Beam Focusing

The goal of beam focusing is to either counteract the effects of beam spreading, signal dispersion, or to determine if there is exists a combination of **BPs** that optimize transmission over different environmental conditions.

The analysis of this approach was unable to generate sufficient results to justify it's use in realistic environments. The directionality of each **BP** tested did not generate significantly different results. The more directional **BPs** tested under-performed the less directional beam patterns in many cases. The **BP** corresponding to the cardioid mode of operation in a Class V flexensional array provided the best results of all

tested device **BPs**. However, the result is marginal and as such can be considered negligible or inconclusive.

6.2 Node Depth Optimization

Node depth optimization takes advantage of the waveguide properties by changing the depths of source and receiver in order to find the optimal depth of operation. This methodology is consistent with first principles for waveguide operation.

The node depth optimization methodology is able to withstand testing against a range of simulated and natural environments, proving to identify a set of optimal depths. Although, there is a considerable overhead requiring the sensor to dive, ascend, and transmit to gauge the environment, this process can be completed in constant time through the use of linear piece-wise interpolation between points of measurement. This procedure reduces both precision and the power expenditure of the sensors. As such there are many opportunities to take advantage of other approaches to expand and perfect this methodology.

6.3 Future Work

The interesting results produced by the node depth optimization simulations open many interesting doors for new discussions and new opportunities. One possibility to apply machine learning techniques to improve sensor functionality. This could be especially interesting considering the wide variety of environmental inputs caused by arctic conditions, such as ice cracking which can saturate a hydrophone preventing signal reception. There are other interesting benefits that may be possible to achieve through the use of machine learning including improved determination of optimal

depths. However, the future of research in node depth optimization is not limited to machine learning.

There is the possibility to test node depth optimization against other modulation schemes. **BPSK** has been used for the simulations and it would be interesting to observe if this methodology works for other modulation schemes. If this methodology works for other modulation schemes, then it may become interesting to revisit the beam focusing methodology. Perhaps, the beam focusing technique may prove to be useful in conjunction with node depth optimization, or perhaps there are other ways in which it may prove beneficial.

6.4 Final Words

The possibility for future work in the area of underwater acoustic communication is somewhat endless, and the motivation limitless. The oceans of this planet are teeming with life and natural resources. Imagine what kind of discoveries could be made, what kinds of life exist in this brave world waiting to be uncovered. Indeed, **UASNs** are at the core of underwater guided and autonomous vehicles. Vehicles which bring forth not only industrial and military applications, but an opportunity to explore and discover.

Glossary

E_b/N_0 Energy Per Bit to Noise Power Spectral Density is a normalized measure for the Signal to Noise Ratio. 4, 26, 28

BER The Bit Error Rate is the rate at which erroneous bits occur during a digital transmission. 4, 27, 28, 47, 48, 49, 54, 63

BP Beam Pattern. 4, 8, 10, 11, 13, 14, 15, 17, 18, 20, 21, 22, 24, 27, 31, 32, 43, 44, 66

BPSK Binary Phase Shift Keying. 4, 22, 47, 68

CPT Circular Piston Transducer. 8, 11, 12, 14, 24, 27

DRDC Defense Research and Development Canada. 19

FM Frequency Modulation. 31, 45

FTA Flextensional "dogbone" Array. 24, 27, 43

OTSAM Off The Shelf Acoustic Modem. 22

PM Phase Modulation. 31, 45

PTP Point to Point. 48, 66

SNR Signal to Noise Ratio. 20, 23, 24, 27, 28

SSP Sound Speed Profile. viii, 5, 16, 23, 24, 23, 27, 28, 30, 54, 58, 60, 61, 62

TCL Thin Cylindrical Line Transducer. 5, 8, 9, 10, 11, 12, 14, 24, 27, 28

UAM Underwater Acoustic Medium. 3, 4, 7, 16, 17, 18

UASN A network of sensors which utilize acoustics, mechanical pressure waves, to communicate underwater. ii, 7, 17, 31, 47, 54, 63, 66, 68

Index

- E_b/N_0 - Energy per Bit to Noise
Power Spectral Density, 4, 5,
27, 28, 30
- BER - Bit Error Rate, 4, 5, 27, 28
- BP - Beam Pattern, 5, 8, 10, 11,
13–15, 17, 18, 20–27, 32, 43,
44, 66
- BPSK - Binary Phase Shift Keying,
22, 68
- BPSK - Binary Phase-Shift Keying, 5
- CPT - Circular Piston Transducer, 8,
11–14, 26, 27
- DRDC - Defense Research & Develop-
ment Canada,
19
- Flextensional Array, 44
- Flextensional Array: Cardioid Mode,
14
- FM - Frequency Modulation, 32, 45
- FTA - Flextensional Array, 26, 28
- Isotropic Radiator, 27
- Isotropic Radiator, 26, 28, 30
- isotropic Radiator, 28
- isotropic radiator, 27
- OTSAM - Off the Shelf Acoustic
Modem, 22
- PM - Phase Modulation, 32, 45
- SNR - Signal to Noise Ratio, 20, 21,
24, 27, 28
- SSP - Sound Speed Profile, 5, 24–28,
30
- TCL - Thin Cylindrical, 27
- TCL - Thin Cylindrical Line, 14
- TCL - Thin Cylindrical Line
Transducer, 5, 8–12, 14, 26,

- 28, 30
- UAM - Underwater Acoustic Medium,
 - 3, 4, 7, 8, 16–19
- UASN - Underwater Acoustic Sensor
 - Network, 3, 17, 18, 66, 68
 - Underwater Acoustic Medium, 17
 - Underwater Acoustic Sensor Network,
 - ii, 7

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