Applications of Acoustic and Electromagnetic Propagation

by

Elias Bircher

Thesis Proposal Submitted in Partial Fulfillment of the
Requirements for the Degree of
Bachelor of Applied Science

in the
School of Engineering Science
Faculty of Applied Science

SIMON FRASER UNIVERSITY
Fall 2023

APPROVAL

Name: Elias Bircher

Degree: Bachelor of Applied Science Honours

Title of Thesis: Applications of Acoustic and Electromagnetic Propagation

Examining Committee:

Dr. Cheng Li, P.Eng
Director, School of Engineering Science

Dr. Rodney Vaughan, P.Eng.
Professor, School of Engineering Science

Christopher Hynes, PhD Candidate
School of Engineering Science

Dr. Shawn Sederberg, P.Eng.
Professor, School of Engineering Science

Date Approved: 2024-01-11

Declaration of Committee

Name:	**Elias Bircher**
Degree:	**Bachelor of Applied Science**
Thesis title:	**Applications of Acoustic and Electromagnetic Propagation**
Committee:	**Dr. Rodney G. Vaughan, P.Eng** Academic Supervisor Professor, Engineering Science
	Dr. Christopher G. Hynes Supervisor Engineering Science
	Dr. Shawn Sederberg, P.Eng Committee Member Professor, Engineering Science

Abstract

A fish tracking model and an acoustic multi-layered structure are presented using the theory of transmission lines to demonstrate propagation through various layered media. The fish tracking model is an electromagnetic propagation model used in conjunction with experimentally collected data to pinpoint the path travelled by spawning salmon, allowing for the study of fine-scale fish migration in remote and challenging landscapes. Although appearing radically different, acoustic propagation shares much the same formalism as electromagnetic propagation; therefore, the second portion of this thesis uses a similar transmission line model to analyze the acoustic loss of a single, double, and triple-pane window – a challenging problem that provides useful information for both architects and researchers alike. Both models provide foundational work and illuminate limitations in applying it directly to real world problems. The electromagnetic propagation yields small deviations in gain across the area of interest resulting in easily accomplished large scale tracking. For finer resolution, more analysis would be required on the data produced. The acoustic transmission line model provides insight into the design of windows, however, current results indicate that only a single layer is modelled accurately.

Keywords: Acoustic Propagation; Electromagnetic Propagation; Electromagnetism; Fresnel Equations; Friis Equation; Oblique Incidence

Acknowledgements

I would like to extend my gratitude to Dr. Rodney Vaughan, my academic supervisor, for the project idea and offering support, addressing queries, and meticulously reviewing the thesis. Furthermore, I thank Dr. Christopher Hynes for his generous provision of a simulation using CST for the fish transmitter, assistance with questions, and contributions to thesis editing. Special thanks to the other lab members for fostering a welcoming environment and their readiness to assist, and to Dr. Shawn Sederberg for serving on the committee. Finally, sincere thanks to my family for their continuous support throughout my degree and this thesis.

Table of Contents

List of Figures

List of Acronyms

ANC Active Noise Cancellation

EM electromagnetic

DFO Department of Fisheries and Oceans

RDL River Dynamics Lab

RF Radio Frequency

TE Transverse Electric

TM Transverse Magnetic

PPE Personal Protective Equipment

MEG Mean Effective Gain

SFU Simon Fraser University

SPL Sound Pressure Level

Chapter 1

Introduction

1.1 Propagation Modelling for Fish Tracking

On June 23, 2019, a landslide was detected 60 km north of Lillooet in a part of the Fraser River canyon known as Big Bar. 110,000 cubic meters of rock fell off a 125-meter cliff into the Fraser River creating a seven-meter waterfall [1, 2]. The hydraulic barrier jeopardized migrating salmon from returning to their spawning locations upstream in the upper Fraser Basin [3]. This in turn impacted the ecology of the river including the current salmon biodiversity [3]. A project is being undertaken by the Simon Fraser University (SFU) School of Environmental Science to radio-track salmon as they encounter the landslide-affected part of the river. This part of the thesis covers the theory and application of propagation analysis at a river system in order to increase the tracking accuracy of the passing salmon.

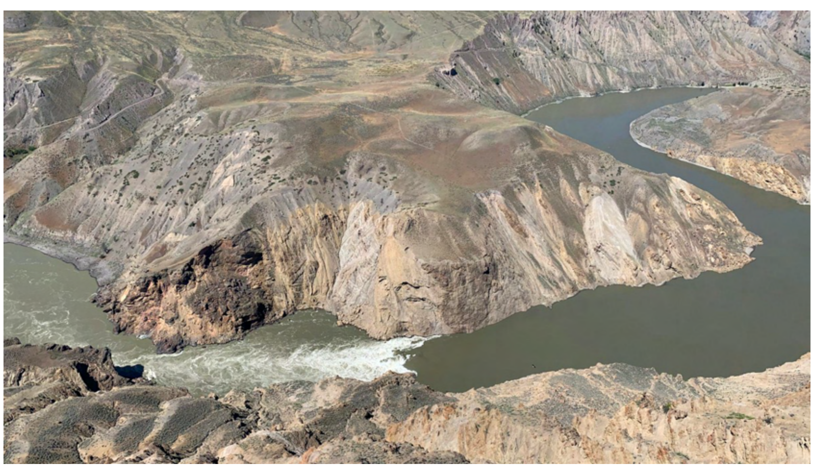


Figure 1.1: The Big Bar landslide in the Fraser Canyon. The landslide caused a massive hydraulic barrier in the river [4].

1.1.1 Background

The landslide obstruction saw a drastic change in the natural spawning with “less than 1% of early Stuart Sockeye and 11% of early Chinook migrating past the slide in 2019" [2] highlighting the devastating impact of the landslide. To preserve the salmon's natural life cycle, the provincial and federal governments, in conjunction with First Nations, have stepped in to assist with saving the salmon. Many approaches have been used to get past the landslide blockage to the salmon including the usage of a helicopter to transport salmon past the slide site, blasting rock to free the blocked area, building a concrete salmon ladder and pumping salmon past the blocked portion using a pneumatic salmon pump system [5]. These solutions have shown various degrees of success going from a handful of fish being able to pass when the slide occurred, to October 24th 2020 when there was a total of "161,000 salmon detected 40 km upstream of slide site to date" [5]. For perspective, in the last decade, this area had seen an estimate in the order of 10 million [6].

Although the multi-pronged response to this natural disaster saved thousands of salmon, there is still a lack of understanding around the intricacies of salmon migration. The Big Bar landslide is not a unique scenario and "the chance of future landslides in the Fraser Canyon is real" [3]. To better understand how the salmon select their migration pathway, Dr. Evan Byrnes, post-doctoral student with the River Dynamics Lab (RDL) at SFU, the Department of Fisheries and Oceans (DFO) and Ms. Sabrina Sixta, a PhD student at the University of Toronto, are analyzing radio tracking data of salmon as they travel through the Big Bar landslide site. This process includes catching and tagging salmon with a radio transmitter downstream of the blockage and using Yagi-Uda antennas along the shoreline to receive the salmon signals. By analyzing the data, the hope is to answer important ecological questions such as [7]:

- How does time spent migrating or the energy used migrating drive the salmon's migration pathway selection?
- Does the pathway selected depend on flow rate, temperature, or some other environmental factor?

The current setup and analysis can determine if a salmon has passed the area under investigation, however, it is not currently possible to locate the salmon. A position estimate is needed to be able to draw any conclusions regarding the pathway selection of the salmon. To assist the research team in answering their ecological migration pathway questions, the goal of this part of the thesis is to determine the theoretical positioning of the salmon in the river based on the power received at the receiver. This propagation model will be used in conjunction with experimental gain data gathered by the RDL and DFO to create a state-space model in order to provide a final estimation of a fish's location. By understanding the migratory behaviour of the salmon, the research has the potential to help navigate salmon through landslides and changing environmental conditions in the future.

Many electromagnetic (EM) textbooks [8, 9, 10, 11] cover propagation topics such as the Fresnel equations, oblique incidence, transmission lines etc., however they do not provide detailed analysis of these topics and their application to real world challenges such as propagation through an air-water interface followed by conductive loss.

Propagation into fresh water has been studied [12] however, the study consisted of planar waves and does not include spherical spreading, antenna gains and any physical geometry of the propagation environment. Fine-scale fish tracking has been investigated [13, 14, 15] but it has either involved a machine learning model [13] that predicted locations based solely on experimental results, or involved mobile tracking using either a boat or car to determine the actual location of the fish by maximizing the received signal [14]. These solutions present their own respective problems and would not work at the Big Bar site. The remote and rugged terrain prevents following fish to identify their position. Also, unlike calm lake conditions, the rapids of the Fraser River require a metal hulled boat with a transmitter on a pole, therefore using solely test data would be erroneous as the experimental measurement represents different conditions to the fish travelling naturally.

1.1.2 Contribution

The main contribution of this thesis is a comprehensive analysis of the propagation problem of fish passing through a high flow river section using a deterministic transmission line model to calculate the gain at every point in a raster of the Fraser River landslide site. The model was generalized such that any raster of river locations along with any receiving antenna pattern can be imported and the code will provide the expected gain. Another contribution is a transmission line analysis for acoustic propagation through multiple layers.

1.2 Acoustic Propagation Model for Multi-layer Structures

In lossless propagation, EM and acoustic propagation share similarities from their respective wave equations [16]. This can be leveraged to analyze an acoustic propagation problem of transmission through a multi-layer window, more commonly known as a multi-pane window. Propagation within homes and specifically through windows is a challenge that manufacturers and architects struggle to analyze or optimize [17].

1.2.1 Background

As cities become more crowded and noisier, it is becoming increasingly important to reduce the noise from our surroundings for both our physical health and mental well-being [18]. "Chronic annoyance and sleep disturbance, resulting in severe heart disease and metabolic disorders such as diabetes, and hearing impairment and poorer mental health" [18] are all conditions attributed to noise pollution. Acoustics has had a recent surge in popularity in academia [19] and in industry where there has been widespread commercialization of Active Noise Cancellation (ANC) devices.

Analyzing the noise pollution problem as a hazard we can use the Hierarchy of Controls in Figure 1.2, a five-step process to reduce risk and a method for ranking a solutions effectiveness against risk created by the National Institute for Occupational Safety and Health [20]. ANC devices would sit at the lowest rung of Personal Protective Equipment (PPE) and offer the least effective protection against the noise pollution. This thesis will investigate the physics behind an "Engineering Solution" of reducing the noise that people are exposed to by altering the construction of windows to provide greater sound isolation.

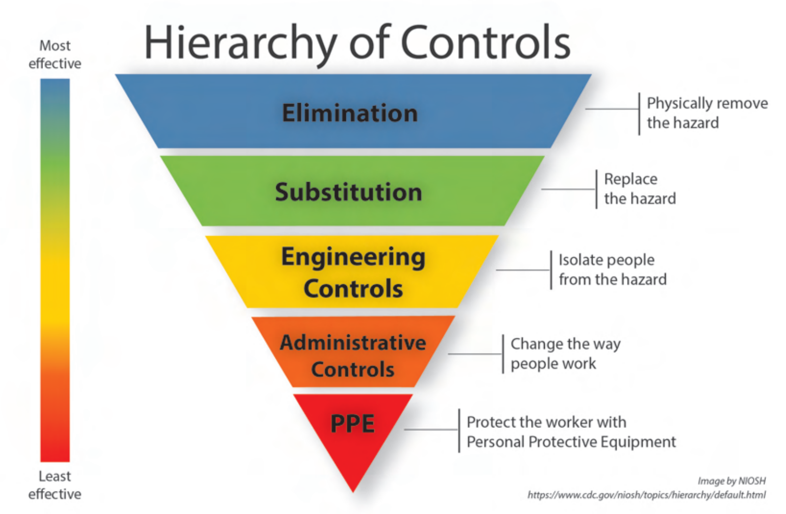


Figure 1.2: Hierarchy of controls. A process to reduce risk and a method to rank a solution's effectiveness at safeguarding a person from a hazard [20].

It is possible to easily compare various construction layouts, different medium and spacing's between the panes and different numbers of glass panes by creating a generalized model with acoustic transmission equations to determine the power loss as the sound propagates through a multi-layer window. This model can be used as a learning tool to rationalize experimental acoustic results and provides an understanding of how to design more acoustically isolating windows.

Acoustic propagation is a relatively well researched topic, and there are a variety of theoretical and experimental works in textbooks and research papers about acoustic propagation, specifically propagation through windows [16, 22, 23, 24, 25]. Many of the works provide very thorough theoretical and experimental analysis to model various types of acoustic scenarios that can't be replicated in an undergraduate thesis.

Figure 1.3: Double, triple and quadruple pane windows [21].

1.2.2 Contributions

The key contribution is using the experimental results presented for single layered acoustic transmission [24] and using them to complete a transmission line model that can be used to analyze more complex, multi-layered scenarios. The transmission line model is leveraged to compare the exponential loss mechanism of EM with the experimental results for both single and double-pane windows.

1.3 Road Map

The thesis has four chapters.

- Chapter 1 provides an introduction and background motivation on the importance and contribution of the thesis to the field of propagation.
- Chapter 2 covers the fish tracking model. It will highlight the underlying principles that the model simulates. The chapter will detail how the model was implemented including any important parameters and assumptions made. The chapter will provide verification of the results and the results for the model. It will then provide discussion points on the results relevant to the scenario.
- Chapter 3 covers the acoustic propagation model for multi-layer structures. It will highlight the underlying principles that the model simulates and delve deeper into the implementation of a multi-layer transmission line. The chapter will detail how the model was implemented including any important parameters and assumptions and it will then provide discussion points on the results.

- Chapter 4 concludes the thesis and provides future work suggestions for both the fish tracking and the acoustic model.

Chapter 2

Fish Tracking

The fish-tracking model uses propagation concepts to get an estimate of the signal strength of a fish at a specific spot in the river. Ideally this model would match with experimentally collected data however there are a variety of assumptions that need to be made. The model can be used as a basis providing information on how realistic it is to track spawning salmon using signal strength.

2.1 Assumptions

The assumptions to simplify the model include:

- The model does not include line-of-sight blockages like the cliffs present in the area under investigation.
- The transmitting antenna is treated as having an averaged gain in all directions, called Mean Effective Gain (MEG). Since we are unsure of the flow of the river or the direction the fish swims, it is impossible to know what angle the EM wave might be emanating from the transmitter. Using the MEG is a useful statistical approach to simplify the situation. The receiving antenna is stationary with a fixed orientation therefore the gain is taken from its gain pattern.
- No multi-path signals are considered. The only path considered is line-of-sight between the transmitter and receiver. This is an important omission since the model occurs within a canyon potentially creating many multi-path signals.
- All waves are assumed to be plane waves, simplifying the field equations and the relationships between the electric and magnetic fields.
- The pattern averaging means that the model uses half of the Transverse Electric (TE) polarisation and half of the Transverse Magnetic (TM) polarisation to describe how the plane wave travels across the water's surface.

- The plane wave crosses a flat surface, there are no waves or ripples in the model of the river surface.

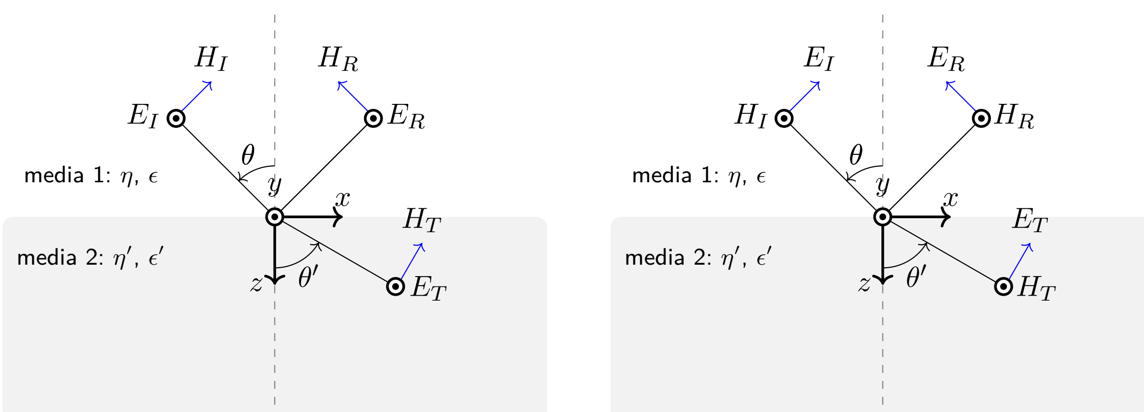
2.2 Underlying Principles

The approach for the salmon tracking propagation follows closely from wireless communications propagation, however a key difference is that this scenario requires transmission between two media, whereas most wireless propagation only involves free space. The key elements that the model include are: the air-water interface, the attenuation due to the water, the antenna gains and the spherical spreading of the EM wave.

2.2.1 Air - Water Interface

Two approaches were taken to model the air-water interface: a fields approach using the Poynting vector and using the Fresnel equations. The Fresnel equations result from the boundary conditions imposed on the electric and magnetic fields. Both the Poynting vector and the Fresnel equations result in the same solution.

Due to the geometry of the problem, the EM fields are obliquely incident on the surface and as such the plane wave needs to be decomposed into TE and TM modes [26].



(a) TE polarisation

(b) TM polarisation

Figure 2.1: TE and TM polarisation diagram.(a) TE polarisation, also commonly referred to as the perpendicular or s-polarisation. The electric field oscillates perpendicular to the plane of the diagram, (b) TM polarisation, also commonly referred to as the parallel or p-polarisation. The electric field oscillates in the plane of the diagram.

Field Approach

The fields approach uses both E and H fields to calculate the time-averaged power flux density using the Poynting vector of the incident wave in air and the transmitted wave in water. The below derivation follows for the TE scenario. With the fields known at any location we can calculate the time-averaged power flux density or equivalently the time-averaged Poynting vector:

$$\langle \vec{S} \rangle = \frac{1}{2}\,\mathrm{Re}\Big\{ \vec{E} \times \vec{H}^{*} \Big\}. \tag{2.1}$$

To obtain the ratio of the transmitted to incident power flux, we first start with the equation for the electric and magnetic fields in both media [8], where the apostrophe denotes the second medium, water:

$$E(r) = \hat{y}E_0[e^{-jk(x\sin\theta_i + z\cos\theta_i)} + \Gamma_{TE}e^{-jk(x\sin\theta_r - z\cos\theta_r)}] \tag{2.2}$$

$$E'(r) = \hat{y}\tau_{TE}E_0e^{-jk'(x\sin\theta' + z\cos\theta')} \tag{2.3}$$

$$\begin{aligned} H(r) = \frac{E_0}{\eta}\Big[&(-\hat{x}\cos\theta_i + \hat{z}\sin\theta_i)e^{-jk(x\sin\theta_i + z\cos\theta_i)} \\ &+ \Gamma_{TE}(\hat{x}\cos\theta_r + \hat{z}\sin\theta_r)e^{-jk(x\sin\theta_r - z\cos\theta_r)}\Big] \end{aligned} \tag{2.4}$$

$$H'(r) = \frac{E_0\tau_{TE}}{\eta'}\Big[(-\hat{x}\cos\theta' + \hat{z}\sin\theta')e^{-jk'(x\sin\theta' + z\cos\theta')}\Big]. \tag{2.5}$$

The complex reflection and transmission coefficients, Γ_{TE} and τ_{TE}, are given by the following Fresnel equations using the notation of [8] for now:

$$\Gamma_{TM} = \frac{\eta'\cos(\theta') - \eta\cos(\theta)}{\eta'\cos\theta' + \eta\cos\theta} \quad , \quad \Gamma_{TE} = \frac{\eta'\cos\theta - \eta\cos\theta'}{\eta'\cos\theta + \eta\cos\theta'} \tag{2.6}$$

$$\tau_{TM} = \frac{2\eta'\cos\theta'}{\eta'\cos\theta' + \eta\cos\theta} = 1 + \Gamma_{TM} \quad , \quad \tau_{TE} = \frac{2\eta'\cos\theta}{\eta'\cos\theta + \eta\cos\theta'} = 1 + \Gamma_{TE}. \tag{2.7}$$

The remaining variables can be written compactly as:

$$\text{Wave Number} = \begin{cases} k = \omega\sqrt{\mu_0\epsilon} \\ k_x = k\sin\theta, k_z = k\cos\theta \end{cases} \tag{2.8}$$

$$\text{Permittivity} = \begin{cases} \epsilon = \epsilon_R - j\epsilon_I \\ \epsilon_R = \epsilon_0\epsilon_r \end{cases} \tag{2.9}$$

$$\text{Wave Impedance: } \eta = \sqrt{\frac{\mu}{\epsilon}} \tag{2.10}$$

The imaginary portion of the permittivity of fresh water complicates the analysis in the water. We can use geometrical properties due to boundary conditions to simplify the analysis. Firstly, the wave number in the x-direction remains the same no matter what material the wave goes into:

$$k'_x = k_x. \tag{2.11}$$

Secondly, the z-component of the wave number changes due to the difference in permittivities. When dealing with non-magnetic materials, such as water and air, $\mu = \mu_0$ is constant across the boundary:

$$k'_z = k' \cos\theta' = \beta'_z - j\alpha'_z.$$

Using the wave numbers we see that the transmitted fields will have a spatial dependence that goes as:

$$e^{-jk'_z z} e^{-jk_x x} = e^{-\alpha'_z z} e^{-j(\beta'_z z + k_x x)}.$$

In the case of a lossy material the attenuation is due to $e^{-\alpha'_z z}$ and the travelling wave is the remaining parts. It is interesting to note that the attenuation portion is only due to the z-component of the wave as it travels.

In the case of the TE Mode, $E_x = 0, E_z = 0,$ and $H_y = 0$, we can split the overall E and H equations (2.5) into the incident, reflected and transmitted portion. Since the wave is continuous in the x-direction, (2.11), we only need to look in the z-direction to find the ratio of incident, reflected and transmitted power flux density. The z-component of the power flux density above the water, using notation from [10] for now, is:

$$P_{Air_z} = \frac{1}{2}\,\mathrm{Re}\Big\{\vec{E} \times \vec{H}^*\Big\}_z = \frac{|E_0|^2}{2\omega\mu_0} k_z \left(1 - |\Gamma_{TE}|^2\right) \tag{2.12}$$

where the incident and reflected fluxes in the z-direction are [8]:

$$P_{I_z} = \frac{1}{2}\,\mathrm{Re}\Big\{\vec{E} \times \vec{H}^*\Big\}_z = \frac{|E_0|^2}{2\omega\mu_0} k_z \tag{2.13}$$

$$P_{R_z} = \frac{1}{2}\,\mathrm{Re}\Big\{\vec{E} \times \vec{H}^*\Big\}_z = -\frac{|E_0|^2}{2\omega\mu_0} k_z |\Gamma_{TE}|^2 \tag{2.14}$$

$$P_{Air_z} = P_{I_z} + P_{R_z}. \tag{2.15}$$

The z-directed transmitted power flux density in the water is [8]:

$$P_{T_z} = \frac{|E_0|^2}{2\omega\mu_0} \beta'_z |\tau_{TE}|^2 e^{-2\alpha'_z z}. \tag{2.16}$$

The ratio of received to transmitted power is:

$$\frac{\text{Transmitted Power}}{\text{Initial Power}} = |\tau_{TE}|^2 \frac{\beta'_z}{k_z} e^{-2\alpha'_z z} = |\tau_{TE}|^2 \frac{\eta}{\cos\theta}\,\mathrm{Re}\left\{\frac{\cos\theta'}{\eta'}\right\} e^{-2\alpha'_z z}. \tag{2.17}$$

This can be generalized to TE and TM polarisations using the following definition for the wave impedance:

$$\eta_T = \begin{cases} \eta_{TE} = \frac{\eta}{\cos\theta} & \text{For the TE case} \\ \eta_{TM} = \eta\cos\theta & \text{For the TM case} \end{cases} \tag{2.18}$$

$$\frac{\text{Transmitted Power}}{\text{Initial Power}} = |\tau|^2 \eta_T \operatorname{Re}\left\{\frac{1}{\eta_T'}\right\} e^{-2\alpha_z' z}. \tag{2.19}$$

2.2.2 Attenuation

When using the Fresnel equations directly, the attenuation needs to be taken separately into account and added since the Fresnel equations only provide the boundary conditions for the fields and for the power at the air-water interface. Although the Fraser River is fresh water, at the site of the land slide there is an associated conductivity of the water. The attenuation due to the conductivity is given by the following variables adapted from [10]:

$$e^{-2\alpha_z' z} = e^{-2\operatorname{Re}\{jk_z' z\}} = e^{2\operatorname{Im} k_z' z} \tag{2.20}$$

$$\operatorname{Im}\{k_z'\} = \operatorname{Im}\left\{\sqrt{\omega^2 \mu_0 \epsilon' - k_x^2}\right\} \tag{2.21}$$

$$\alpha_z' = \left[\frac{\sqrt{(\omega^2 \mu_0 \epsilon_R' - k_x^2)^2 + (\omega^2 \mu_0 \epsilon_I')^2} - (\omega^2 \mu_0 \epsilon_R' - k_x^2)}{2}\right]^{\frac{1}{2}} \tag{2.22}$$

with the permittivity as defined by (2.9). The attenuation due to the conductive losses contains an angular dependence with the k_x term, however, due to the small conductivity value, the difference in attenuation between normal incidence and 90° incidence is only 0.08 dB at a depth of five meters. For the depths of interest, the incident angle does not impact the attenuation.

2.2.3 Transmission Lines

Using a two-layer semi-infinite transmission line model, see Figure 2.2, it is possible to obtain the same values as either the fields approach or the combined Fresnel equations and attenuation term.

It is important to recast the EM variables, wave impedance and wave number, into transmission line equation variables, characteristic impedance, and propagation constant. The transmission line explicitly works for one dimension of propagation, yet still models oblique incidence, since the lossy propagation parameters are derived solely from the terms perpendicular to the interface, as shown in (2.16) and (2.15). The characteristic impedance of the transmission line is equal to the transverse wave impedance that is used when analyzing

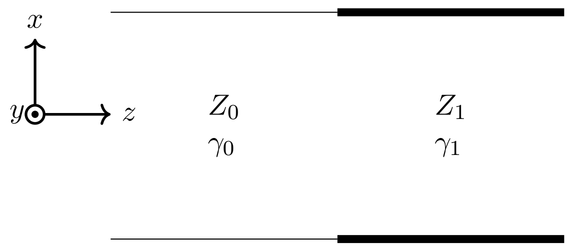


Figure 2.2: Semi-infinite transmission line modelling the air-water interface and attenuation within the water. In our model the water is viewed as infinitely deep therefore there are no reflections at the bottom of the river.

the problem from a fields perspective:

$$Z = \begin{cases} \eta_{TE} = \frac{\eta}{\cos\theta} & \text{TE polarisation} \\ \eta_{TM} = \eta\cos\theta & \text{TM polarisation} \end{cases} \tag{2.23}$$

The complex propagation constant is related to the wave number, here expressed as:

$$\gamma = jk_z = \alpha_z + j\beta_z. \tag{2.24}$$

Whereas with EM fields we are dealing with E and H fields, with the transmission line we use voltages and currents. The general solutions to the transmission line follow from a wave equation:

$$V(z) = V_0\left(e^{-\gamma_0 z} + \Gamma_T e^{\gamma_0 z}\right) \quad , \quad I(z) = \frac{V_0}{Z_0}\left(e^{-\gamma_0 z} - \Gamma_T e^{\gamma_0 z}\right). \tag{2.25}$$

The γ_0 refers to γ in free space. The reflection and transmission coefficient given in terms of impedance are:

$$\Gamma_T = \frac{Z_1 - Z_0}{Z_1 + Z_0} \quad , \quad \tau = \frac{2Z_1}{Z_1 + Z_0}. \tag{2.26}$$

The specific solution for the semi-infinite transmission line is known:

$$V(z), I(z) = \begin{cases} V(z) = V_0 e\left(e^{-\gamma_0 z} + \Gamma_T e^{\gamma_0 z}\right) & z \leq 0 \\ I(z) = \frac{V_0}{Z_0}\left(e^{-\gamma_0 z} - \Gamma_T e^{\gamma_0 z}\right) & z \leq 0 \\ V(z) = V_1 e^{-\gamma_1 z} & z \geq 0 \\ I(z) = \frac{V_1}{Z_1} e^{-\gamma_1 z} & z \geq 0 \end{cases}$$

The voltage and current must be continuous across the boundary. Placing the boundary at $z = 0$, we obtain that $V(0^-) = V(0^+)$ and $I(0^-) = I(0^+)$, reducing our solutions to:

$$V(0) = V_0(1 + \Gamma_T) = V_1 \tag{2.27}$$

$$I(0) = \frac{V_0}{Z_0}(1 - \Gamma_T) = \frac{V_1}{Z_1} \tag{2.28}$$

$$V_1 = V_0(1 + \Gamma_T) \tag{2.29}$$

$$V_1 = \frac{V_0 Z_1}{Z_0}(1 - \Gamma_T) \tag{2.30}$$

The power, here in watts rather than power density in watts/m^2, at any point can be calculated using:

$$P = \frac{1}{2}\,\mathrm{Re}\{V(z)I(z)^*\} \tag{2.31}$$

with V_0 and I_0 being the maximum amplitude values. The power input to the transmission line is given by:

$$P_{in} = \frac{|V_0|^2}{2Z_0}. \tag{2.32}$$

The power at any point l in the water can be given as:

$$P(l) = \frac{1}{2}\,\mathrm{Re}\left\{\frac{1}{Z_1^*}\right\}|V_1|^2 e^{-2\alpha l} = \frac{|V_0|^2}{2Z_0}\left(1 - |\Gamma_T|^2\right) e^{-2\alpha l}. \tag{2.33}$$

Taking the ratio of received to transmitted power:

$$\frac{P(l)}{P_{in}} = \frac{\frac{1}{2}\,\mathrm{Re}\left\{\frac{1}{Z_0^*}\right\}|V_0|^2\left(1 - |\Gamma_T|^2\right) e^{-2\alpha l}}{\frac{1}{2}\,\mathrm{Re}\left\{\frac{1}{Z_0^*}\right\}|V_0|^2} = \left(1 - |\Gamma_T|^2\right) e^{-2\alpha l} = |\tau|^2\,\mathrm{Re}\left\{\frac{\eta_T}{\eta_T'}\right\} e^{-2\alpha l}, \tag{2.34}$$

we observe the transmission line model yields accurate results for oblique incidence into a lossy medium, and these results align with the previous two sections (2.19).

2.2.4 Transmit and Receive Antennas

The implementation of the antennas into the propagation model follows two steps: the directional gain of the antenna and the polarisation mismatch due to the alignment of the antennas.

Gain of the Antenna

The directivity of the antenna provides information on the ratio of radiation intensity in a given direction from the antenna to the total radiation density in all directions. It requires both information on the co-polar power and cross-polar power patterns. The directivity is calculated as follows:

$$D(\theta_0, \phi_0) = \frac{|\mathbf{g}(\theta_0, \phi_0|^2}{\frac{1}{4\pi}\int_0^{2\pi}\int_0^{\pi} |\mathbf{g}(\theta, \phi)|^2 \sin\theta \, d\theta d\phi}, \tag{2.35}$$

where $\mathbf{g}(\theta, \phi)$ is the electric field pattern:

$$\mathbf{g}(\theta, \phi) = g_\theta(\theta, \phi)\hat{\theta} + g_\phi(\theta, \phi)\hat{\phi}. \tag{2.36}$$

The gain of the antenna is given by the directivity of the antenna and the antenna efficiency [27] and can be expressed as:

$$G(\theta, \phi) = \eta_{ant} D(\theta, \phi) \tag{2.37}$$

The antenna efficiency includes the ohmic losses but not any feed mismatch loss, the *realized* gain includes both [28].

Mean Effective Gain

In a mobile setting, oftentimes used for mobile communications, a MEG will be used instead of a directive gain to describe the behaviour of an antenna under a statistical distribution of incoming waves. This technique can be leveraged in the fish transmitter scenario as the MEG can be used to statistically account for the motion of the fish and its transmitter.

$$MEG = \int \left(\frac{XPD}{1+XPD} P_\theta(\Omega) G_\theta(\Omega) + \frac{1}{1+XPD} P_\phi(\Omega) G_\phi(\Omega) \right) d\Omega \tag{2.38}$$

$$= \eta \int \left(\frac{XPD}{1+XPD} P_\theta(\Omega) D_\theta(\Omega) + \frac{1}{1+XPD} P_\phi(\Omega) D_\phi(\Omega) \right) d\Omega \tag{2.39}$$

$$XPD = \frac{P_\theta}{P_\phi} \tag{2.40}$$

with P_θ the total power in θ-polarisation and P_ϕ the total in the ϕ-polarisation [27]. XPD is defined as "the ratio between two average polarisation powers" [27].

The power quantities and directivity are normalised such that:

$$\int P_\theta(\Omega) d\Omega = 1 \tag{2.41}$$

$$\int P_\phi(\Omega) d\Omega = 1. \tag{2.42}$$

In a completely random environment with the incoming wave being uniform in three dimensions, we can take $XPD = 1$ and the power in each polarisation to be $P_\theta = P_\phi = \frac{1}{4\pi}$.

The MEG will then evaluate to be half of the efficiency of the radiating antenna [29, 27].

$$MEG_{\text{random}} = \eta \int \left(\frac{1}{1+1} \frac{1}{4\pi} D_\theta(\Omega) + \frac{1}{1+1} \frac{1}{4\pi} D_\phi(\Omega) \right) d\Omega = \frac{\eta}{2} \tag{2.43}$$

2.2.5 Spherical Spreading

Plane waves do not have any spherical spreading, therefore a term is added in free space calculations to account for the geometric spreading. The model has the added complication that the source continues to spread as it crosses the air-water interface. Instead of calculating the path loss for each portion, we add the distance-to-wavelength ratios of both the air and water component.

$$\text{Path gain due to spherical spreading} = \left(\frac{1}{4\pi \left(\frac{d_1}{\lambda_1} + \frac{d_2}{\lambda_2} \right)} \right)^2 \tag{2.44}$$

In this scenario d_1, and λ_1 are the distance the ray travels and the wavelength in air. d_2 and λ_2 are similarly defined for water. Since we are calculating a point-to-point gain, the (2.44) term accounts for the spherical radiation that occurs in all directions and not just in two-dimensional space. At 150 MHz, $\lambda_1 = 1.9986$ m and $\lambda_2 = 0.2221$ m.

2.2.6 Total Path Loss

The total path loss, inverse of path gain, can be best expressed using the Friis path loss equation with some modification. The Friis equation is derived solely for free space [30] therefore we have to add meaningful additions to account for the air-water interface and the subsequent attenuation. The original Friis equation can be written as:

$$\frac{P_r}{P_t} = G_t G_r \left(\frac{\lambda}{4\pi d} \right)^2 \tag{2.45}$$

where G_t and G_r are the gains of the transmitting and receiving antenna respectively. Using the modified spherical spreading, the conductive attenuation, the polarisation mismatch and the reflected power at the air-water interface, we can adapt the Friis free space equation to the following form:

$$\frac{P_r}{P_t} = G_t G_r \left(\frac{1}{4\pi \left(\frac{d_1}{\lambda_1} + \frac{d_2}{\lambda_2} \right)} \right)^2 |\tau|^2 \operatorname{Re}\left\{ \frac{\eta_T}{\eta_T'} \right\} e^{-2\alpha_z' z} \eta_{pol} \tag{2.46}$$

where τ, η_T and η_T' are selected as either their TE or TM values depending on the scenario. The spherical spreading term is (2.44). The conductive attenuation is (2.20). The polarisation mismatch is η_{pol}. Here, it is assumed that η_{pol} represents an averaged polarisation mismatch between the transmit and receive antennas. The reflected power at the air-water interface is given by equation(2.19).

2.3 Model Implementation and Verification

The fish tracking model was implemented using Matlab. Dr. Evan Byrnes and the RDL provided csv rasters for each of the 13 receivers set up along the Big Bar Fraser River site. These rasters included the following data: height of the antenna, distances from the antenna to the 20,814 latitude and longitudes of the rivers surface, the bearing and the pitch of the antenna and a variety of other data. The model output is a csv file including the site name, the longitude and latitude of a spot on the river surface, depth in the river ranging from -0.1 m to -1.6 m, the gain value of TE and TM polarisations and an equally weighted combination of the two, 0.5(TE+TM), antenna latitude and longitude and the height of the antenna.

In order to provide a meaningful comparison for the river conditions during the experimental data collection, low tide, and when the fish will pass through the river site, each antenna site was run ranging the offset height from -1 m to +15 m. A 15 m offset means that the river is 15 m closer to the Yagi-Uda receiving antenna than at the time of measurement. The rasters of predicted gain data provided by this thesis alongside experimental data collected by the DFO and the RDL will then be fed into a machine learning model developed to determine the final prediction location of the fish based on the received signal strength.

For our model we used the following values and constants. The conductivity was the only value that was measured and provided by the DFO:

$$\epsilon_0 = 8.854 \times 10^{-12} \text{ F/m}$$
$$\epsilon_r' = 81$$
$$\mu_0 = 4\pi \times 10^{-7} \text{ H/m}$$
$$\sigma = 0.014 \text{ S/m}$$
$$f = 150 \text{ MHz.}$$
$$\epsilon' = \epsilon_0 \epsilon_r' - j\frac{\sigma}{\omega}$$

2.3.1 Media Interface

The first step is to calculate the loss due to the Fresnel equations, (2.6) and (2.7), on the raster. In reality the salmon is the transmitter and the Yagi-Uda is the receiver, however due to the nature of the Fresnel equations it is possible that a point source emanating from the salmon would not necessarily meet the Yagi-Uda as a point-to-point ray. Using either the Yagi-Uda as the transmitter or the salmon tag as the transmitter results in the same total path gain. At this stage, a basic model is made that considers the propagation across the river surface depending on the angle of incidence. A shortened raster of the river site for one of the locations is shown in Figure 2.3 with the angles of incidence from the Yagi-Uda. Based on the angles of incidence, the Fresnel TE and TM polarisation transmissivity values are shown in the following two plots, Figure 2.4. This represents the amount of power that gets transmitted at the surface of the river.

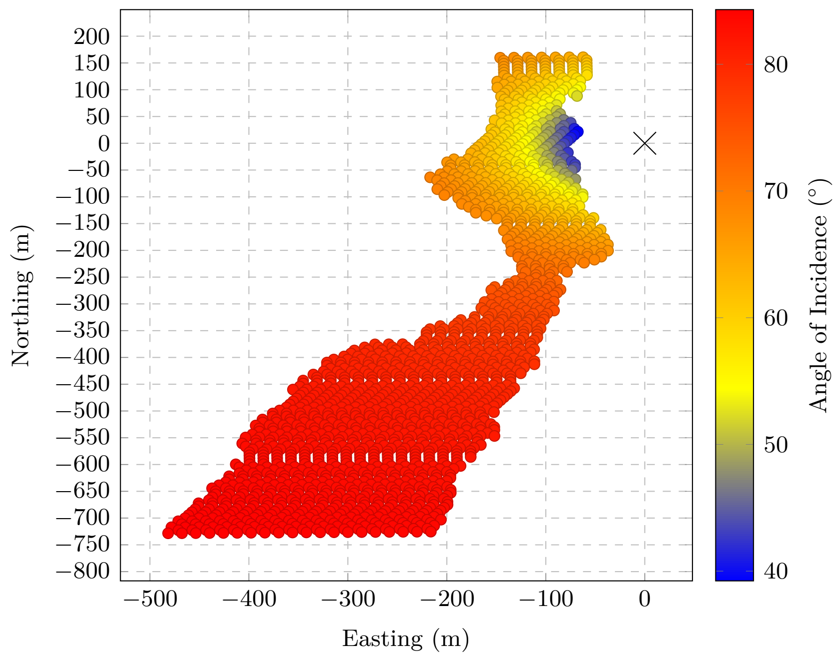


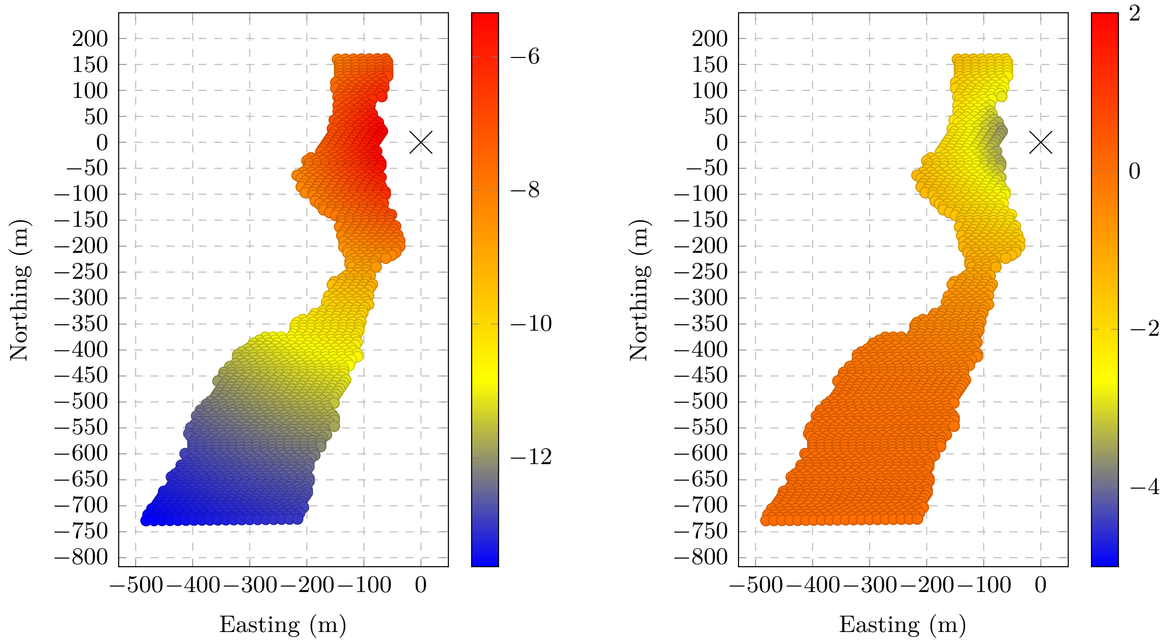
Figure 2.3: Angle of incidence in degrees at the air-water interface across the river site for the Eastside downstream receiver. The angle is defined as the angle from the normal to the surface of the river. The Eastside downstream receiver is located at 10U 559418.259 km E, 15674469.934 km N.

2.3.2 Attenuation and Spherical Loss

The two remaining propagation losses are added. The first propagation loss is due to spherical spreading of the EM wave, (2.44), and the second is due to the attenuation within the water (2.20). The impact of the spherical spreading of the EM wave is presented in Figure 2.5 and Figure 2.6.

Although the antennas are situated in different locations, the iBeam antenna is 36 m to the water and the Eastside antenna is 240 m, the spherical spreading relationship, (2.44) means that most of the power loss occurs in the first few meters after the transmission.

The attenuation in water exhibits a linear loss in dB relative to the depth of water that is independent of the incoming angle. This is because the conductivity was measured to be very small. Therefore, the conductive attenuation does not differentiate between antenna sites.



(a) Eastside downstream TE

(b) Eastside downstream TM

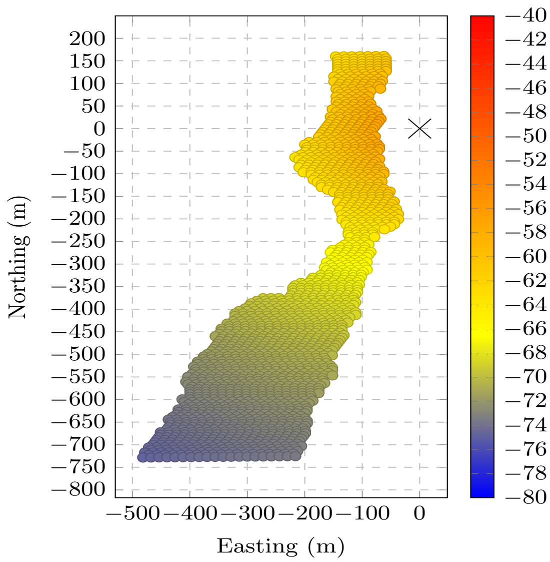
Figure 2.4: The calculated transmissivity, $|\tau|^2 \operatorname{Re}\left\{\frac{\eta_T}{\eta'_T}\right\}$ (dB), due to the wave crossing the air-water interface. a) Fresnel TE - Transmissivity (dB). b) Fresnel TM - Transmissivity (dB).

2.3.3 Transmit and Receive Antennas

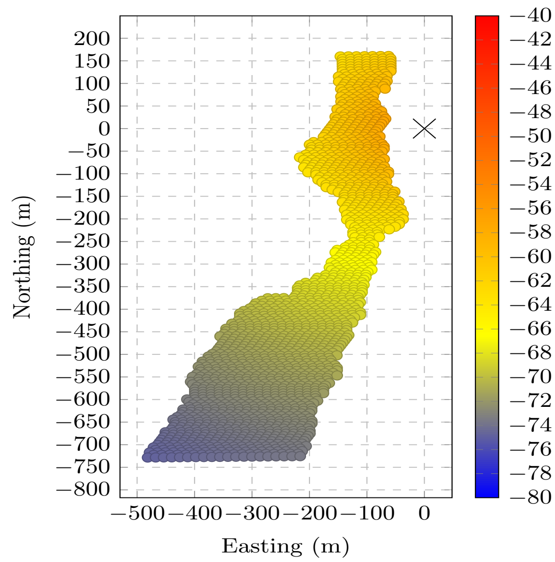
Following the loss terms, the antenna gains are added to complete the Friis equation (2.47). The radiation patterns of both transmitting and receiving antenna couldn't be verified experimentally since our pattern measurement chambers do not go to a low enough frequency.

Gain of the Antennas

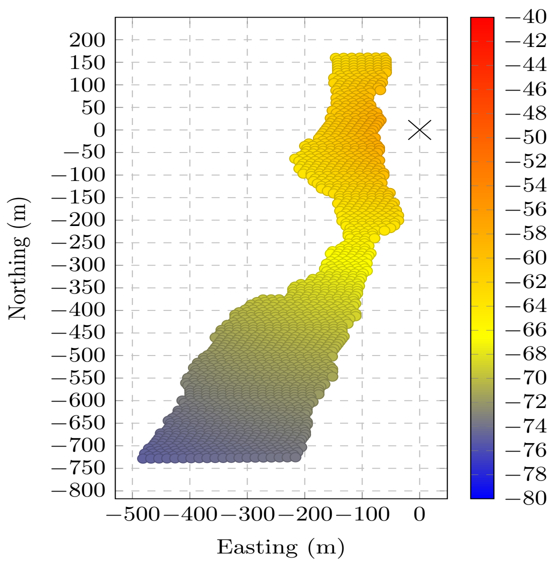
The receive antenna was a three element Yagi-Uda antenna. Photos of the experimental gain profile of the Yagi-Uda antennas were received from the manufacturer. The azimuthal and elevation plots that were received indicated there was an error in the analysis of the radiation pattern. The peak gain in the azimuthal plot did not correspond to the peak gain in the elevation plot. However, the difference was marginal, approximately one dB between the cuts. The elevation plot was selected, and it was assumed that the radiation pattern was symmetrical around the boom of the Yagi-Uda antenna. Yagi-Uda antennas do contain a high level of symmetry. The data points were extrapolated visually from the photo into a csv file. With these points, an interpolation was done in Matlab to calculate the gain of the antenna at any point. The final Matlab model of the Yagi-Uda gain pattern can be seen in Figure 2.7.



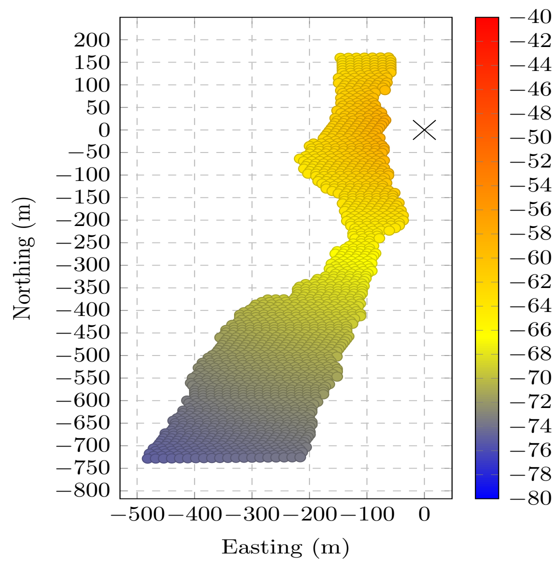
(a) Eastside Path Loss 0.1 m



(b) Eastside Path Loss 0.6 m



(c) Eastside Path Loss 1.1 m

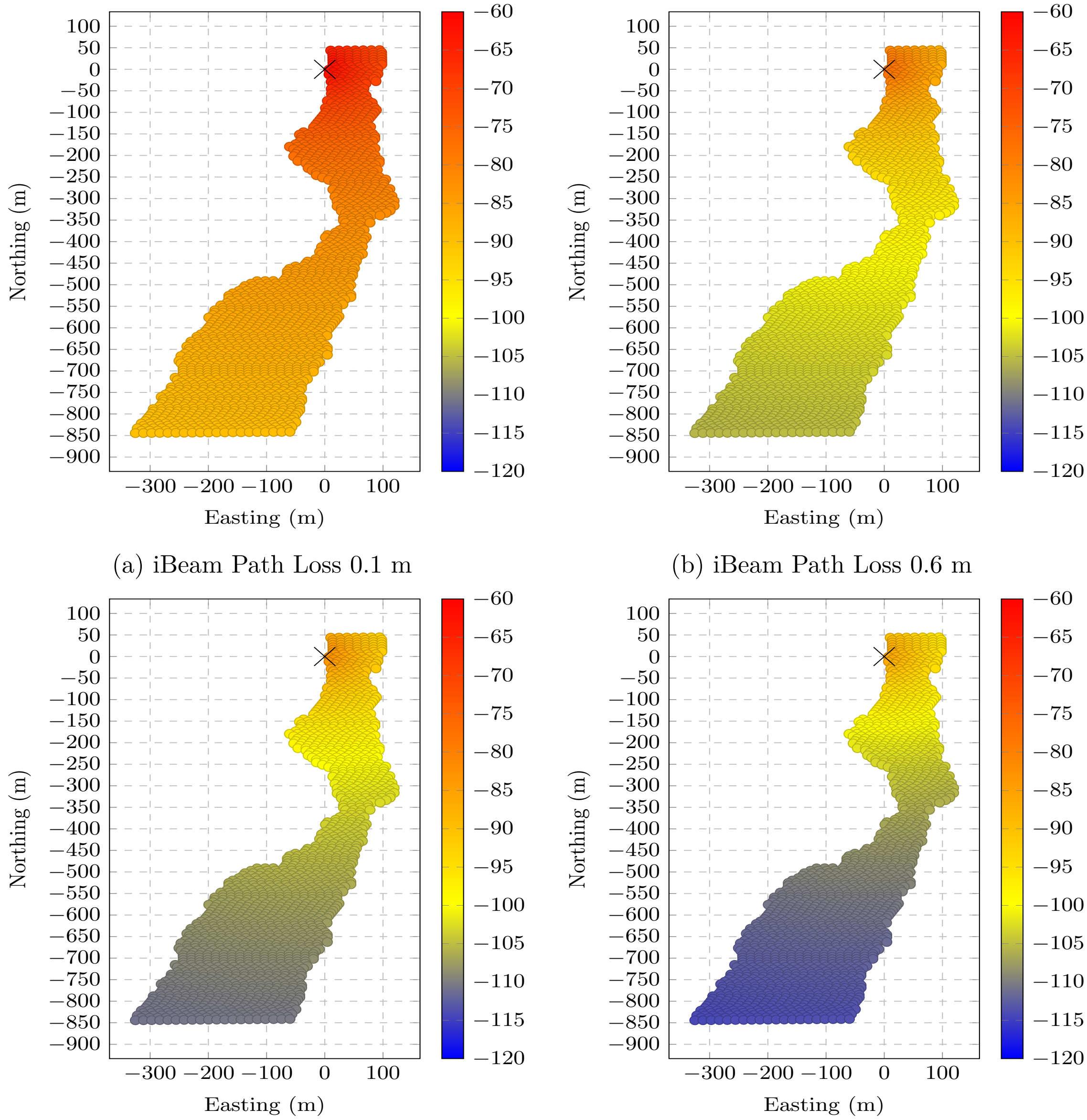


(d) Eastside Path Loss 1.6 m

Figure 2.5: Spherical spreading loss at Eastside downstream site (dB).

For each coordinate point on the surface of the river, the model calculated the angle in both elevation and azimuthal planes between the boom of the antenna and the location of the water's surface. The symmetry of the radiation pattern around the boom allowed the maximum of these two angles to be used to provide the final gain value, this value was G_R. The gain in-situ for two sites is presented in Figure 2.8 showcasing the spherical nature of the main lobe.

There are two different transmit antennas used by the DFO, the Sigma Eight TX-PSC-I-1200 and a Lotek MCFT3-3A tag. These tags consist of a small electronics capsule



(a) iBeam Path Loss 0.1 m

(b) iBeam Path Loss 0.6 m

(c) iBeam Path Loss 1.1 m

(d) iBeam Path Loss 1.6 m

Figure 2.6: Spherical spreading loss at iBeam P1 site (dB). The iBeam P1 site is located at 10U 559261.998 km E, 15674586.021 km N.

attached to a dipole that is anywhere from 27.6 - 31.5 cm. In use, the capsule gets inserted into the fish's mouth and the dipole is left trailing out of the mouth and along the length of the fish. No data was provided for the operation of these devices therefore a simulation was carried out. The simulation included a 30 cm dipole, electrically short in free space, that was aligned with the electronics capsule, see Figure 2.9. The resultant directivity pattern was that of an electrically *long* dipole with multiple lobes, see Figure 2.9. Due to the complexity of the physical implementation of this antenna, the dipole being able to bend and rotate

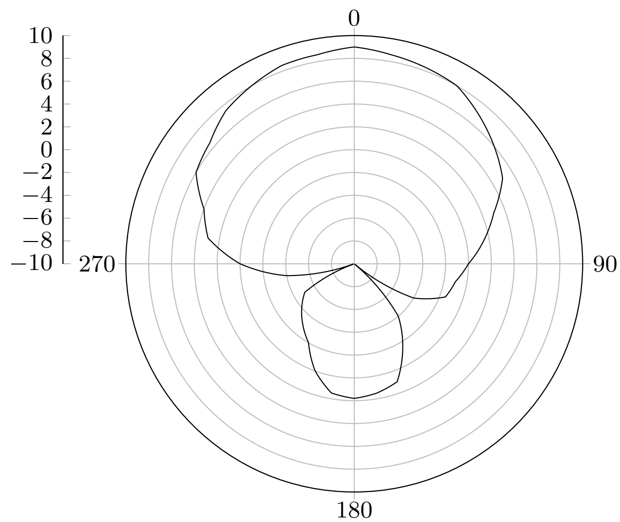
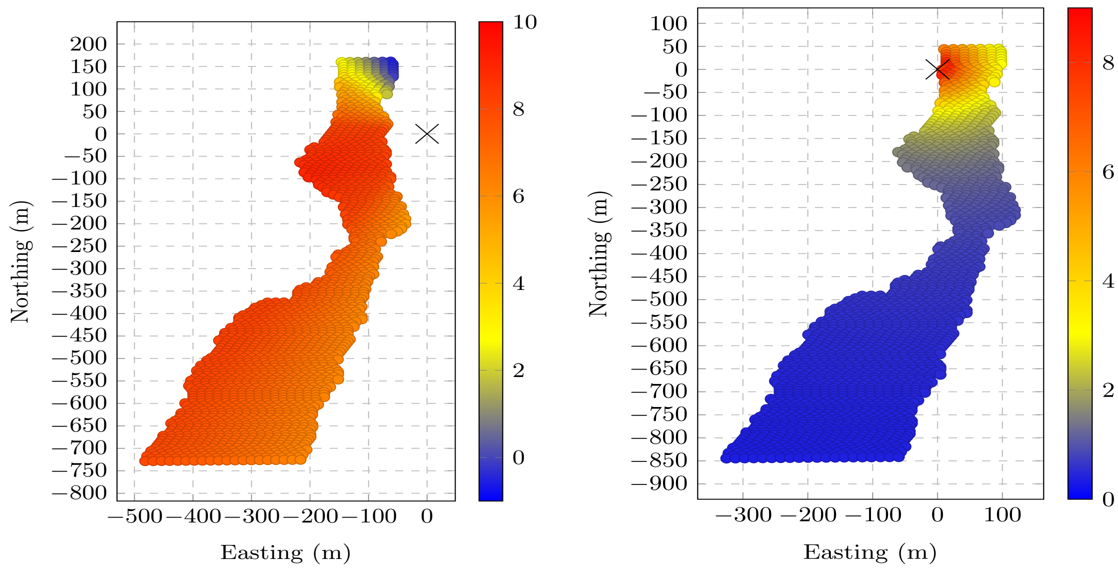


Figure 2.7: Interpolated Yagi-Uda Gain.

around the fish, the fish changing orientation, and the currents impacting both the fish and the antenna, an MEG was taken instead of a directive gain. Assuming the incoming wave distribution is omni-directional and equally-polarized, the MEG is evaluated to be half of the efficiency, (2.43). Under the model of a perfect electric conductor, the efficiency of the antenna is 0 dB i.e. 100%. If we include an approximation that the transmitting antenna is impedance matched but has a radiation efficiency of $\eta = -1$ dB and we then factor half of the power (2.43), resulting in -3 dB, the overall mean effective realized gain is -4 dB, this value was taken for G_T in the simplified Friis equation below.



(a) Eastside Yagi-Uda Gain Pattern

(b) iBeam Yagi-Uda Gain Pattern

Figure 2.8: Yagi-Uda Gain Pattern in situ (dB). a) Eastside downstream receiver location. b) iBeam p1 receiver location.

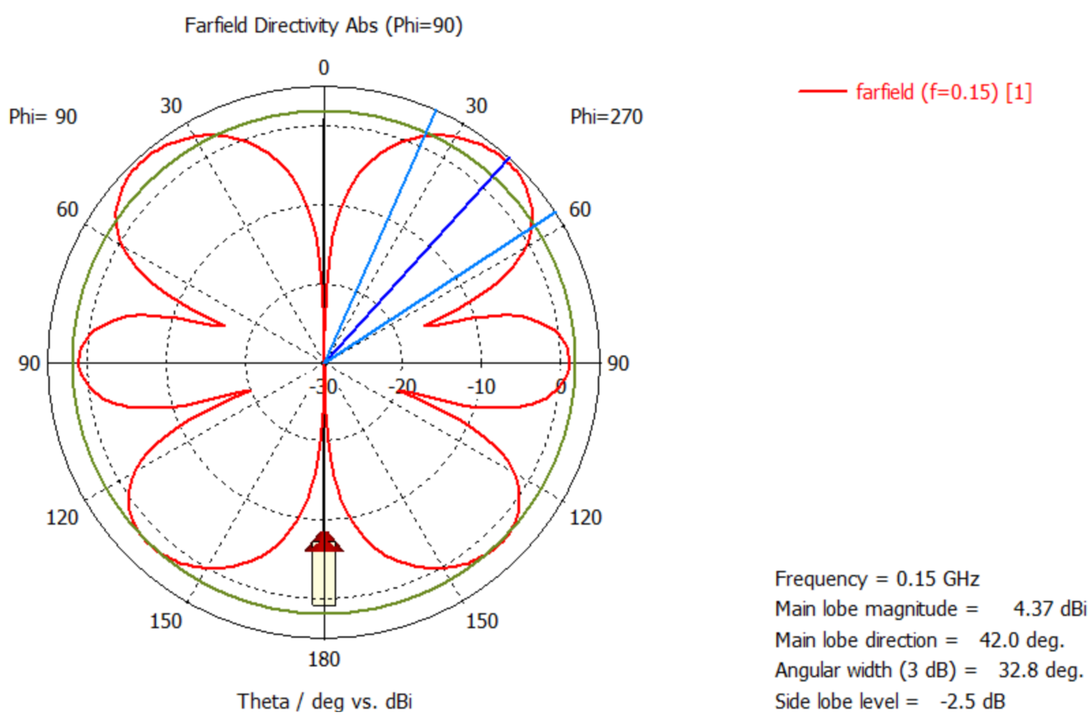


Figure 2.9: Simulation of directivity of a transmitter similar to the Sigma Eight TX-PSC-I-1200 and Lotek MCFT3-3A transmitter. Plot generated by, and used with permission from Dr. Christopher Hynes.

Polarisation Mismatch of Air-Water Interface

An option for future work is to implement a more complex and potentially accurate polarisation matching system. A correct polarisation mismatch could not be implemented in this thesis due to the lack of data on the position and orientation of the fish transmitter. Instead of using the exact polarisation mismatch, a statistical approximation was taken where the plane wave was decomposed equally with half of the signal being TE polarisation and the other half TM polarisation. The two antennas were also assumed to have a polarisation mismatch of $\eta_{pol} = -3$ dB in the model. The total path loss equation then becomes:

$$\frac{P_r}{P_t} = G_t G_r \left(\frac{1}{4\pi \left(\frac{d_1}{\lambda_1} + \frac{d_2}{\lambda_2} \right)} \right)^2 e^{-2\alpha'_z z} \tag{2.47}$$

$$\times \frac{1}{2} \left(|\tau_{TE}|^2 \operatorname{Re}\left\{ \frac{\eta_{TE}}{\eta'_{TE}} \right\} + |\tau_{TM}|^2 \operatorname{Re}\left\{ \frac{\eta_{TM}}{\eta'_{TM}} \right\} \right) \eta_{pol}. \tag{2.48}$$

Note that it has been assumed here that there is a single polarisation mismatch efficiency term, η_{pol}, and the total power is equal in each polarisation.

2.4 Results

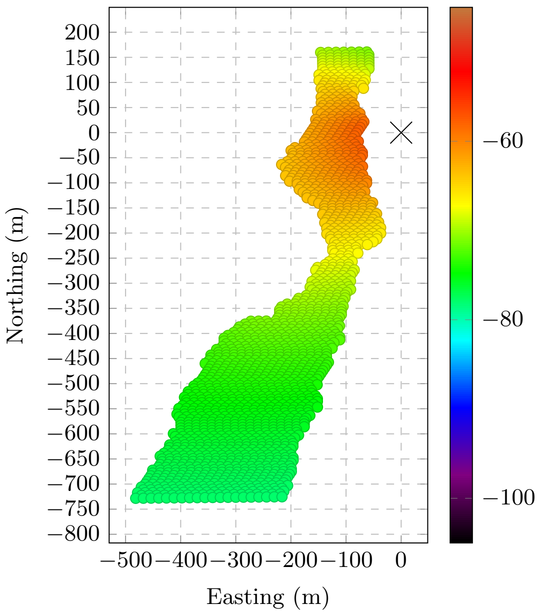
As previously mentioned, the polarisation that was selected was half of the TE and half of the TM polarisation. Although this is the final result, the TE and the TM polarisation are presented individually in Appendix A.2 to highlight the differences and the impact that these differing polarisations have on the overall system. Individually the TE and the TM polarisations share similarities with the combined polarisation plots in terms of the spatial gain resolution trends. If a receiver location demonstrates high spatial resolution with the combined polarisation plots, the TE and TM polarisations will individually show similar resolution. The key difference however between combined polarisation and single polarisation occurs for locations in the river that are far from the receiver, in these limits the TE polarisation plots show the signal strength decreasing faster compared to the TM. The combined polarisation plot does not show this difference.

2.4.1 TE and TM

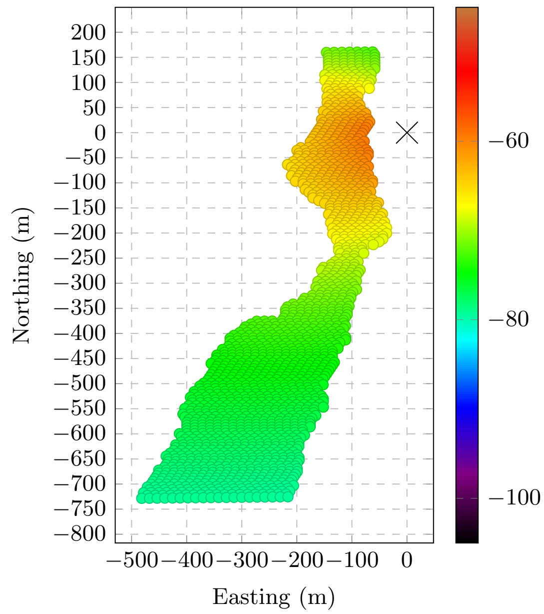
Setting the scene for the figures below,

- The Eastside downstream receiver is pointed at a bearing of 245° angled at 20° below horizontal. Its closest point to the water is 112 m away.
- The iBeam p1 receiver is angled at 45° below horizontal. Its closest point to the water is 36 m away.

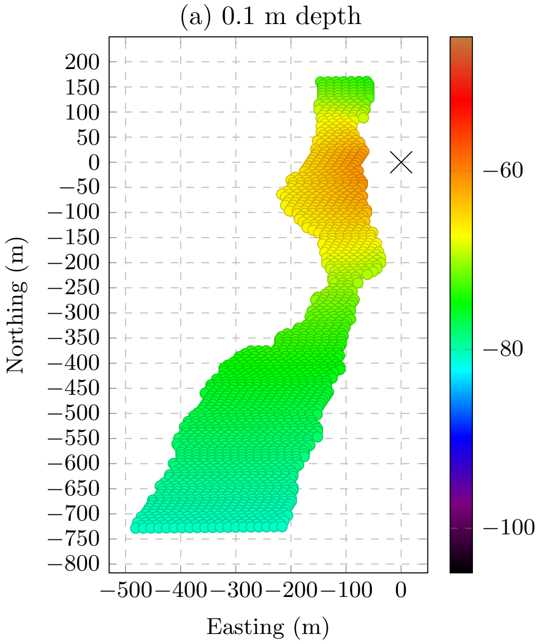
- The Razorback upstream receiver is pointed at a bearing of 113° angled at 18.8° below horizontal. Its closest point to the water is 76 m away.



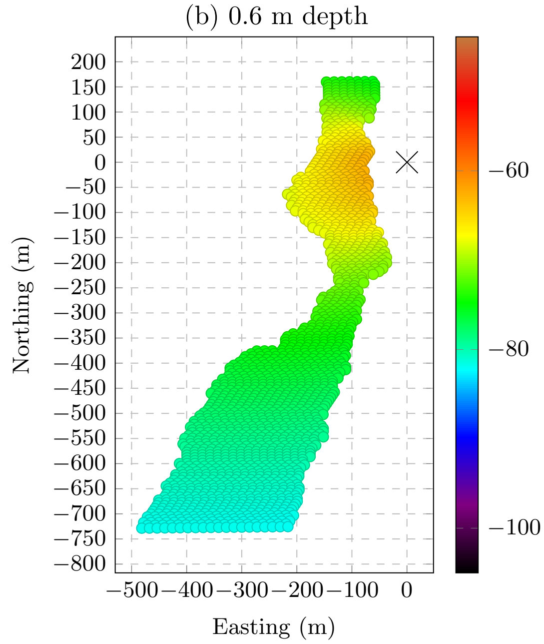
(a) 0.1 m depth



(b) 0.6 m depth

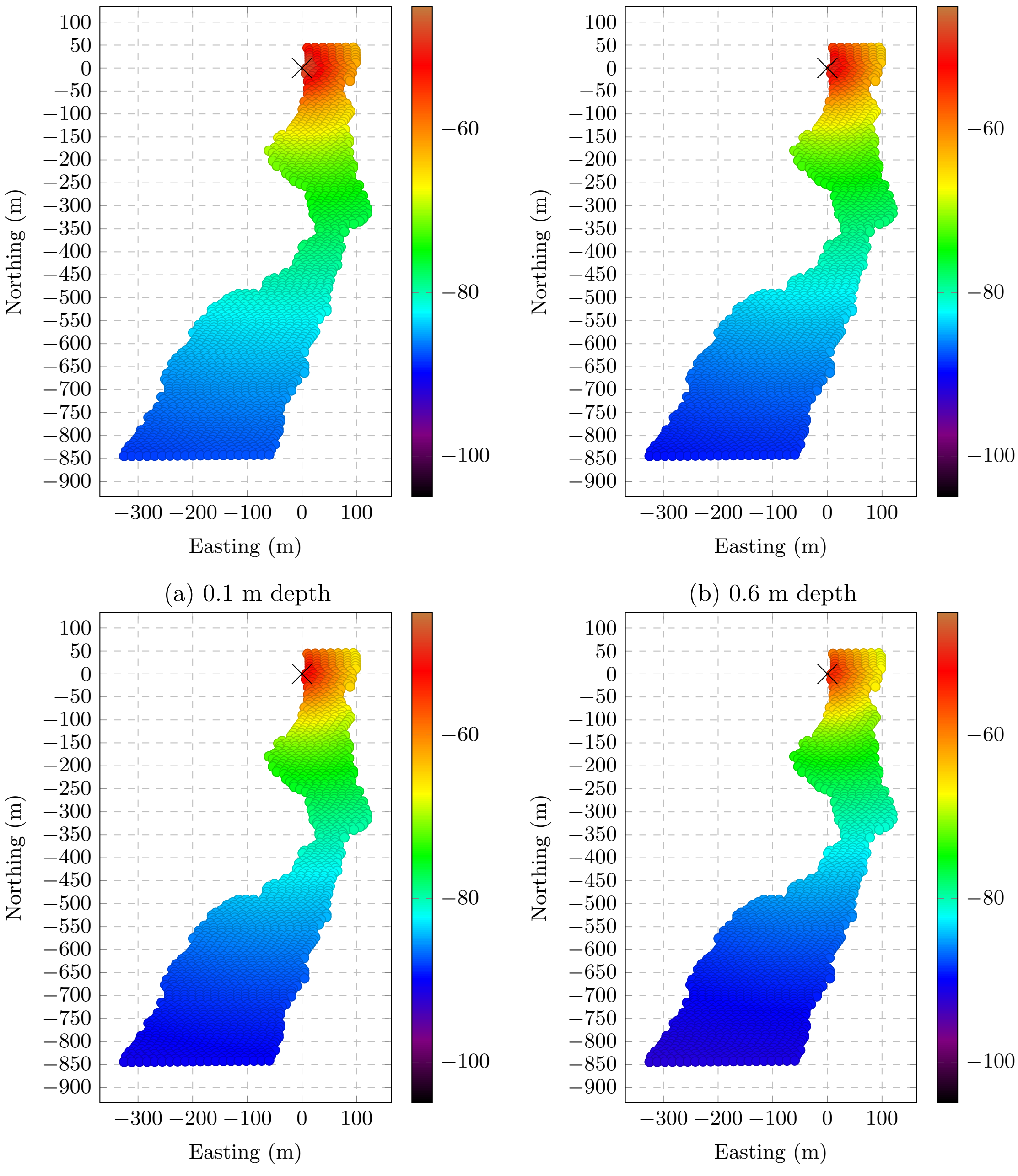


(c) 1.1 m depth



(d) 1.6 m depth

Figure 2.10: Total system loss 0.5(TE+TM) - Eastside downstream site (dB).



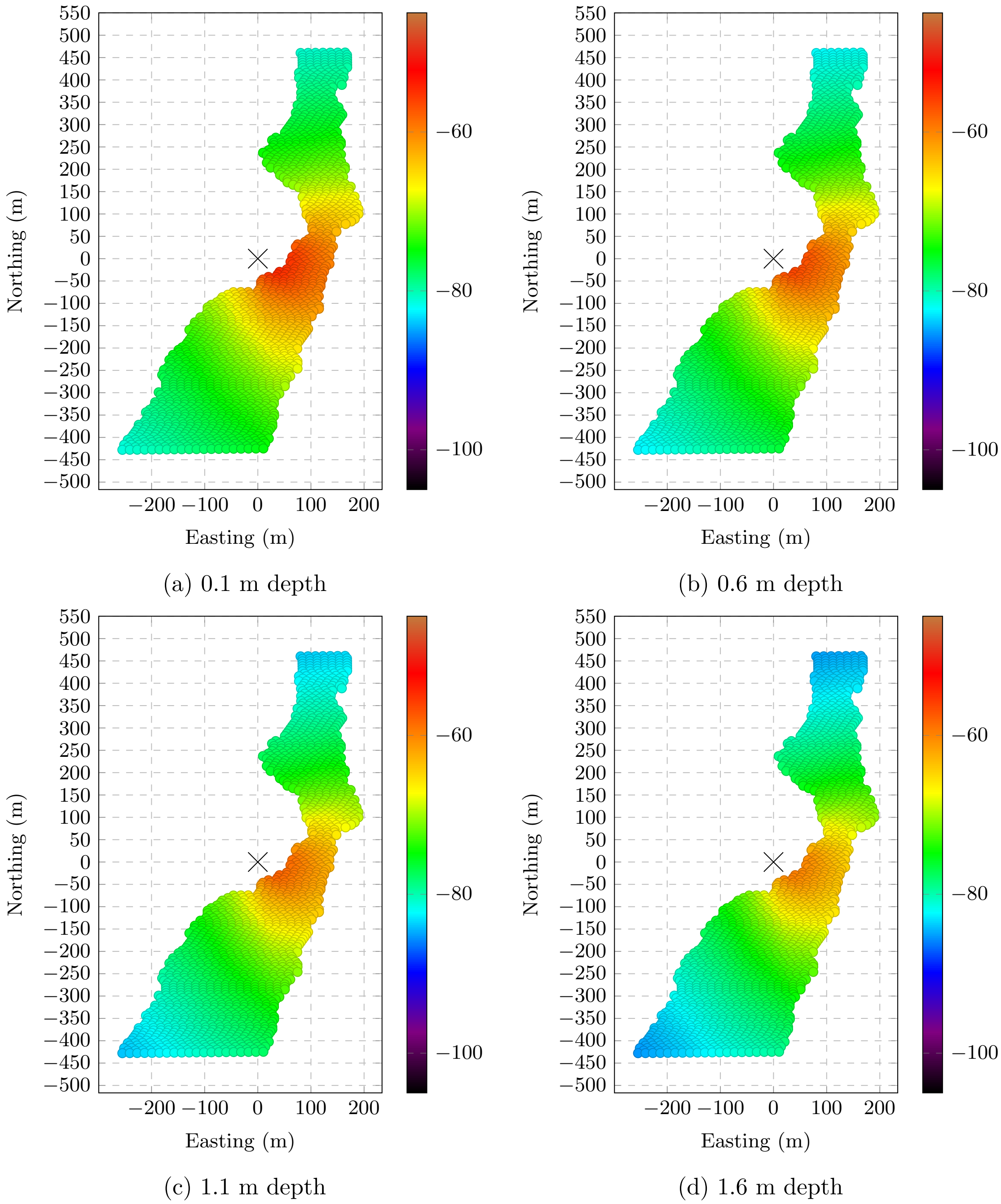
(a) 0.1 m depth

(b) 0.6 m depth

(c) 1.1 m depth

(d) 1.6 m depth

Figure 2.11: Total system loss 0.5(TE+TM) - iBeam p1 site (dB).



(a) 0.1 m depth

(b) 0.6 m depth

(c) 1.1 m depth

(d) 1.6 m depth

Figure 2.12: Total system loss 0.5(TE+TM) - Razorback upstream site (dB). Razorback upstream is located at 10U 559191.649 km E, 15674169.357 km N.

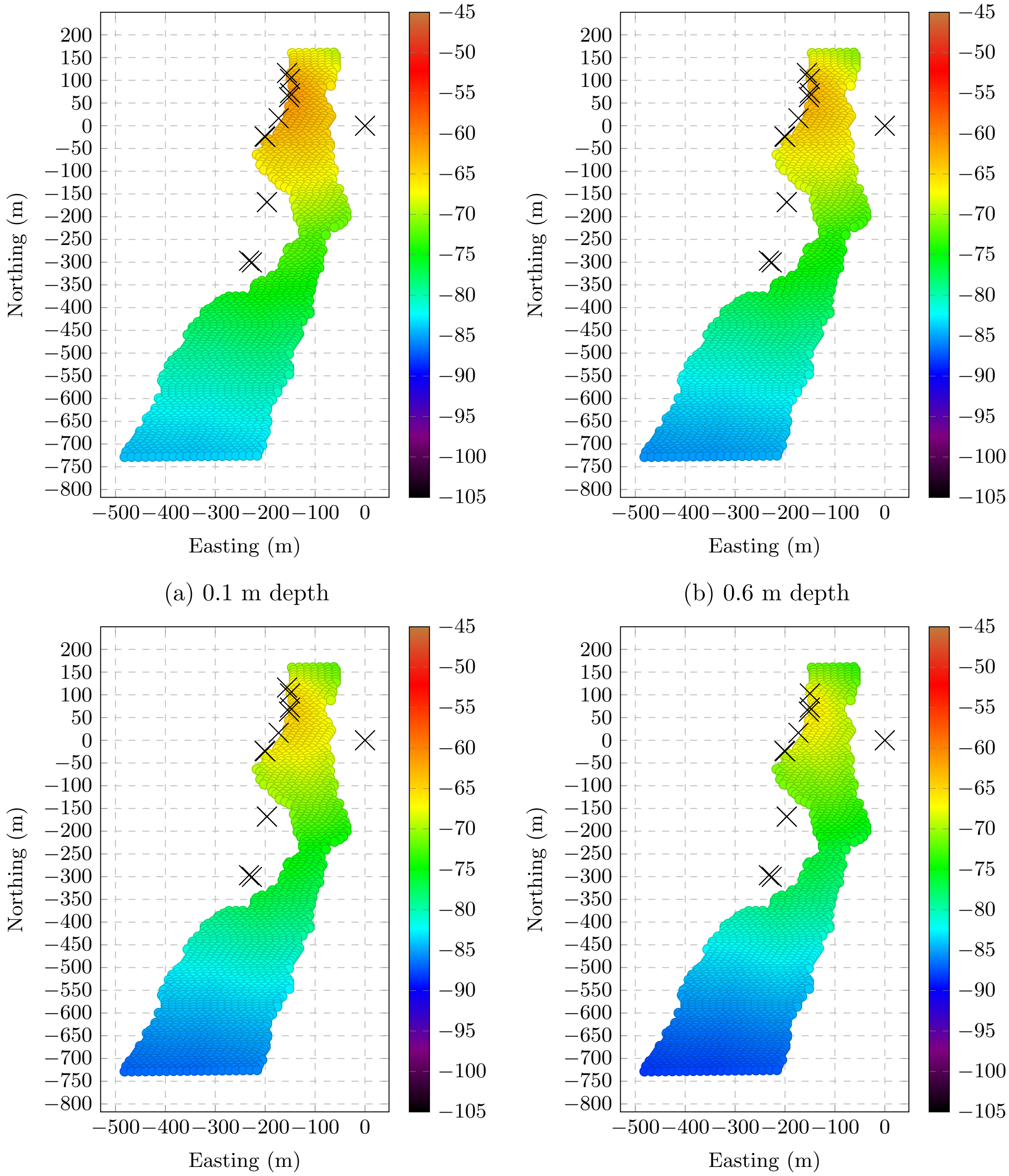
2.5 Discussion

The results show that some of the antenna locations don't provide high spatial resolution compared to other locations. At a latitude of 51.21852, the largest spatial resolution across the 92 m span of the river is 8.5 dB difference for the "Eddy" upstream receiver while the Razorback upstream receiver has the worst resolution with a difference of 0.77 dB across the river span. In order for the detection location to be useful, the total received power would be high, and there would be large fluctuations of received values across the river, at various depths within the river, and along the length of the river.

Of the three receiver locations presented, the iBeam receiver provides the greatest discrepancy along the width, length, and depth of the river. This receiver was unique in that it was pointing almost directly down into the water. The antennas that are further from the water and pointing closer to the horizon, Eastside and Razorback, show no differences across the width of the river however they do provide sensitivity for where a fish might be along the length of the river. The Eastside and Razorback positions also receive greater signal strength from the entire river whereas the iBeam receiver has a simulated received power of less than -90 dB for the spots on the river furthest from its position.

Irrespective of antenna location and the angle that the antenna is facing, the TM gain shows lower loss overall compared to TE. The overall power is an important consideration as it is better to have a stronger signal than a weaker signal that could be close to the noise floor. The difference between polarisation gains agrees with the Fresnel equation theory, see Figures A.1, A.2 and 2.4, where we see that the larger the incident angle is from normal, the less power we have transmitted in the TE polarisation however we have more power transmitted in the TM polarisation.

These results are three from thirteen of the receiver locations, see Appendix A.2 for all sites. Individually each placement has a strength, whether it is greater received power overall or greater discrepancy in power along the river, however tracking a fish will be challenging using only one of the receiver locations. The biggest opportunity in tracking will be to use some combination of these locations together to minimize the regions that the fish can be located in, see Figure 2.13. Averaging over all of the locations provides a bleak outlook. Based on the current receiver locations the gain pattern does not give a high resolution in terms of the spatial gain variation. It is also clear that there are a lot of antenna locations all within a nearby proximity. The average gain leads to a pattern that is similar to the iBeam p1 site, see Figure 2.11. The current averaging of all locations creates a distribution that is similar to if there was only one receiver located near the large cluster of receivers. Although it would be beneficial to space the antennas out and place them in a configuration close to the rivers surface the topography of the river canyon does not make this an easy task.



(a) 0.1 m depth

(b) 0.6 m depth

(c) 1.1 m depth

(d) 1.6 m depth

Figure 2.13: Total loss 0.5(TE+TM) - Averaged dB gain over all sites (dB). All distances referenced to Eastside downstream, 10U 559418.2593 km E, 15674469.93 km N.

2.5.1 System Improvement

There are a variety of possible improvements that can be made to improve the radio tracking. Although there are diverse theoretical ways to improve the system, there are many limitations. The limitations primarily revolve around the physical environment in which the tracking is taking place. The rugged terrain limits the possible locations where antennas can be placed and the rushing river with debris eliminates the possibility of placing any equipment inside the river, whether it be acoustic or radiofrequency. There are some elements that are within our control and could be implemented with relative ease.

- Use antennas orthogonal to one another; the ability to use both polarisations would be beneficial in order to get more data.
- Position the antennas as close as possible to the river's surface. Minimizing the distance between the receiver and the water will eliminate most of the path loss leading to an overall higher received strength.
- Orient the antennas with the boom towards the river. The more the antenna points towards the river the greater differentiation along the surface of the river. This approach has lower received strength further from the receiver location but that can be overcome by spacing out the remaining antennas.
- Obtain more directional antennas. The beam width of the current antennas is approximately 110° and as such when these antennas are positioned a large distance from the rivers surface, the gain of the antennas is seen as very uniform over large areas of interest.
- Try and leverage the advantages of TM polarisation to obtain a larger received signal compared to using the TE polarisation.

Chapter 3

Acoustic Modelling Multi-layer Structures

The acoustic modelling uses multi-layer transmission lines to model the transmission and reflection mimicking windowpanes and spacings between panes. The following figure represents a window model schematically:

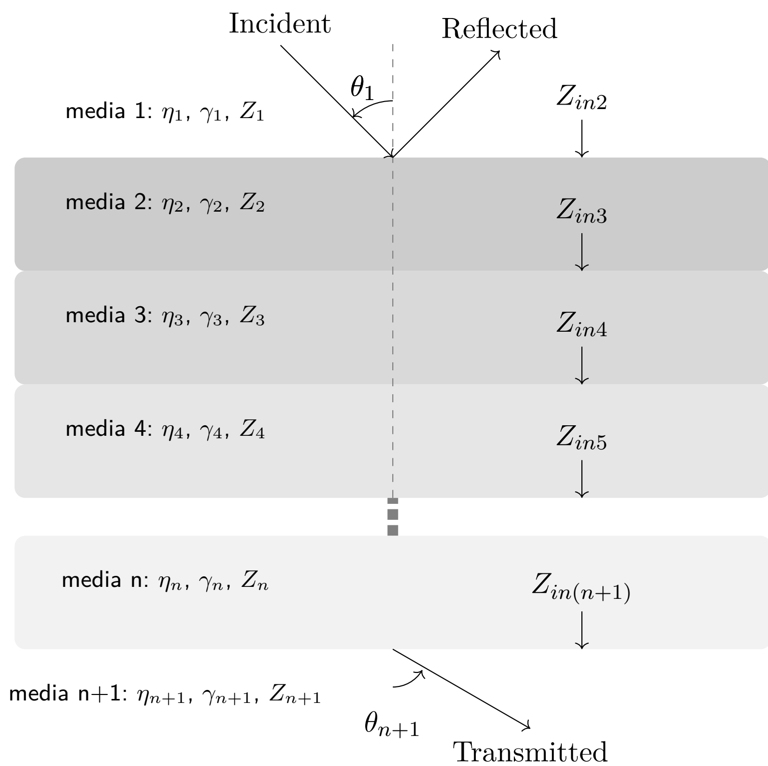


Figure 3.1: Multi-layer transmission and reflection

3.1 Assumptions

Like the EM model there are a few assumptions:

- The attenuation follows the same exponential decay used in EM propagation (2.20). When a wave enters a medium, the signal decays exponentially, this allows the acoustic propagation to be modelled with a transmission line.
- The model uses random incidence, modelled here by having no oblique incidence. This is a commonly used technique in acoustics for propagation between rooms [24].
- Gasses such as air and argon, commonly used gasses between panes, are lossless materials and there is no dissipation as the sound wave propagates.
- There is no spherical spreading of the acoustic wave. The spreading would have to be considered for a more realistic dataset however this model considers only a plane wave with no spreading.

3.2 Underlying Principles

3.2.1 Acoustic Electromagnetic Equivalent

In liquids the lossless acoustic propagation model and the lossless EM propagation scenarios share similarities due to their respective wave equation [31, 32]. The fundamental element comparisons are:

Acoustic Terminology	**Electromagnetic Equivalent**
Pressure: p	E
Velocity: v	H
Density: ρ	Permeability: μ
Compressibility: $K = \frac{1}{B}$	Permitivity: ϵ

Table 3.1: EM acoustic analogy. Some texts prefer an interchange of E and H here depending on if it is using TE or TM polarisation [31].

In liquids, the acoustic model contains a relationship to the conductivity in EM propagation:

$$\sigma = \frac{1}{\text{Viscosity}} = \frac{1}{\eta}$$

[31, 32]. The only qualifier is that this only holds for visco-elastic fluids [31, 32]. An important relationship that relates material parameters is that the compressibility $K = \frac{1}{B}$ is equal to the inverse of B, the Bulk modulus. Bulk modulus is the stiffness of the material. Putting these fundamental variables together means that many of the useful parameters such as the wave impedance and wave number can be re-written in terms of the acoustic parameters.

Acoustic Terminology	Electromagnetic Equivalent
$Z = \sqrt{\rho B} = \sqrt{\frac{\rho}{K}} = \frac{\rho\omega}{k}(3.1)$	$\eta = \sqrt{\frac{\mu}{\epsilon}} = \frac{\mu\omega}{k}$
$k = \omega\sqrt{\frac{\rho}{B}} = \omega\sqrt{K\rho} = \frac{\omega}{c}(3.2)$	$k = \omega\sqrt{\mu\epsilon} = \frac{\omega}{c}$
$c = \sqrt{\frac{B}{\rho}} = \frac{1}{\sqrt{K\rho}}$	$c = \frac{1}{\sqrt{\mu\epsilon}}$

Table 3.2: EM acoustic analogy for composite variables.

3.2.2 Power, Intensity and Hearing

Unlike EM where the power flux density (2.1) is the key metric, acoustics has multiple measurements of importance since human hearing does not explicitly recognize the power or intensity of an acoustic wave. The important quantities in acoustics are:

- Sound Pressure Level (SPL):

$$SPL = 10\log_{10}\left(\frac{p^2}{p_{ref}^2}\right) \tag{3.3}$$

  where p_{ref} is the dynamic pressure of the smallest sound that a human can hear. Its value is 20 µPa or $20 \cdot 10^{-6}$ N/m^2 [16, 33]. The human ear can hear a range of 1 dB SPL, the quietest sound, to over 120 dB SPL, the point at which noise can cause immediate damage to the ear [34]. The SPL is the metric commonly attributed to any measurement of how "noisy" an object is.

- Intensity level (IL):

$$IL = 10\log_{10}\left(\frac{I}{I_{ref}}\right) \tag{3.4}$$

  with the reference intensity, $I_{ref} = 10^{-12}$ W/m^2, corresponds to the intensity of the reference dynamic pressure. Intensity in a plane wave is defined using [33] as:

$$I = \frac{p^2}{\rho_0 c}$$

  with p the pressure. The relationship between intensity level and sound pressure level is:

$$IL = SPL + 10\log_{10}\left(\frac{p_{ref}^2}{\rho_0 c I_{ref}}\right) \tag{3.5}$$

3.2.3 Single-pane and Double-pane

Although the lossless model offers a direct relationship between EM and acoustic parameters, the different mechanical implementations, whether it is single-pane or double-pane transmission, require separate considerations. Acoustic propagation is complicated due to different propagation phenomena based on the surrounding mechanical setup of the problem, how the windowpanes are attached to one another, how they are held within the frame impact the results [24].

Single-pane - Mass Law

The transmission loss and absorption coefficient of single layers, or single-pane construction, follows the theoretical mass law [24, 33]. The absorption coefficient is defined as [24]:

$$\alpha = 1 - |R|^2 = \frac{1}{1 + \left(\frac{\omega m_s}{2Z_0}\right)^2} \tag{3.6}$$

with Z_0 the specific impedance of air, units of rayl: kg/m^{2}s, and m_s is the surface mass density. The transmission loss, or sound reduction is defined as [24]:

$$R_{Tloss} = -10\log_{10}\tau = 10\log_{10}\frac{I_0}{I_t} = 10\log_{10}\left[1 + \left(\frac{\omega m_s \cos\theta}{2\rho_0 c}\right)^2\right] \tag{3.7}$$

with I_0 the incident sound intensity and I_t the transmitted intensity. This results in a theoretical transmission loss that follows the trend of Figure 3.2.

Double-pane - Mass Law

For constructions with more than one layer, there are added acoustic complications. The primary reason is the gap between the panes, whether it be air, argon, or some other gas, acts like a spring. For various frequency regions, the mass elements and the spring behave differently complicating the issue. This frequency dependence has a large impact on the overall performance of the system [24]. The theoretical transmission loss of a double layer

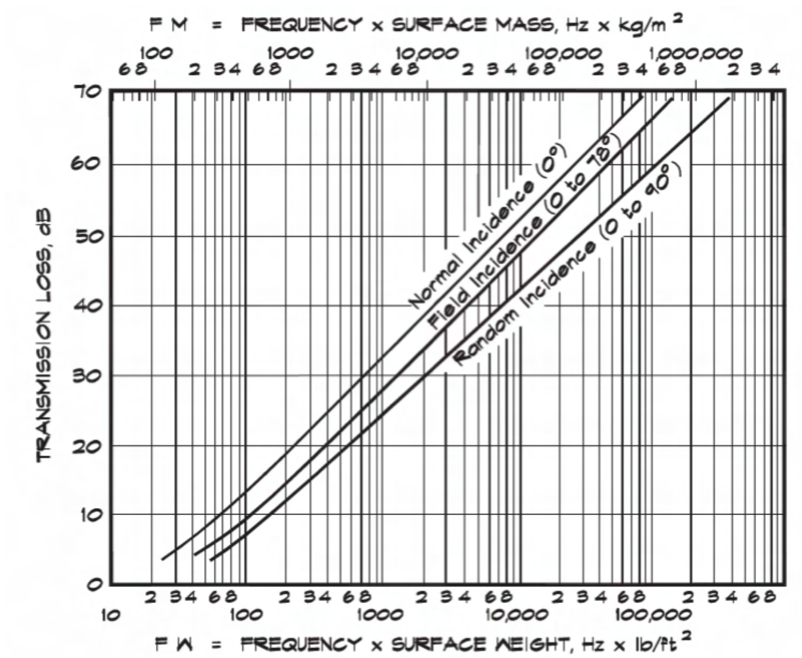


Figure 3.2: The theoretical transmission loss based on the mass law theory of a single-panel. Image copied from [35].

configuration is:

$$R_{Tloss} = -10\log_{10}\tau = 10\log_{10}\frac{I_0}{I_t}$$

$$= 10\log_{10}\left(1 + \left[\frac{\omega M}{3.6\rho_0 c_0} - \frac{\omega^2 m_1 m_2}{(3.6\rho_0 c_0)^2}\left(1 - e^{-2jkd}\right)\right]^2\right) \quad (3.8)$$

$$M = m_1 + m_2 \quad (3.9)$$

$$k = \frac{2\pi f}{c_0} \quad (3.10)$$

$$d = \text{Panel spacing} \quad (3.11)$$

$$m_1, m_2 = \text{Surface mass density of the layers.} \quad (3.12)$$

This results in a theoretical transmission loss that follows the trend of Figure 3.3.

3.2.4 Transmission Loss and Absorption Coefficient

In EM the two important parameters that dictate the propagation of the wave are the wave impedance, η (2.10) and the propagation constant, γ (2.24). Since the permittivity can be a complex function, for lossy materials the wave impedance and propagation constant become complex functions resulting in a model that covers both lossless and lossy propagation. The theoretical derivation of complex acoustic impedance and propagation constant are not well

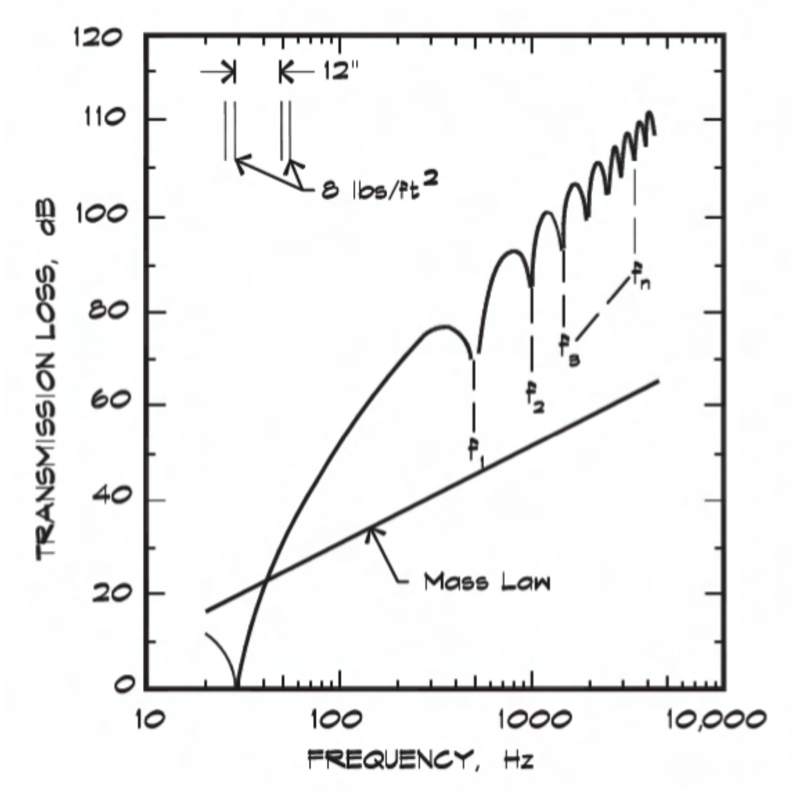


Figure 3.3: The theoretical transmission loss for a double-panel compared to the mass law theory of a single-panel. Image copied from [35].

defined, therefore experimental results can be used to calculate these values. Propagation between rooms is a commonly researched topic that provides information to researchers, architects, and companies alike on the acoustic qualities of their products [24, 36, 35, 37, 23, 33]. The most common measurements often provide two pieces of data: the absorption coefficient and the sound reduction index, otherwise known as the transmission loss.

- Random incidence absorption coefficient is defined as :

$$\alpha = 1 - |R|^2. \tag{3.13}$$

  This is the portion of the incident wave power that enters the layer. From an EM point of view, this is the Fresnel transmissivity power, the power that is immediately available at the surface of the interface.

- The sound reduction or transmission loss is defined as:

$$R_{Tloss} = -10\log_{10}\tau = 10\log\frac{I_0}{I_T}. \tag{3.14}$$

This corresponds to the power lost travelling through a layer. In the case of a single-pane of glass, the sound reduction is the ratio of intensity incident on the glass to the intensity directly after the pane of glass.

The absorption coefficient and transmission loss measurements are done using international standards: ISO 354 for the absorption coefficient and ISO 16283, ISO 140 for the sound reduction index. Both the absorption coefficient and the sound reduction index values are for random incidence therefore allowing our model to use normal incidence. Knowing the intensity at the incident interface and at the interface leaving the structure, the absorbed intensity can be calculated, and the entire layer can be characterized with a transmission line.

3.2.5 Transmission Lines

The acoustic transmission line model requires adapting the transmission line model presented in the fish tracking model see Section 2.2.3, to encompass multiple layers, more than two. One of the key tools in analyzing multi-layer transmission line models is the ABCD matrix from two-port modelling. It is possible to solve wave equations using boundary conditions and arrive at the correct solution however this approach is cumbersome when dealing with a three-pane window design, or equivalently, a seven-layer transmission line.

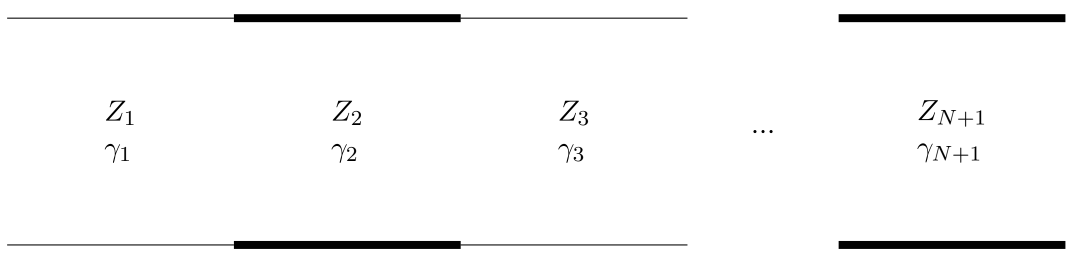


Figure 3.4: Multi-Layer transmission line.

The ABCD matrix relates the voltage and current at the input of the two-port network to the voltage and current at the output of the network. Cascading these systems allows for modelling of multiple layers of a transmission line by relating the input and output voltage and currents of the system. Each two-port network is its own transmission line with a characteristic impedance and wave propagation constant. The values of a transmission line

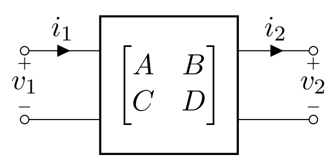


Figure 3.5: Two-port network model relating the input voltage and current to the output voltage and current.

ABCD matrix are covered thoroughly in many texts, eg. [8], and the result will be given:

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix} \tag{3.15}$$

For transmission lines the ABCD matrix is given by:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} \cosh(\gamma l) & Z\sinh(\gamma l) \\ Y\sinh(\gamma l) & \cosh(\gamma l) \end{bmatrix} \tag{3.16}$$

Plugging this into an inverted ABCD matrix we can calculate the voltage and current at the outlet, or port two, compared to the inlet, or port 1. This is given by:

$$\begin{aligned} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix} &= \frac{1}{\cosh^2(\gamma l) + \sinh^2(\gamma l)} \begin{bmatrix} \cosh(\gamma l) & -Z\sinh(\gamma l) \\ -Y\sinh(\gamma l) & \cosh(\gamma l) \end{bmatrix} \begin{bmatrix} V_1 \\ I_1 \end{bmatrix} \\ &= \begin{bmatrix} \cosh(\gamma l) & -Z\sinh(\gamma l) \\ -Y\sinh(\gamma l) & \cosh(\gamma l) \end{bmatrix} \begin{bmatrix} V_1 \\ I_1 \end{bmatrix} \end{aligned} \tag{3.17}$$

Cascaded matrices can easily be implemented into a recursive relation making it easier for the computer to solve. To initialize the values, we collapse the multi-layer transmission line down to a single interface to calculate the overall reflection coefficient. This determines the voltage and current at the first interface relative to the incoming signal. This can be accomplished by transforming the impedance of the transmission lines or by analyzing the small signal reflections and transmissions to determine an equation for the overall reflection of the system. For a multi-layered system with more than three layers, it is easier to calculate the reflection by transforming the impedances:

$$Z_{in} = Z_0 \frac{Z_L + Z_0\tanh(\gamma l)}{Z_0 + Z_L\tanh(\gamma l)}. \tag{3.18}$$

This can be re-written recursively:

$$Z_{in(i)} = Z_i \frac{Z_{in(i+1)} + Z_n\tanh(\gamma_i l_i)}{Z_i + Z_{in(i+1)}\tanh(\gamma_i l_i)} \quad i = n, n-1, n-2, ..., 2. \tag{3.19}$$

Using the notation from Figure 3.4 we first initialize $Z_{in(i+1)}$ to be Z_{n+1}. Then the equation can be solved recursively to find the input impedance at layer 1. With the input impedance, the reflection coefficient can be calculated:

$$\Gamma = \frac{Z_{in2} - Z_1}{Z_{in2} + Z_1}. \tag{3.20}$$

This method immediately takes into account all of the various reflections between layers. The voltage and current can now be initialized at the first interface as:

$$V_1 = V_{1+}(1 + \Gamma) \tag{3.21}$$

$$I_1 = \frac{V_{1+}}{Z_1}(1 - \Gamma) \tag{3.22}$$

where V_{1+} is the input voltage. Both V_1 and I_1 can then be input into (3.17) and recursively calculated to find the output voltage and current.

3.3 Model Implementation and Verification

Although there are theoretical models, see Figures 3.3 and 3.2, the complications arise from modelling real lossy media as a transmission line. One of the challenges of acoustic modelling for real materials is represented by the thirteen different equations needed to estimate the speed of sound in different materials depending on the type of vibrational wave [35]. Instead of calculating the acoustic parameters for materials, the following values were used for the speed of sound and the densities of the materials:

Variable	**Air**	**Glass**	**Argon**
c [m/s]	343	4540	319
ρ[kg/m^3]	1.293	2500	1.603

Table 3.3: Material acoustic properties used throughout

To fit the reality of the acoustic transmission to a transmission line model, we had to make a simplification in terms of the analysis and use experimental data to obtain the impedance and propagation constants. Viewing this problem in terms of a transmission line problem, we can model the single-pane window problem as a three-layer transmission line with air, glass, and lastly, another air layer. Using the transmission line techniques covered in Section 3.2.5 it is possible to solve the transmission line equation using the absorption coefficient and the transmission loss values to obtain unknown parameters in the transmission line model. The transmission loss is defined as (3.14) however for the sake of this thesis all results presented will be taken as the negative of this value to follow the same convention as the EM scenario. Using the absorption coefficient and the transmission loss value in the transmission line model, the lossy impedance and wave propagation constant of glass were taken to be an unknown. The gasses before and after a pane of glass were considered to be lossless and were taken as a given value using the impedance of a lossless fluid, (3.1), and the wave number, (3.2).

For the system to converge to a solution for the impedance and wave propagation constant of glass, a few assumptions were made on the variables based on theory from the EM scenario. The wave impedance should be a complex value that is positive. Therefore, the real impedance portion was set to (3.1). The imaginary portion was constrained to be positive but was left to be fitted. The wave propagation factor was fitted similarly with the imaginary portion of the term being to be equal to (3.2). The real part of the propagation constant was constrained to be positive to ensure that the material attenuated correctly. Once the terms were fit for the six test frequencies given in [24, 33, 35, 23, 38, 39, 40], a linear, polynomial and spline fit in MATLAB were applied to obtain the total impedance and propagation constant over the whole range of frequencies: 125 Hz to 4 kHz. Implementing these values into the propagation model allowed for certain elements such as: the number of layers, the spacing of the layers, the thickness of the glass and the chemical compositions of the media in between the panes of windows to be changed.

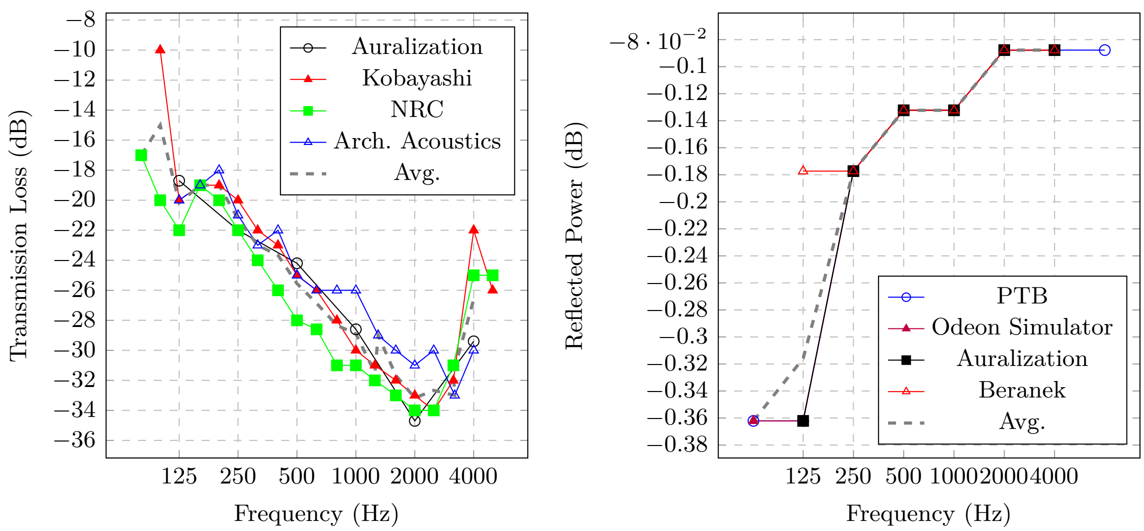
Three different configurations were simulated, single-pane, double-pane and triple-pane with both air and argon as the medium between panes. The transmission line model values were also compared against experimental results found in Auralization [24] for a three mm single-pane window as well for a double-pane system with 4 mm thick glass and a 6 mm spacing.

3.3.1 Single-pane Three mm Experimental Result Comparison

There are a variety of sources providing experimental data on three mm single-pane glass [24, 33, 35, 23, 38, 39, 40], these datasets include the sound transmission loss, and in some instances, the absorption coefficient. There are fewer sources providing the absorption coefficient of glass since it is commonly used as a barrier between two rooms and not to absorb noise within a room. The different experimental results are tabulated and averaged in Figure 3.8. There are some experimental differences specifically with the transmission loss values at high frequencies. Although these experiments do follow standards, there is a high variability owing to the challenging nature of acoustic experiments [23].

3.3.2 Linear, Polynomal, Spline - Single-pane Comparison

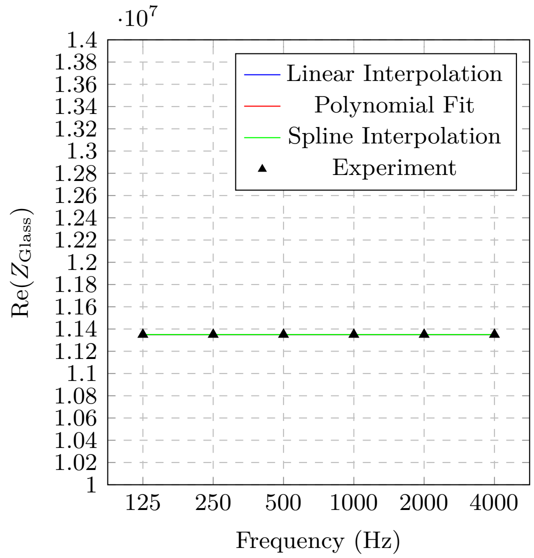
Using data from the single-pane of glass, it is possible to compare the experimental values from the textbook to the final extrapolated impedance values that were obtained. To do this, three different interpolations were used, a linear, polynomial and spline interpolation. Since the values are interpolated, the results of the single-pane transmission window won't match exactly the averaged experimental measurements that were used. We can analyze the differences between the interpolation results and the experimental results in two ways, by comparing the results from the solved impedance and wave propagation constant and by comparing the final transmission model to the experimental data. The comparison of interpolated versus non interpolated data for the impedance and propagation constant is shown in Figure 3.8.



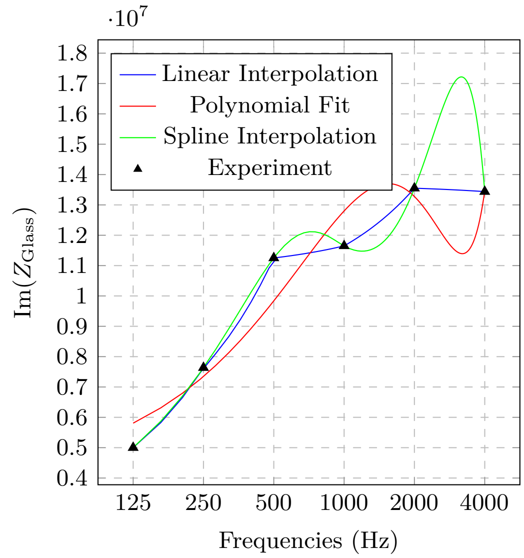
(a) Negative value of transmission loss

(b) Reflected power

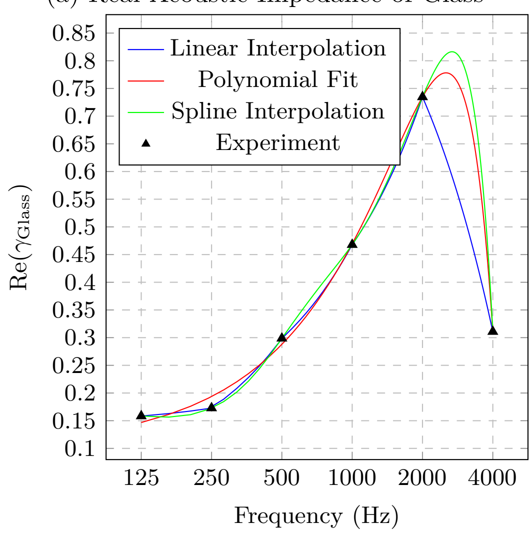
Figure 3.6: Experimental transmission loss and reflected power. a) Transmission loss through the Three mm single-pane of glass from various studies and an average value of the studies. These values are the negative of the experimental value for consistency with the way loss is defined in the fish tracking b) Using the absorption coefficients to calculate the reflected power. Beranek data provides an averaged data set of two different experiments.



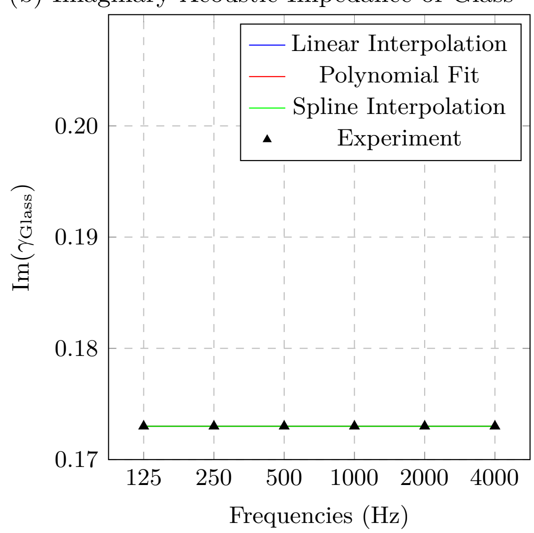
(a) Real Acoustic Impedance of Glass



(b) Imaginary Acoustic Impedance of Glass



(c) Real Acoustic Propagation Constant Glass



(d) Imaginary Acoustic Propagation Constant Glass

Figure 3.7: Real and imaginary components of fitted parameters compared to experimental values. a) Real portion of Z_{glass}, b) Imaginary portion of Z_{glass}, c) Real portion of γ_{glass}, d) Imaginary portion of γ_{glass}

3.4 Results

3.4.1 Single-pane

Using the linear, polynomial and spline data, we can get the following single-pane theoretical versus experimental comparison: There are small discrepancies due to the fitting of the

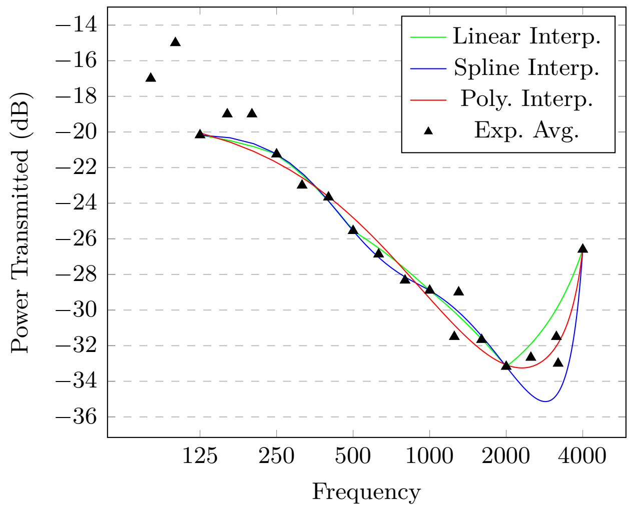
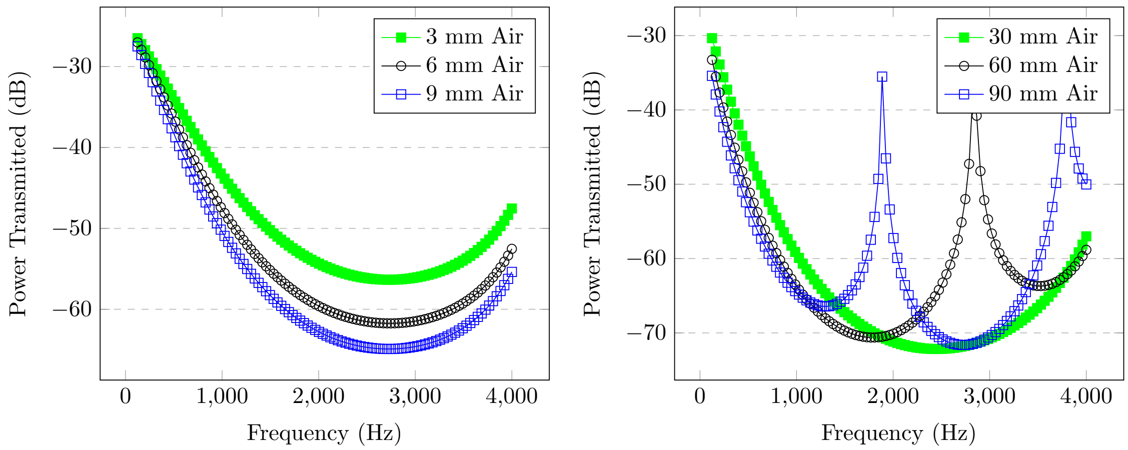


Figure 3.8: Experimental transmit power for a single-pane Three mm window compared with the interpolated transmission line solution. There is extra transmission loss data that was not considered in the interpolations since the corresponding absorption coefficients did not exist. The only data points that were fitted were 125, 250, 500, 1000, 2000, 4000 Hz.

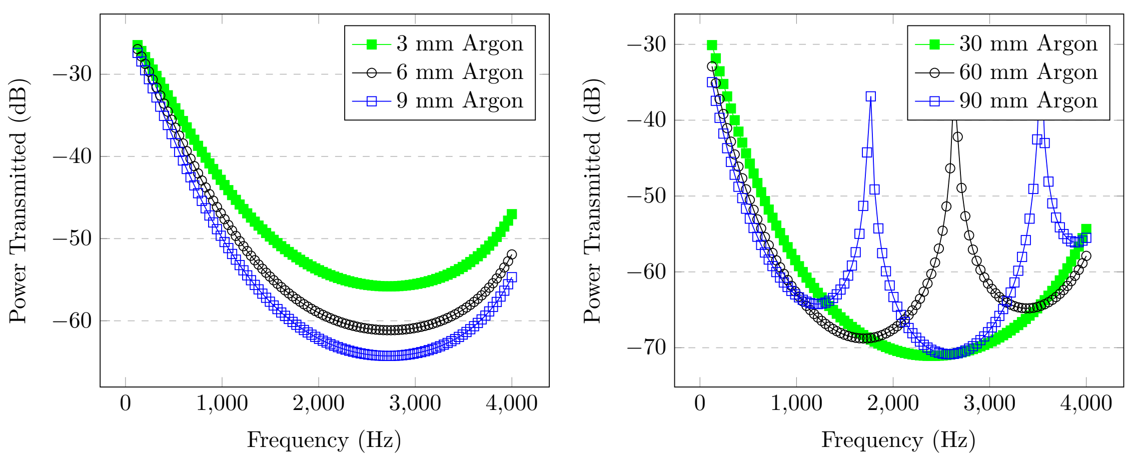
parameters between the experimental results and interpolated results with the polynomial fit providing the closest interpolation to the experimental data.

3.4.2 Double-pane



(a) Thin Spacing (b) Medium Spacing

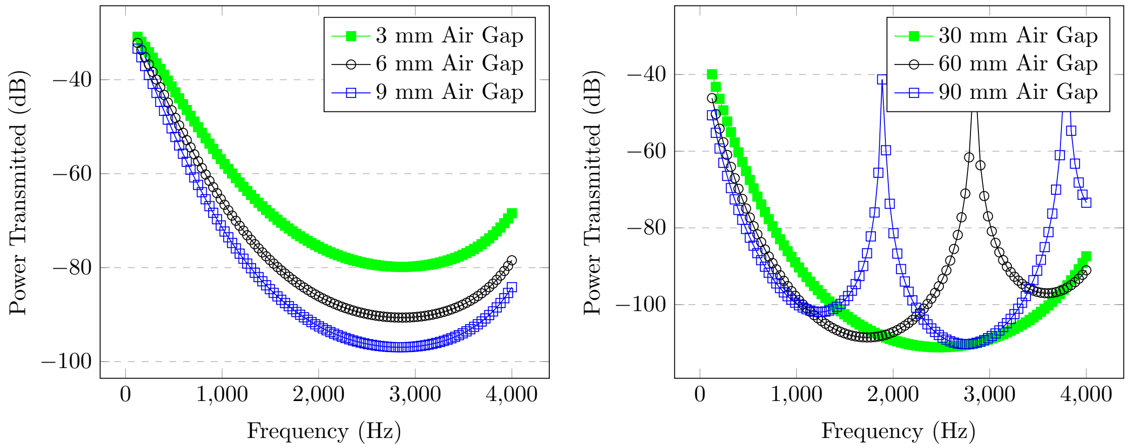
Figure 3.9: Polynomial fit used on a double-pane window setup. Three mm glass with varying thickness air spacing between panes.



(a) Thin Spacing (b) Medium Spacing

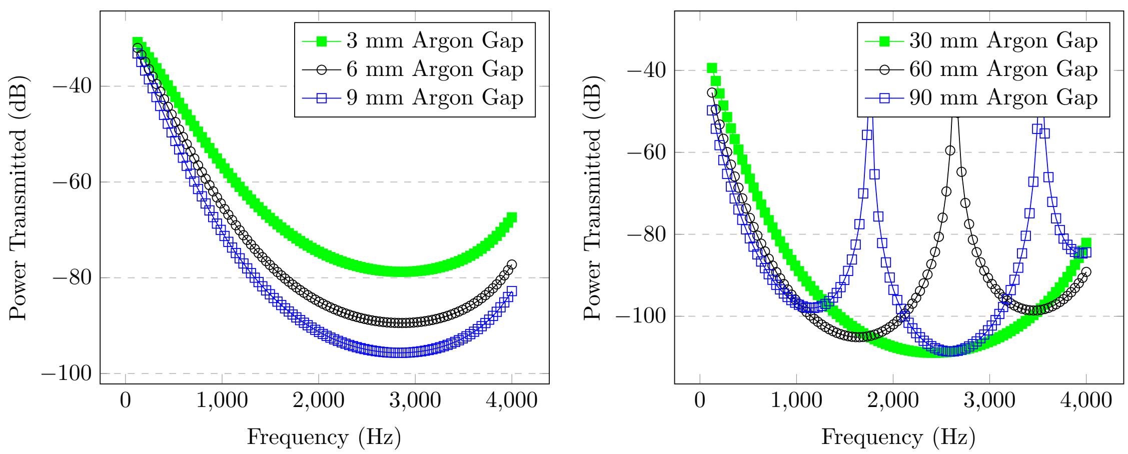
Figure 3.10: Polynomial fit used on a double-pane window setup. Three mm glass with varying thickness argon spacing between panes.

3.4.3 Triple Pane



(a) Thin Spacing (b) Medium Spacing

Figure 3.11: Polynomial fit used on a triple-pane window setup. Three mm glass with varying thickness air spacing between panes.

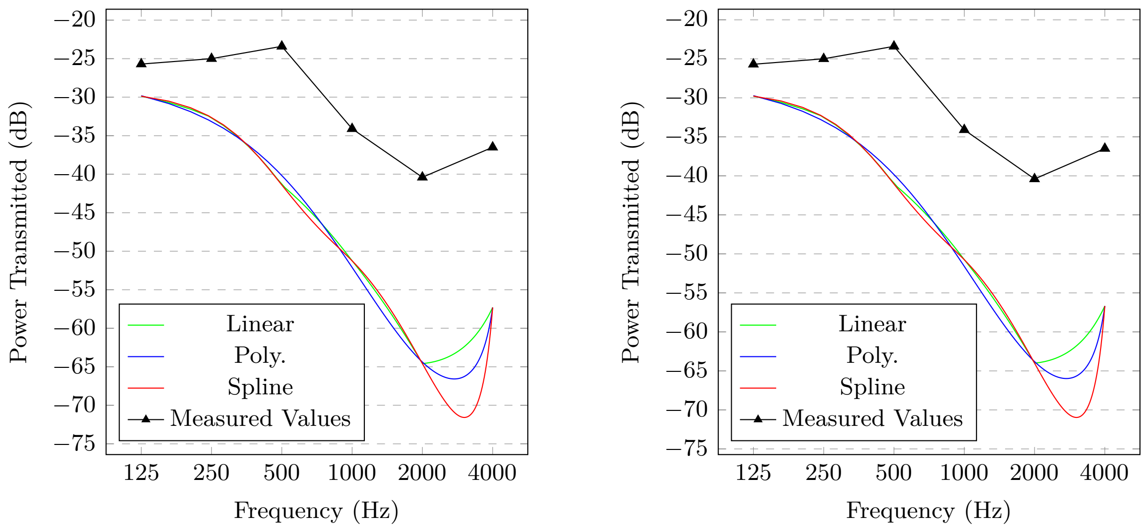


(a) Thin Spacing (b) Medium Spacing

Figure 3.12: Polynomial fit used on a triple-pane window setup. Three mm glass with varying thickness argon spacing between panes.

3.4.4 Double-pane Verification - 4 mm Glass, 6 mm Spacing

Using the same interpolated impedance values obtained from the single-pane measurements, it is possible to change the thickness of the glass. As a comparison and as a form of verification for the transmission line, a double-pane configuration that was measured in [24] was reconstructed with the transmission line. This configuration uses a pane of glass that is 4 mm thick followed by a spacing of 6 mm. Below are the results and comparison between the experimental and 4 mm thick double-pane window model. There are large discrepancies between the two models with differences greater than 20 dB. The experimental values result in much more power being transmitted compared to the transmission line model.



(a) Air gap

(b) Argon gap

Figure 3.13: Measured transmitted power for a double-pane, 4 mm glass and 6 mm spacing, window compared with the transmission line solution that has been interpolated. This is using an argon gap.

3.5 Discussion

Although the transmission line model provides ease of understanding and implementation, there are clear shortcomings in reconciling its results with known experimental results. The results using the transmission line technique for a double-pane window led to less power transmitted through the window compared to the experimental data. This is possibly due to the resonance frequency of the double-pane window causing the window to perform worse than what would be theoretically expected or due to error in experimental measurement.

Even though the transmission line model does not provide great agreement there are a variety of other interesting results obtained through its use. Depending on the spacings between the panes of glass, there are resonances that occur wherein the window has worse acoustic blocking. These resonances are the large peaks in the graphs where the window transmits most of the incident power. At the lowest frequency that is tested, 125 Hz, sound in air has a wavelength of 2.7 m and at the largest frequency, 4000 Hz, sound has a wavelength of 8.58 cm. For the double-pane window with an air gap of 9 cm there are two resonant frequencies, 1886.36 Hz and 3804.26 Hz which correspond to a wavelength of 0.1818 m and 0.0902 m. Therefore, it makes sense that a 9 cm window spacing would result in a large amount of the sound transmitted at these frequencies as the gap is equal to both λ and $1/2\lambda$ of those frequencies. In this scenario, the transmission line is acting like a quarter wave transformer, or more specifically, an integer multiple of a quarter wave transformer. In the application of windows in a building scenario, we would want to minimize any of these resonances as they lead to a large portion of the sound transmitting through the system.

Argon, an excellent heat insulator, does not make a noticeable impact for small spacings between panes. When analyzing the acoustic parameters, table 3.3 there is a discrepancy between the values for air and argon. There is a difference of 24 m/s in the speed of sound and a difference of 0.31 kg/m^3 however this does not translate to a visible difference in transmitted power at small spacings between panes. At larger spacing, however, there is a noticeable difference with air gaps creating a larger spread in transmitted powers compared to argon, especially at resonant frequencies.

The real-life experimental measurements showcase the flaws with using the mass law for single layer acoustic transmission. The mass law predicts a trend of -6db/octave [25]. Using Figure 3.8 between 125 Hz and 1000 Hz there are 3 octaves which corresponds to a theoretical decrease of 18 dB. Both the experimental and fitted transmission line data models have a drop of only 10 dB over the same octaves. The mass law also suggests that this roll-off continues, see Figure 3.2 however the experimental results clearly demonstrate that after 2000 Hz, the trend is reversed, and more power begins making its way through the window.

Chapter 4

Conclusion and Recommendations

4.1 Conclusion

A physics-based approach has been implemented to model the received signal strength of a fish as it swims upstream. This model can be used moving forward in conjunction with experimental data gathered by the RDL and the DFO to create a state space model that can pinpoint the location of a salmon. The results of the physics-based approach show that there are current drawbacks and setbacks to the current arrangement of receiving antennas and limitations due to the underlying phenomena.

The existing system suffers from low received signal strength, due to the large distances that the antennas are positioned from the rivers surface. This path loss in air works against us with the majority of the loss occurring in the first few meters as it propagates through air. The physical geography of the canyon limits how close the antennas can be placed to the water. The system also suffers from a low resolution in terms of spatial positioning based on the received gain. The low spatial resolution is compounded as the attenuation in water is exponential decay that shows no variance based on incoming angle. Therefore, if there is no spatial resolution obtained near the surface of the water, there won't be more spatial resolution at lower depths. The attenuation does however provide reasonable differentiation within depths of the river with a 5 dB difference for every 2 meters in depth. This is an improvement over the roughly 8.5 dB change we see over 92 meters at the surface of the river.

Acoustic propagation was evaluated using both experimental data and using the concepts of transmission line models. The transmission line model provides good agreement for the results for single-pane transmission, this is to be expected as the data was fitted using this data. The double-pane transmission line model no longer shows close agreement with differences in excess of 20 dB. This difference is due to the transmission line theory not adequately modelling the impact of the spring-like gap between the panes or errors with the experimental results. Instead, the transmission line models only the reflections, refractions, and attenuations within the material and while this works for EM propagation, the mechanical impacts of acoustic propagation mean that there needs to be further research into the attenuation model. Although the theory currently does not explain these phenomena well, the single-pane transmission model provides a fresh perspective on acoustic propagation and a new way to think about the concept, opening the doors to many possibilities currently employed in the electromagnetic world such as designing filters.

Propagation is an important field of research and underpins many of the key fundamentals behind Radio Frequency (RF) communication and auditory communication. This thesis allowed for a comprehensive analysis into the underlying principles of propagation for both acoustics and electromagnetics. The work that was done offered a wide variety of research opportunities from mathematical derivations and EM principles to going through specification sheets for various receivers and transmitters. As well, this project demonstrated my technical abilities from the usage of software tools such as Matlab to the implementation of both the salmon and the acoustic model. This project provided invaluable foundational theoretical knowledge while also creating useful models that can have a real-world impact in the ongoing research fields of ecological salmon studies and acoustic modelling. Although the project provided important results, it also revealed further questions laying the groundwork for many future projects and areas of research.

4.2 Future Work - Fish Tracking

- A more advanced attenuation model could be implemented using experimentally measured permittivity of the Fraser River water at the frequency of operation, 150 MHz. The ϵ_I may not follow the known conductivity loss using the guessed conductivity in σ/ω.
- Use flow simulation to estimate the position and orientation of the fish transmitter to implement a more accurate quantification of the polarisation mismatch. The transmitting antenna could be simulated in its actual position allowing for the fields to be calculated and the polarisation mismatch calculation could be carried out.
- Use the current model to simulate a variety of locations and orientations to get greater received power and larger variations in received signal across the river.
- A more statistical model could be beneficial whereby the exact details of the propagation scenario become less important, but the statistical significance of an occurrence becomes more important. This could allow for a rough layer of a specific distribution to be used to model waves on the surface of the river.
- The RDL has recently completed a LiDAR measurement campaign whereby they measured the details of the elevation of the canyon alongside a secondary dataset where the riverbed was also scanned and measured. This was recently completed and

there is current work being undertaken to stitch these two models together to create one dataset with both the canyon wall elevation and riverbed data together. This data could be a platform to complete a ray tracing scenario.

- The current experimental dataset that has been collected shows a high degree of variability certain downfalls primarily with the method that it was collected. Using a metal boat has impacts the results that were obtained changing any possible values that were collected.
- Redesign the fish transmitter to either use a completely different system, or to optimize the current system.

4.3 Future Work - Acoustic Modelling

- Include the temperature dependence of a material's properties to analyze how changing environmental conditions impact the acoustic insulating qualities of windows.
- Use an acoustic impedance tube to find values for the absorption coefficient and for the transmission loss values to compare with existing experimental results.
- Research the loss mechanism that occurs in double-pane and triple-pane setups. Unlike the electromagnetic attenuation given by an exponential decay, it is not currently clear if acoustic attenuation can be modelled using an exponential decay or if an alternative formalism is needed.
- When the double-pane transmission line model aligns closer with experimental data, various tasks can be performed using EM techniques, such as filters. This allows for the design of a window with specific characteristics, such as improved frequency response within a particular range of interest.
- Include spherical spreading of the acoustic wave. This would have an impact even over the small distances of a window frame and the impact should be studied accordingly.

Bibliography

[1] Government of Canada, Fisheries and Oceans Canada, "Big bar landslide response summary." pac.dfo-mpo.gc.ca https://www.pac.dfo-mpo.gc.ca/pacific-smon-pacifique/big-bar-landslide-eboulement/response-reponse-eng.html(accessed September 7,2023).

[2] E. Seagren, J. Venditti, E. Byrnes, J. Larimer, M. Hurson, K. Menounos, K. Robinson, M. Saletti, A. Steelquist, C. Williams, M. Wright, and S. Wuitchik, "Landslide impact on flow dynamics, fish migration and genetics of fraser river salmon," 2022.

[3] J. Venditti, "Landslide Impact on Flow Dynamics, Fish Migration and Genetics of Fraser River Salmon," proposal, Simon Fraser University, Jan. 2021.

[4] CTV News, "Photos of big bar landslide." bc.ctvnews.ca https://bc.ctvnews.ca/photos-show-big-bar-area-before-and-after-landslide-1.4510958(accessed September 10,2023).

[5] Government of Canada, Fisheries and Oceans Canada, "Infographic: Big bar landslide response - 2020 timeline of key events." pac.dfo-mpo.gc.ca https://www.pac.dfo-mpo.gc.ca/pacific-smon-pacifique/big-bar-landslide-eboulement/docs/timeline-chronologie-2020-eng.html(accessed September 7,2023).

[6] Karin Larsen, "Work at big bar slide site means fraser river salmon should have better chance this year." cbc.ca https://www.cbc.ca/news/canada/british-columbia/work-at-big-bar-slide-site-means-fraser-river-salmon-should-have-better-chance-this-year-1.6076838.

[7] E. Byrnes, K. Robinson, M. Saletti, R. Vaughan, S. Sixta, V. Leos, J. Venditti, and D. Patterson, "Drivers of migration pathway selection of Pacific salmon: time vs energy," 2023.

[8] D. M. Pozar, *Microwave engineering.* Addison-Wesley series in electrical and computer engineering, Reading, Mass: Addison-Wesley, 1990.

[9] S. Ramo, J. R. Whinnery, and T. Van Duzer, *Fields and waves in communication electronics.* New York: Wiley, 1965.

[10] S. J. Orfanidis, *Electromagnetic Waves and Antennas.* Piscataway, NJ, USA: Rutgers, 2016.

[11] J. R. Wait, *Electromagnetic wave theory.* New York: Harper & Row, 1985.

[12] S. Jiang and S. Georgakopoulos, "Electromagnetic Wave Propagation into Fresh Water," *Journal of Electromagnetic Analysis and Applications*, vol. 2011, July 2011. Publisher: Scientific Research Publishing.

[13] A. B. Harbicht, T. Castro-Santos, W. R. Ardren, D. Gorsky, and D. J. Fraser, "Novel, continuous monitoring of fine-scale movement using fixed-position radiotelemetry arrays and random forest location fingerprinting," *Methods in Ecology and Evolution*, vol. 8, pp. 850–859, July 2017.

[14] J. Koehn, Eiler, M. J.A., and O. W.G, "An improved method for obtaining fine-scale location of radio tags when tracking by boat.," pp. 379–384, Jan. 2012.

[15] K. C. Heim, W. R. Ardren, and T. Castro-Santos, "Using recovered radio transmitters to estimate positioning error and a generalized Monte Carlo simulation to incorporate error into animal telemetry analysis," *Animal Biotelemetry*, vol. 11, p. 26, June 2023.

[16] Y.-H. Kim, *Sound propagation: an impedance based approach.* Singapore ; Hoboken, NJ: Wiley, 2010. OCLC: ocn586123126.

[17] N. Granzotto, F. Bettarello, A. Ferluga, L. Marsich, C. Schmid, P. Fausti, and M. Caniato, "Energy and acoustic performances of windows and their correlation," *Energy and Buildings*, vol. 136, pp. 189–198, Feb. 2017.

[18] Inger Andersen, "The world's cities must take on the cacophony of noise pollution." unep.org
`https://www.unep.org/news-and-stories/opinion/worlds-cities-must-take-cacophony-noise-pollution`(accessed September 12,2023).

[19] Google Scholar, "Signal processing top publications?." scholar.google.ca
`https://scholar.google.ca/citations?view_op=top_venues&hl=en&vq=eng_signalprocessing`(accessed September 15,2023).

[20] OSHA, "Identifying hazard control options: The hierarchy of controls." osha.gov
`https://www.osha.gov/sites/default/files/Hierarchy_of_Controls_02.01.23_form_508_2.pdf`(accessed September 16,2023).

[21] Walker Peek, "Soundproof windows - how effective are they?." residential-acoustics.com
`https://residential-acoustics.com/soundproof-windows-how-effective-are-they/`(accessed September 13,2023).

[22] F. Brinkmann, L. Aspöck, D. Ackermann, S. Lepa, M. Vorländer, and S. Weinzierl, "A round robin on room acoustical simulation and auralization," *The Journal of the Acoustical Society of America*, vol. 145, pp. 2746–2760, Apr. 2019.

[23] J. D. Quirt, "Sound transmission through windows I. Single and double glazing," *The Journal of the Acoustical Society of America*, vol. 72, pp. 834–844, Sept. 1982.

[24] M. Vorländer, *Auralization: fundamentals of acoustics, modelling, simulation, algorithms and acoustic virtual reality.* RWTHedition / RWTH Aachen, England Wales: ASA Press, second edition ed., 2020.

[25] A. D. Pierce, *Acoustics: an introduction to its physical principles and applications.* Cham: ASA Press, Springer, third edition ed., 2019.

[26] S. W. Ellingson, *Electromagnetics, Volume 2.* VT Publishing, Jan. 2020.

[27] R. Vaughan and J. Bach Andersen, *Channels, propagation and antennas for mobile communications.* No. 50 in IEE electromagnetic waves series, London: Institution of Electrical Engineers, 2003. OCLC: ocm49691547.

[28] C. A. Balanis, *Antenna theory: analysis and design.* New York: Wiley, 2nd ed ed., 1997.

[29] C. Hynes, P. Hui, J. van Wonterghem, and D. Michelson, "Cross-correlation and total efficiencies of two closely spaced sleeve dipole antennas," in *2005 IEEE Antennas and Propagation Society International Symposium*, vol. 1B, pp. 799–802 vol. 1B, July 2005. ISSN: 1947-1491.

[30] J. A. Shaw, "Radiometry and the Friis transmission equation," *American Journal of Physics*, vol. 81, pp. 33–37, Jan. 2013.

[31] J. M. Carcione, *Wave fields in real media: wave propagation in anisotropic, anelastic, porous and electromagnetic media.* No. 38 in Handbook of geophysical exploration. Seismic exploration, Amsterdam Boston [etc.]: Elsevier, 2015.

[32] L. T. Ikelle, "On elastic-electromagnetic mathematical equivalences," *Geophysical Journal International*, vol. 189, pp. 1771–1780, June 2012.

[33] L. L. Beranek, *Acoustics.* New York, N.Y: Published by the American Institute of Physics for the Acoustical Society of America, 1986 ed ed., 1986.

[34] CDC, "What noises cause hearing loss?." www.cdc.gov `https://www.cdc.gov/nceh/hearing_loss/what_noises_cause_hearing_loss.html`(accessed November 1,2023).

[35] M. Long, *Architectural Acoustics.* San Diego, United States: Elsevier Science & Technology, 2014.

[36] P. Lord and D. Templeton, *Detailing for Acoustics.* Taylor & Francis, 3 ed., Oct. 2019.

[37] Ignacio Fernández Solla, "Acoustic properties of glass: not so simple." www.glassonweb.com `http://www.glassonweb.com/article/acoustic-properties-glass-not-so-simple`(accessed October 21,2023).

[38] Physikalisch-Technische Bundesanstalt, "Absorption coefficient database." www.ptb.de `https://www.ptb.de/cms/ptb/fachabteilungen/abt1/fb-16/ag-163/absorption-coefficient-database.html`(accessed October 25,2023).

[39] "Odeon Room Acoustics Software."

[40] Kien Safety Glass Sdn Bhd, "Sound insulation of glass." irp-cdn.multiscreensite.com `https://irp-cdn.multiscreensite.com/05d76747/files/uploaded/Sound%20Insulation%20of%20Glass%20%281396%20KB%29.pdf`(accessed October 23,2023).

Appendix A

Fish Tracking - Details

A.1 Fresnel Equations - Comparison between References

A.1.1 Perpendicular - TE

Pozar

Reflection Coefficient:

$$\Gamma = \frac{\eta' \cos(\theta) - \eta \cos(\theta')}{\eta' \cos(\theta) + \eta \cos(\theta')} \tag{A.1}$$

$$\eta = \sqrt{\frac{\mu_0}{\epsilon}} \quad \eta' = \sqrt{\frac{\mu_0}{\epsilon'}} \tag{A.2}$$

Transmission Coefficient:

$$\tau = 1 + \Gamma = \frac{2\eta' \cos\theta}{\eta' \cos\theta + \eta \cos\theta'} \tag{A.3}$$

Power Reflection:

$$|\Gamma|^2 \tag{A.4}$$

Power Transmission:

$$|\tau|^2 \frac{\mathrm{Re}\{\eta \cos\theta'\}}{\mathrm{Re}\{\eta' \cos\theta\}} = 1 - |\Gamma|^2 \tag{A.5}$$

MIT

Reflection Coefficient:

$$\Gamma = \frac{N_i - N_t}{N_i + N_t} \tag{A.6}$$

$$N_i = \frac{\cos\theta}{\eta} \tag{A.7}$$

$$N_t = \frac{\cos\theta'}{\eta'} \tag{A.8}$$

η and η' being the same definition as Pozar. Note that N is *not* the refractive index.

Proof.

$$\Gamma = \frac{\frac{\cos\theta}{\eta} - \frac{\cos\theta'}{\eta'}}{\frac{\cos\theta}{\eta} + \frac{\cos\theta'}{\eta'}} = \frac{\frac{\cos\theta\eta' - \cos\theta'\eta}{\eta\eta'}}{\frac{\cos\theta\eta' + \cos\theta'\eta}{\eta\eta'}} = \frac{\eta'\cos(\theta) - \eta\cos(\theta')}{\eta'\cos(\theta) + \eta\cos(\theta')}$$

□

Transmission Coefficient:

$$\tau = 1 + \Gamma = \frac{2N_i}{N_i + N_t} \tag{A.9}$$

Power Reflection:

$$|\Gamma|^2 \tag{A.10}$$

Power Transmission:

$$|\tau|^2 \frac{\mathrm{Re}\{N_t\}}{\mathrm{Re}\{N_i\}} = 1 - |\Gamma|^2 \tag{A.11}$$

James Wait

Reflection Coefficient:

$$\begin{aligned} \Gamma &= \frac{N - N'}{N + N'} \\ N &= \frac{u}{j\mu_0\omega} \ , \ N' = \frac{u'}{j\mu_0\omega} \\ u &= \gamma\cos\theta \ , \ u' = \gamma'\cos\theta' \\ \gamma &= \sqrt{j\mu\omega(\sigma + j\epsilon_{Re}\omega)} \end{aligned} \tag{A.12}$$

Proof.

$$\Gamma = \frac{\frac{\sqrt{j\mu\omega(\sigma+j\epsilon_{Re}\omega)}\cos\theta}{j\mu_0\omega} - \frac{\left(\sqrt{j\mu\omega(\sigma+j\epsilon_{Re}\omega)}\right)'\cos\theta'}{j\mu_0\omega}}{\frac{\sqrt{j\mu\omega(\sigma+j\epsilon_{Re}\omega)}\cos\theta}{j\mu_0\omega} + \frac{\left(\sqrt{j\mu\omega(\sigma+j\epsilon_{Re}\omega)}\right)'\cos\theta'}{j\mu_0\omega}} = \frac{\sqrt{j\mu\omega(\sigma+j\epsilon_{Re}\omega)}\cos\theta - \left(\sqrt{j\mu\omega(\sigma+j\epsilon_{Re}\omega)}\right)'\cos\theta'}{\sqrt{j\mu\omega(\sigma+j\epsilon_{Re}\omega)}\cos\theta + \left(\sqrt{j\mu\omega(\sigma+j\epsilon_{Re}\omega)}\right)'\cos\theta'}$$

$\sigma = 0$

$$= \frac{\sqrt{j\mu\omega(j\epsilon_{Re}\omega)}\cos\theta - \left(\sqrt{j\mu\omega(\sigma+j\epsilon_{Re}\omega)}\right)'\cos\theta'}{\sqrt{j\mu\omega(j\epsilon_{Re}\omega)}\cos\theta + \left(\sqrt{j\mu\omega(\sigma+j\epsilon_{Re}\omega)}\right)'\cos\theta'} = \frac{j\omega\sqrt{\mu\epsilon_{Re}}\cos\theta - \left(\sqrt{j\mu\omega(\sigma+j\epsilon_{Re}\omega)}\right)'\cos\theta'}{j\omega\sqrt{\mu\epsilon_{Re}}\cos\theta + \left(\sqrt{j\mu\omega(\sigma+j\epsilon_{Re}\omega)}\right)'\cos\theta'}$$

$$= \frac{j\sqrt{\mu}\sqrt{\epsilon_{Re}}\cos\theta - j\sqrt{\mu'}\sqrt{\epsilon'_{Re} - j\frac{\sigma'}{\omega}}\cos\theta'}{j\sqrt{\mu}\sqrt{\epsilon_{Re}}\cos\theta + j\sqrt{\mu'}\sqrt{\epsilon'_{Re} - j\frac{\sigma'}{\omega}}\cos\theta'}$$

$$= \frac{\frac{\sqrt{\mu}\sqrt{\epsilon_{Re}}\cos\theta - \sqrt{\mu'}\sqrt{\epsilon'_{Re}-j\frac{\sigma'}{\omega}}\cos\theta'}{\sqrt{\epsilon_{Re}}\sqrt{\epsilon'_{Re}-j\frac{\sigma'}{\omega}}}}{\frac{\sqrt{\mu}\sqrt{\epsilon_{Re}}\cos\theta + \sqrt{\mu'}\sqrt{\epsilon'_{Re}-j\frac{\sigma'}{\omega}}\cos\theta'}{\sqrt{\epsilon_{Re}}\sqrt{\epsilon'_{Re}-j\frac{\sigma'}{\omega}}}}$$

$$= \frac{\frac{\sqrt{\mu}}{\sqrt{\epsilon'_{Re}-j\frac{\sigma'}{\omega}}}\cos\theta - \frac{\sqrt{\mu'}}{\sqrt{\epsilon_{Re}}}\cos\theta'}{\frac{\sqrt{\mu}}{\sqrt{\epsilon'_{Re}-j\frac{\sigma'}{\omega}}}\cos\theta + \frac{\sqrt{\mu'}}{\sqrt{\epsilon_{Re}}}\cos\theta'}$$

Note that $\mu = \mu'$

$$= \frac{\frac{\sqrt{\mu'}}{\sqrt{\epsilon'_{Re}-j\frac{\sigma'}{\omega}}}\cos\theta - \frac{\sqrt{\mu}}{\sqrt{\epsilon_{Re}}}\cos\theta'}{\frac{\sqrt{\mu'}}{\sqrt{\epsilon'_{Re}-j\frac{\sigma'}{\omega}}}\cos\theta + \frac{\sqrt{\mu}}{\sqrt{\epsilon_{Re}}}\cos\theta'} = \frac{\eta'\cos(\theta) - \eta\cos(\theta')}{\eta'\cos(\theta) + \eta\cos(\theta')}$$

□

Transmission Coefficient:

$$\tau = \frac{2N}{N+N'} = 1 + \Gamma \tag{A.13}$$

Power Reflection:

$$|\Gamma|^2 \tag{A.14}$$

Power Transmission:

$$|\tau|^2 \frac{\mathrm{Re}\{N'\}}{\mathrm{Re}\{N\}} = 1 - |\Gamma|^2 \tag{A.15}$$

Rutgers

Reflection Coefficient:

$$\Gamma_{TE} = \frac{k_z - k'_z}{k_z + k'_z} \tag{A.16}$$

With k_z and k'_z given by 2.8

Proof.

$$\begin{aligned}\Gamma &= \frac{\omega\sqrt{\mu\epsilon}\cos\theta - \omega\sqrt{\mu\epsilon'}\cos\theta'}{\omega\sqrt{\mu\epsilon}\cos\theta + \omega\sqrt{\mu\epsilon'}\cos\theta'} \\ &= \frac{\frac{\omega\sqrt{\mu\epsilon}\cos\theta - \omega\sqrt{\mu\epsilon'}\cos\theta'}{\sqrt{\epsilon\epsilon'}}}{\frac{\omega\sqrt{\mu\epsilon}\cos\theta + \omega\sqrt{\mu\epsilon'}\cos\theta'}{\sqrt{\epsilon\epsilon'}}} \qquad = \frac{\omega\sqrt{\frac{\mu}{\epsilon'}}\cos\theta - \omega\sqrt{\frac{\mu}{\epsilon}}\cos\theta'}{\omega\sqrt{\frac{\mu}{\epsilon'}}\cos\theta + \omega\sqrt{\frac{\mu}{\epsilon}}\cos\theta'} \\ &= \frac{\eta'\cos(\theta) - \eta\cos(\theta')}{\eta'\cos(\theta) + \eta\cos(\theta')}\end{aligned}$$

□

Transmission Coefficient:

$$\tau_{TE} = 1 + \Gamma_{TE} = \frac{2k_z}{k_z + k'_z} \tag{A.17}$$

Power Reflection:

$$|\Gamma|^2 \tag{A.18}$$

Power Transmission:

$$|\tau|^2 \frac{\text{Re}\{k'_z\}}{\text{Re}\{k_z\}} = 1 - |\Gamma|^2 \tag{A.19}$$

A.1.2 Parallel - TM

Pozar

Reflection Coefficient:

$$\Gamma = \frac{\eta'\cos(\theta') - \eta\cos(\theta)}{\eta'\cos(\theta') + \eta\cos(\theta)} \tag{A.20}$$

With η defined the same way as (A.2)
Transmission Coefficient:

$$\tau = \frac{2\eta'\cos\theta'}{\eta'\cos(\theta') + \eta\cos(\theta)} = 1 + \Gamma \tag{A.21}$$

Power Reflection:

$$|\Gamma|^2 \tag{A.22}$$

Power Transmission:

$$|\tau|^2 \, \mathrm{Re}\left\{ \frac{\eta \cos\theta}{\eta' \cos\theta'} \right\} \tag{A.23}$$

MIT

Reflection Coefficient:

$$\Gamma = \frac{M_i - M_t}{M_i + M_t} \tag{A.24}$$

$$M_i = \eta \cos\theta \tag{A.25}$$

$$M_t = \eta' \cos\theta' \tag{A.26}$$

η and η' being the same definition as Pozar (A.2).

$$\Gamma = \frac{\eta \cos\theta - \eta' \cos\theta'}{\eta \cos\theta + \eta' \cos\theta'}$$

This results in a value that is the negative of the Pozar textbook.

Transmission Coefficient:

$$\tau = 1 + \Gamma = \frac{2M_i}{M_i + M_t} = \frac{2\eta \cos\theta}{\eta \cos\theta + \eta' \cos\theta'} \tag{A.27}$$

Power Reflection:

$$|\Gamma|^2 \tag{A.28}$$

Power Transmission:

$$|\tau|^2 \, \mathrm{Re}\left\{ \frac{\eta' \cos\theta'}{\eta \cos\theta} \right\} = 1 - |\Gamma|^2 \tag{A.29}$$

Although this form is different as compared to Pozar the resultant power is correct.

Rutgers

Reflection Coefficient

$$\Gamma = \frac{k'_z \epsilon - k_z \epsilon'}{k'_z \epsilon + k_z \epsilon'} \tag{A.30}$$

With k_z and k'_z the same as (2.8)

Proof.

$$\Gamma = \frac{\omega\sqrt{\mu\epsilon'}\cos\theta'\epsilon - \omega\sqrt{\mu\epsilon}\cos\theta\epsilon'}{\omega\sqrt{\mu\epsilon'}\cos\theta'\epsilon + \omega\sqrt{\mu\epsilon}\cos\theta\epsilon'}$$
$$= \frac{\frac{\omega\sqrt{\mu\epsilon'}\cos\theta'\epsilon - \omega\sqrt{\mu\epsilon}\cos\theta\epsilon'}{\epsilon\epsilon'}}{\frac{\omega\sqrt{\mu\epsilon'}\cos\theta'\epsilon + \omega\sqrt{\mu\epsilon}\cos\theta\epsilon'}{\epsilon\epsilon'}}$$
$$= \frac{\omega\sqrt{\frac{\mu}{\epsilon'}}\cos\theta' - \omega\sqrt{\frac{\mu}{\epsilon}}\cos\theta}{\omega\sqrt{\frac{\mu}{\epsilon'}}\cos\theta' + \omega\sqrt{\frac{\mu}{\epsilon}}\cos\theta}$$
$$= \frac{\eta'\cos(\theta') - \eta\cos(\theta)}{\eta'\cos(\theta') + \eta\cos(\theta)}$$

□

Transmission Coefficient

$$\tau = \frac{2k_z'\epsilon}{k_z'\epsilon + k_z\epsilon'} = 1 + \Gamma \tag{A.31}$$

Power Reflection

$$|\Gamma|^2 \tag{A.32}$$

Power Transmission:

$$|\tau|^2\frac{\text{Re}\{k_z\epsilon'\}}{\text{Re}\{k_z'\epsilon\}} = 1 - |\Gamma|^2 \tag{A.33}$$

James Wait

Reflection Coefficient

$$\Gamma = -\frac{K_{water} - K_{air}}{K_{water} + K_{air}} \tag{A.34}$$
$$K = \frac{u}{\sigma + j\epsilon_d\omega} \tag{A.35}$$

K is James Wait's notation for η the wave impedance.

$$u = \gamma\cos(\theta) = \sqrt{j\mu\omega(\sigma + j\epsilon_d\omega)}\cos(\theta) \tag{A.36}$$

Proof.

$$\Gamma = -\frac{\frac{\sqrt{j\mu\omega(\sigma'+j\epsilon'_{Re}\omega)}\cos(\theta')}{\sigma'+j\epsilon'_{Re}\omega} - \frac{\sqrt{j\mu\omega(\sigma+j\epsilon_{Re}\omega)}\cos(\theta)}{\sigma+j\epsilon_{Re}\omega}}{\frac{\sqrt{j\mu\omega(\sigma'+j\epsilon'_{Re}\omega)}\cos(\theta')}{\sigma'+j\epsilon'_{Re}\omega} + \frac{\sqrt{j\mu\omega(\sigma+j\epsilon_{Re}\omega)}\cos(\theta)}{\sigma+j\epsilon_{Re}\omega}}$$

$$\sigma = 0$$

$$\Gamma = -\frac{\frac{\sqrt{j\mu\omega(\sigma'+j\epsilon'_{Re}\omega)}\cos(\theta')}{\sigma'+j\epsilon'_{Re}\omega} - \frac{\sqrt{\mu\omega(\epsilon_{Re}\omega)}\cos(\theta)}{\epsilon_{Re}\omega}}{\frac{\sqrt{j\mu\omega(\sigma'+j\epsilon'_{Re}\omega)}\cos(\theta')}{\sigma'+j\epsilon'_{Re}\omega} + \frac{\sqrt{\mu\omega(\epsilon_{Re}\omega)}\cos(\theta)}{\epsilon_{Re}\omega}}$$

$$= -\frac{\frac{j\omega\sqrt{\mu}\sqrt{\epsilon'_{Re}-j\frac{\sigma'}{\omega}}\cos(\theta')}{\sigma'+j\epsilon'_{Re}\omega} - \frac{\sqrt{\mu\omega(\epsilon_{Re}\omega)}\cos(\theta)}{\epsilon_{Re}\omega}}{\frac{j\omega\sqrt{\mu}\sqrt{\epsilon'_{Re}-j\frac{\sigma'}{\omega}}\cos(\theta')}{\sigma'+j\epsilon'_{Re}\omega} + \frac{\sqrt{\mu\omega(\epsilon_{Re}\omega)}\cos(\theta)}{\epsilon_{Re}\omega}}$$

$$= -\frac{\frac{j\omega\sqrt{\mu\epsilon'}\cos(\theta')}{j\omega(\epsilon'_{Re}-j\frac{\sigma'}{\omega})} - \frac{\omega\sqrt{\mu\epsilon\cos(\theta)}}{\epsilon_{Re}\omega}}{\frac{j\omega\sqrt{\mu\epsilon'}\cos(\theta')}{j\omega(\epsilon'_{Re}-j\frac{\sigma'}{\omega})} + \frac{\omega\sqrt{\mu\epsilon}\cos(\theta)}{\epsilon_{Re}\omega}}$$

$$= -\frac{\frac{j\omega\sqrt{\mu\epsilon'}\cos(\theta')}{j\omega\epsilon'} - \frac{\omega\sqrt{\mu\epsilon\cos(\theta)}}{\epsilon\omega}}{\frac{j\omega\sqrt{\mu\epsilon'}\cos(\theta')}{j\omega\epsilon'} + \frac{\omega\sqrt{\mu\epsilon}\cos(\theta)}{\epsilon\omega}}$$

$$= -\frac{\frac{\sqrt{\mu\epsilon'}\cos(\theta')}{\epsilon'} - \frac{\sqrt{\mu\epsilon\cos(\theta)}}{\epsilon}}{\frac{\sqrt{\mu\epsilon'}\cos(\theta')}{\epsilon'} + \frac{\sqrt{\mu\epsilon}\cos(\theta)}{\epsilon}}$$

$$\Gamma = -\frac{\eta'\cos(\theta') - \eta\cos(\theta)}{\eta'\cos(\theta') + \eta\cos(\theta)}$$

□

This results in a value that is the negative of the Pozar textbook. It results in the same value as calculated with MIT approach.

Transmission Coefficient

$$\tau = \frac{2K_{air}}{K_{water} + K_{air}} \tag{A.37}$$

Power Reflection

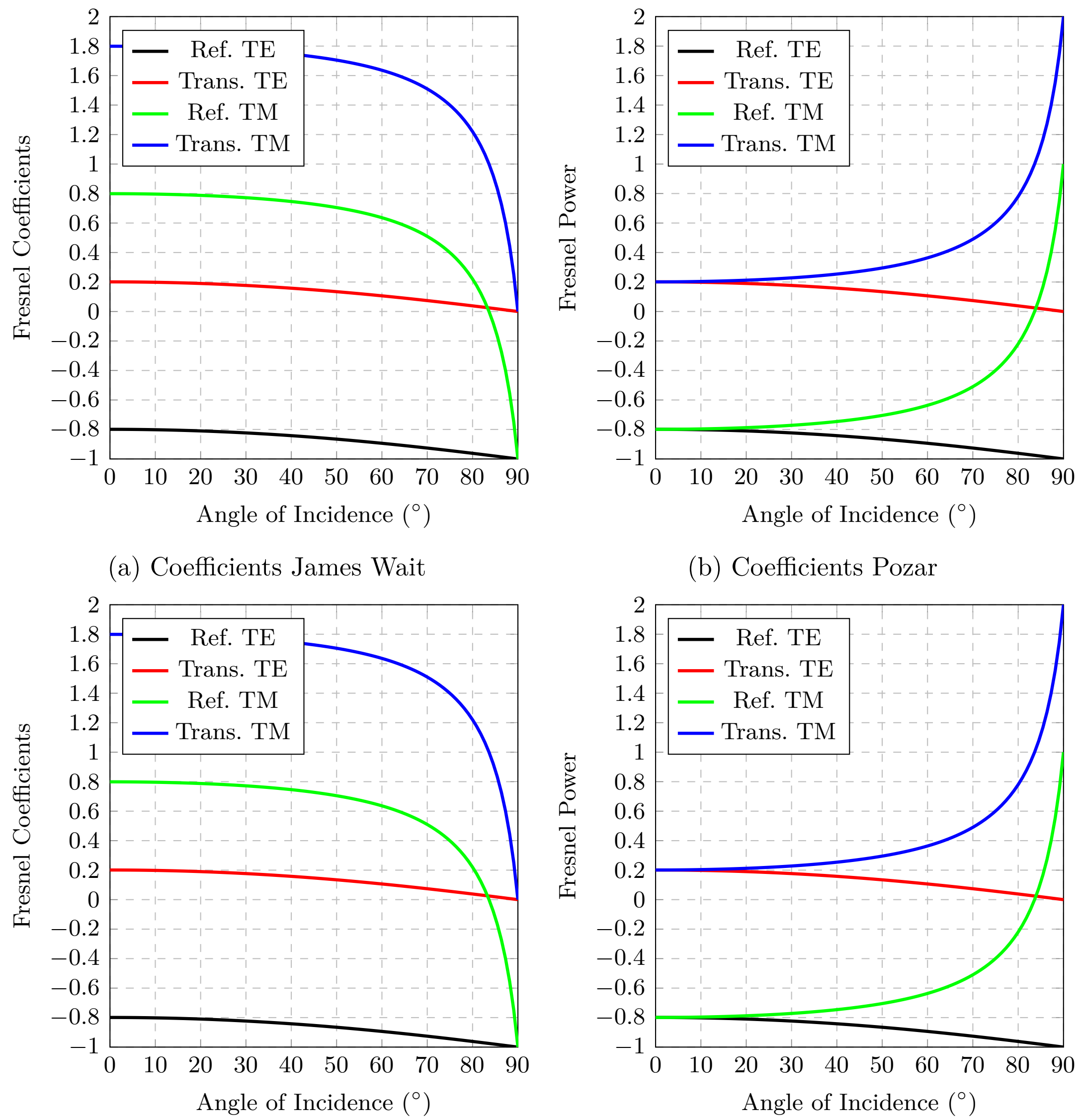
$$|\Gamma|^2 \tag{A.38}$$

Power Transmission:

$$|\tau|^2 \operatorname{Re}\left\{\frac{K_{water}}{K_{air}}\right\} = 1 - |\Gamma|^2 \tag{A.39}$$

A.1.3 TE and TM Polarisation Plots

Coefficients for TE and TM modes:



(a) Coefficients James Wait

(b) Coefficients Pozar

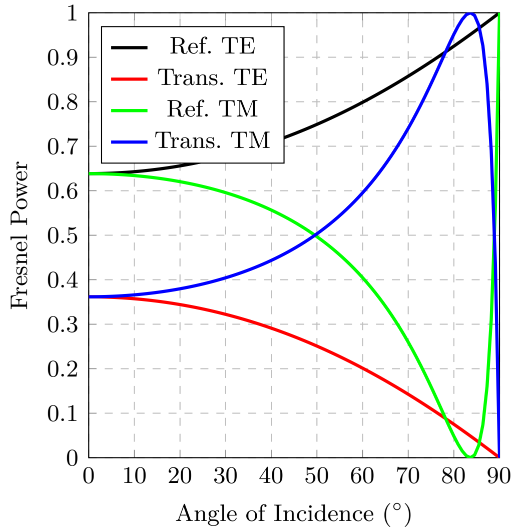
(c) Coefficients MIT

(d) Coefficients Rutgers

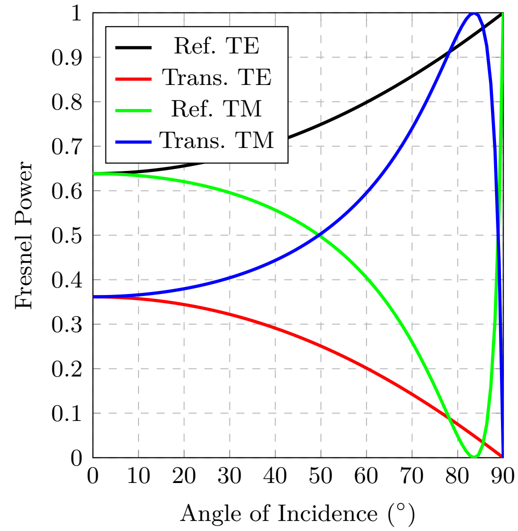
Figure A.1: TE and TM Fresnel coefficients.

This highlights that the coefficients for the TM polarisation are not in agreement with two textbooks containing a difference of a multiplication of negative one.

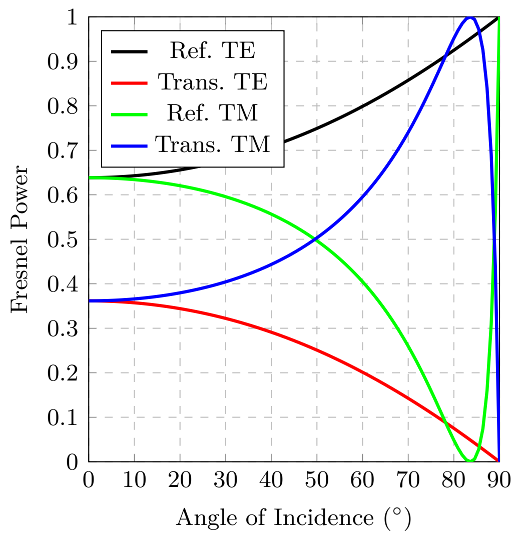
The power values however agree for both TE and TM polarisations for all 4 derivations. The magnitude squared element removes any of the issues of the negative sign of the coefficients.



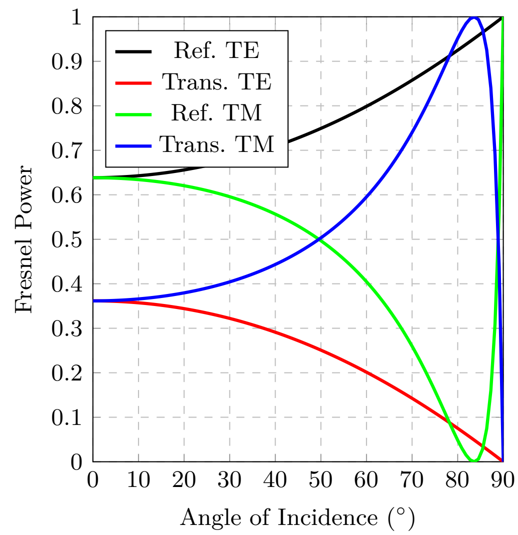
(a) Power James Wait



(b) Power Pozar



(c) Power MIT

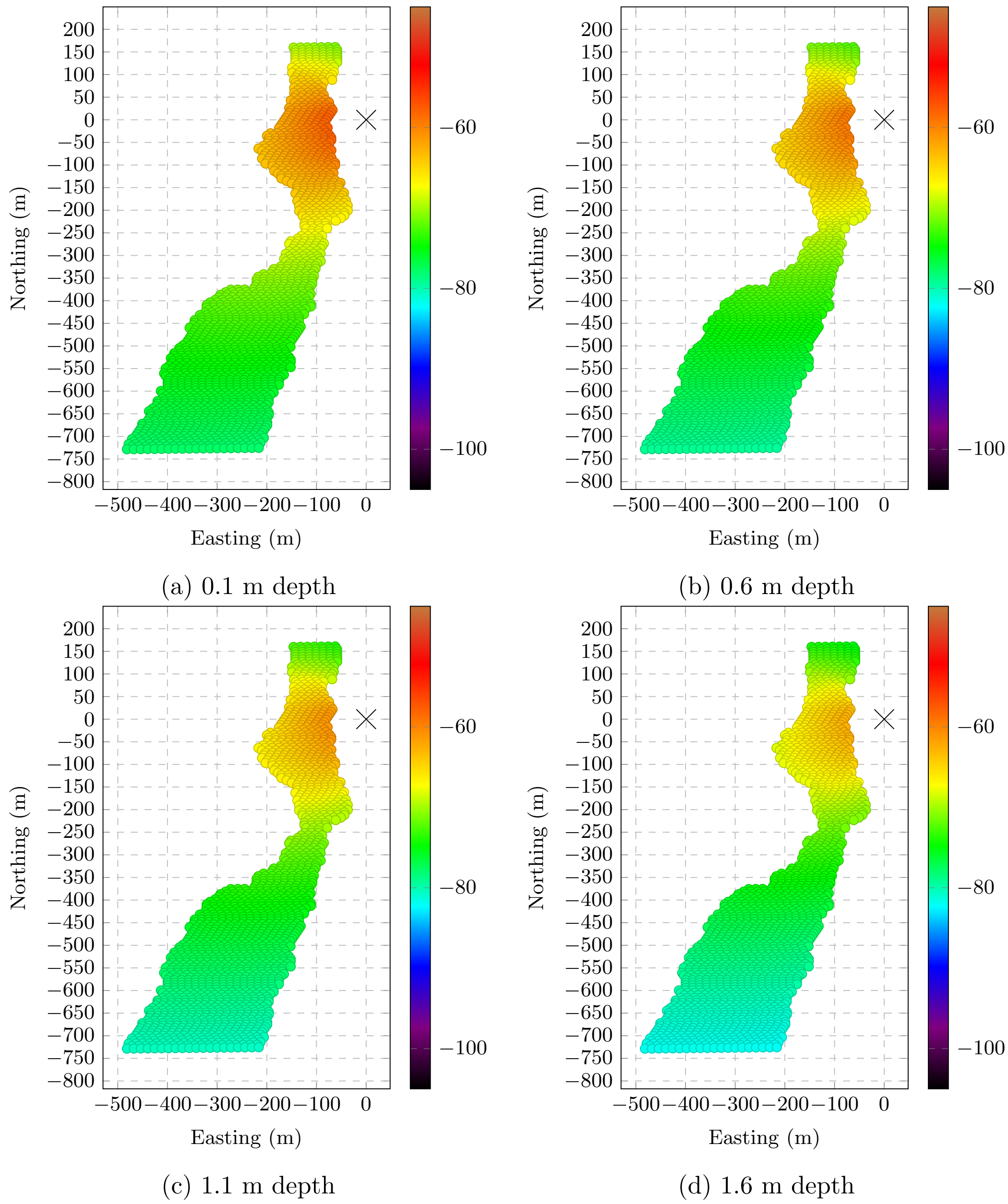


(d) Power Rutgers

Figure A.2: TE and TM Fresnel Power.

A.2 Overall Power

A.2.1 TE+TM Gain



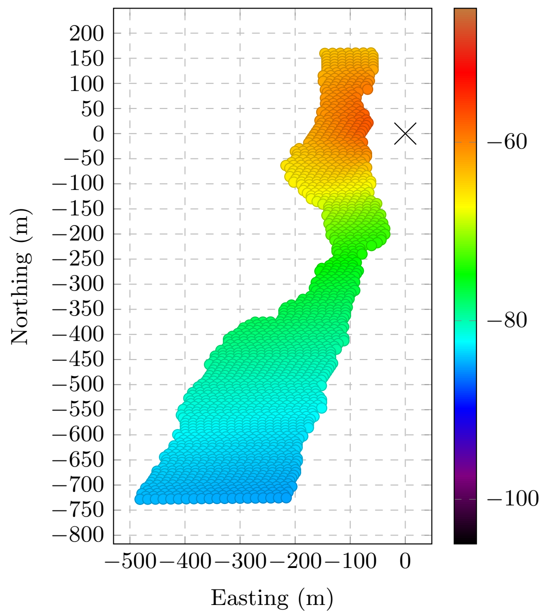
(a) 0.1 m depth

(b) 0.6 m depth

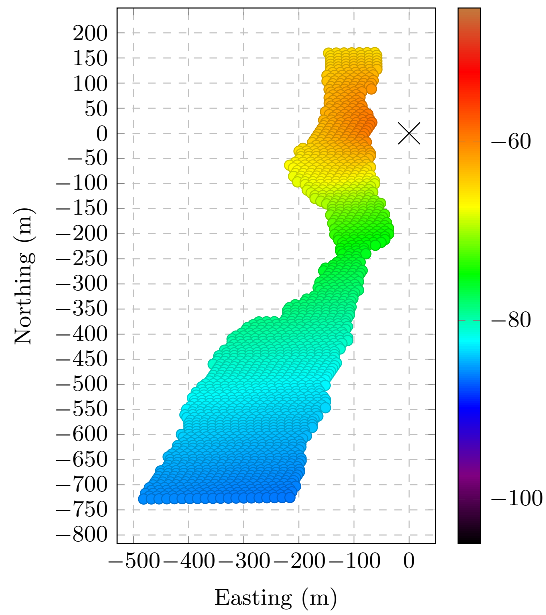
(c) 1.1 m depth

(d) 1.6 m depth

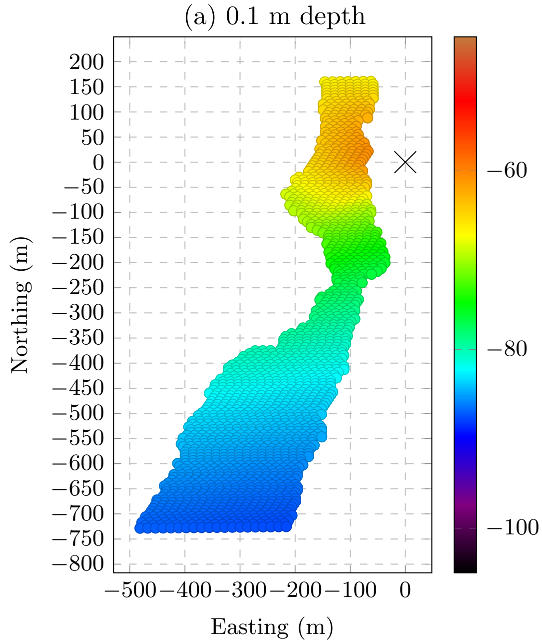
Figure A.3: Total system Loss 0.5(TE+TM)- Eastside Downstream site (dB). The receiver is located at 10U 559418.2593 km E, 15674469.93 km N.



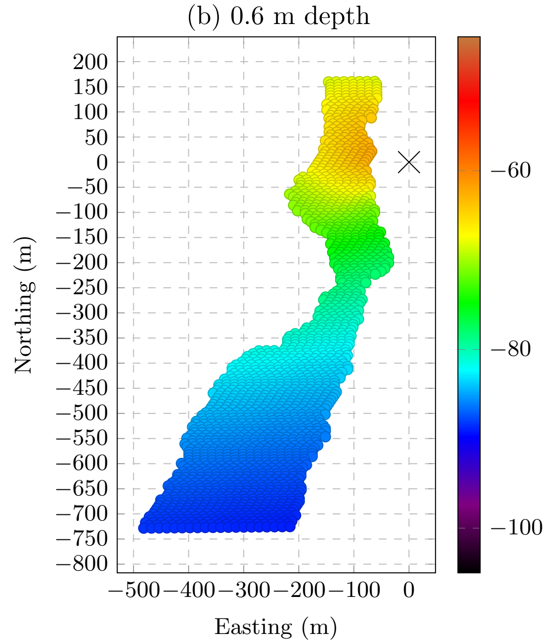
(a) 0.1 m depth



(b) 0.6 m depth



(c) 1.1 m depth



(d) 1.6 m depth

Figure A.4: Total system Loss 0.5(TE+TM)- Eastside Upstream site (dB). The receiver is located at 10U 559418.2593 km E, 15674469.93 km N.

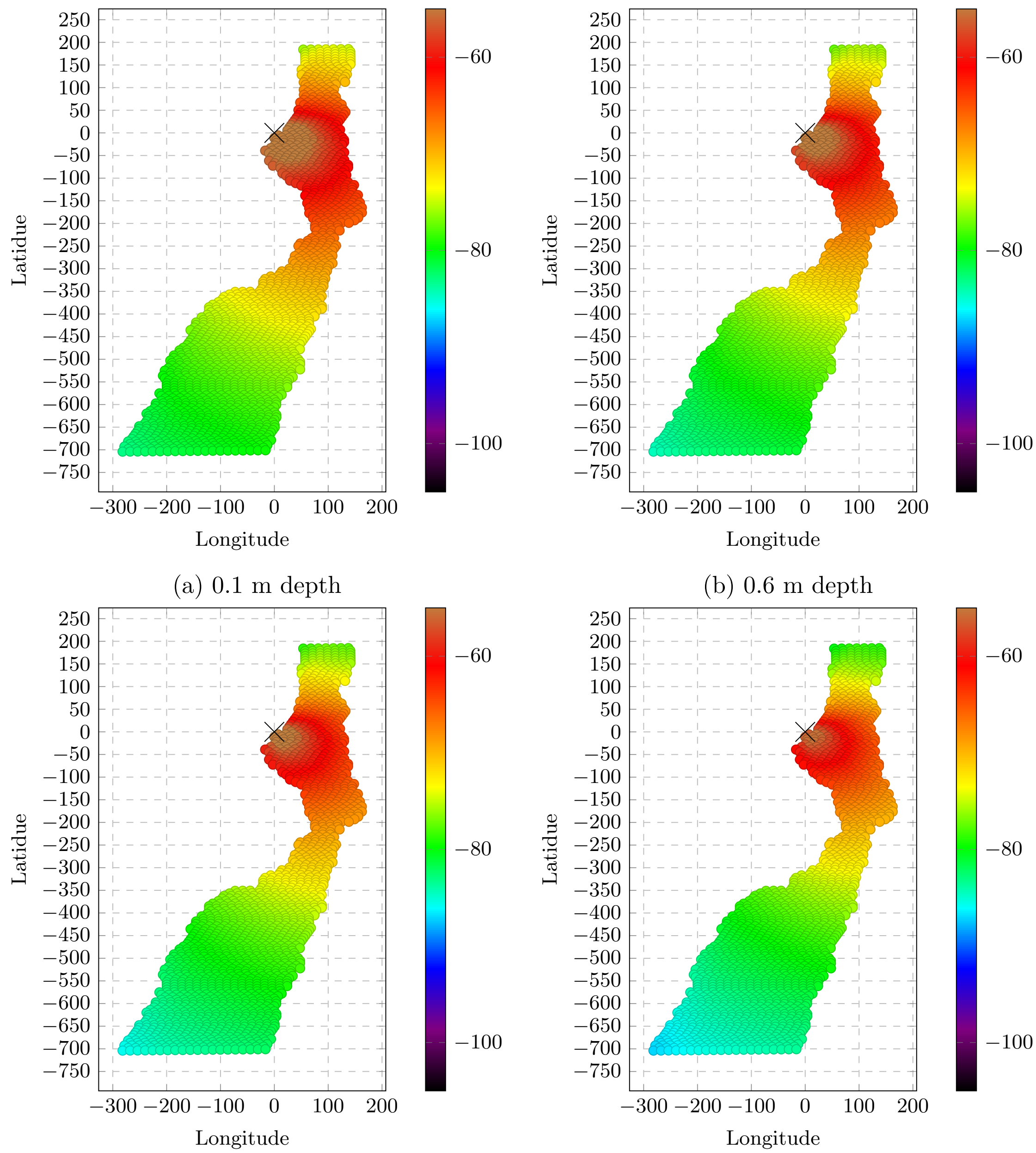
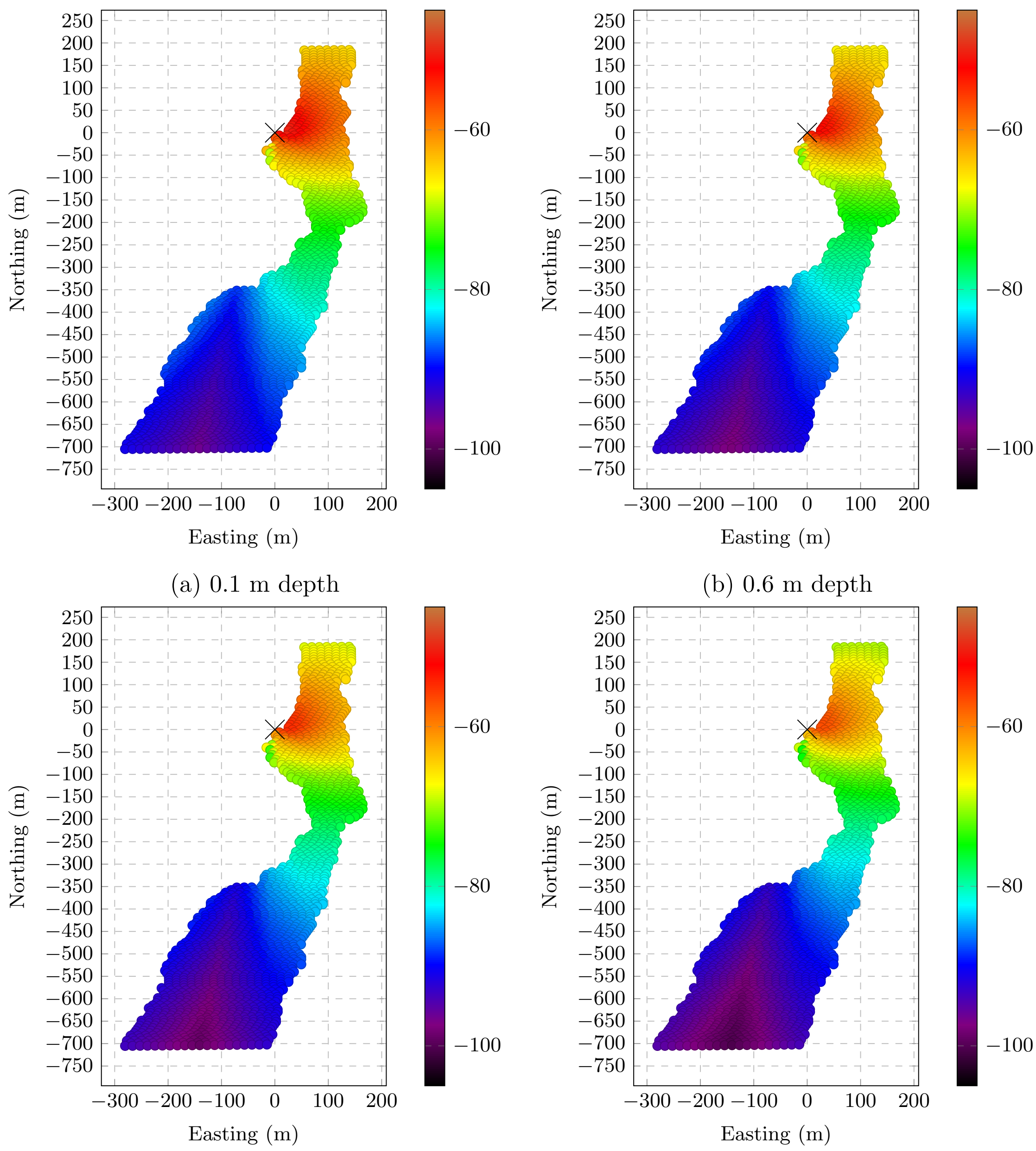


Figure A.5: Total system Loss 0.5(TE+TM)- Eddy Downstream site (dB). The receiver is located at 10U 559218.498 km E, 15674445.6 km N.



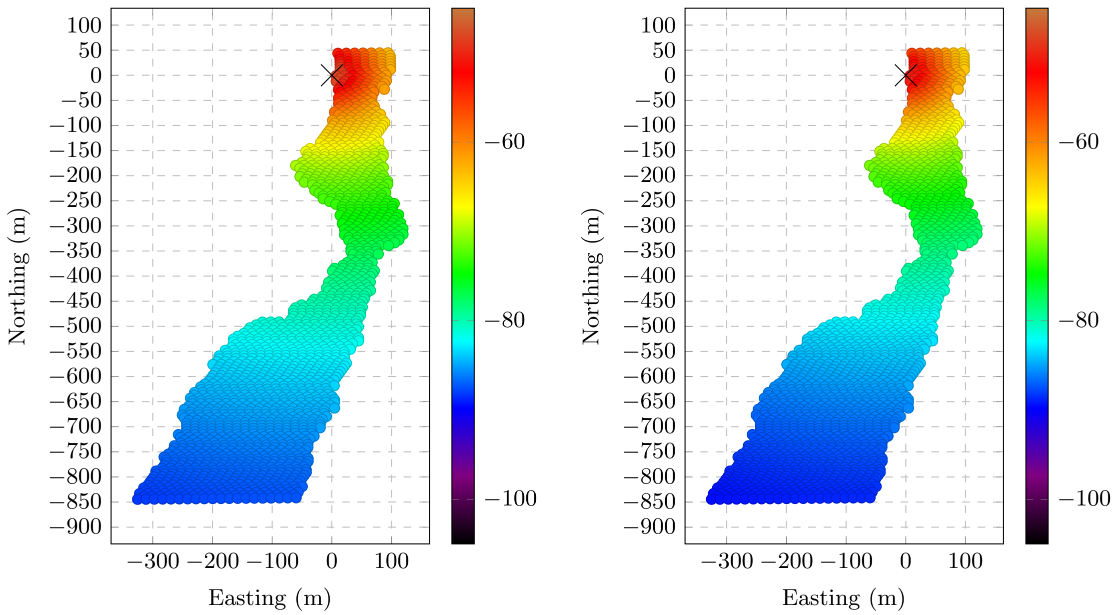
(a) 0.1 m depth

(b) 0.6 m depth

(c) 1.1 m depth

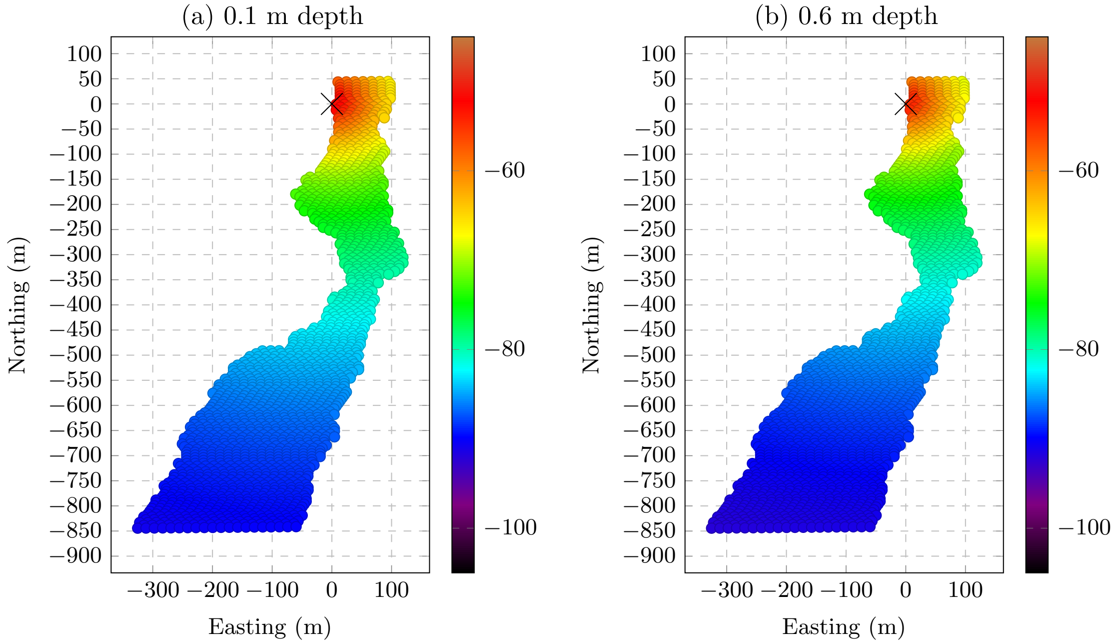
(d) 1.6 m depth

Figure A.6: Total system Loss 0.5(TE+TM)- Eddy Upstream site (dB). The receiver is located at 10U 559217.0907 km E, 15674446.48 km N.



(a) 0.1 m depth

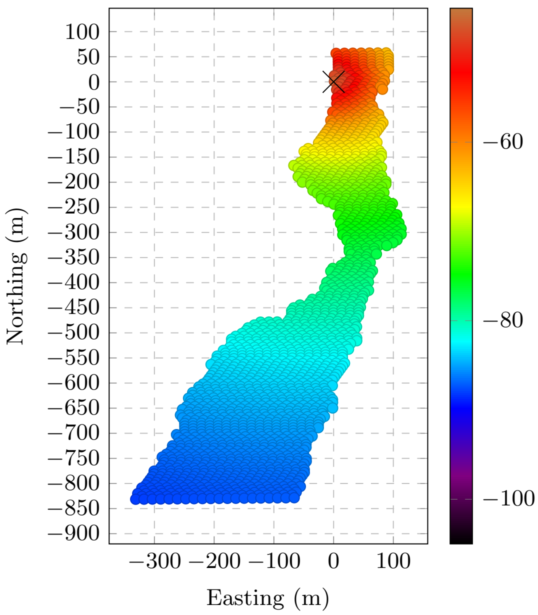
(b) 0.6 m depth



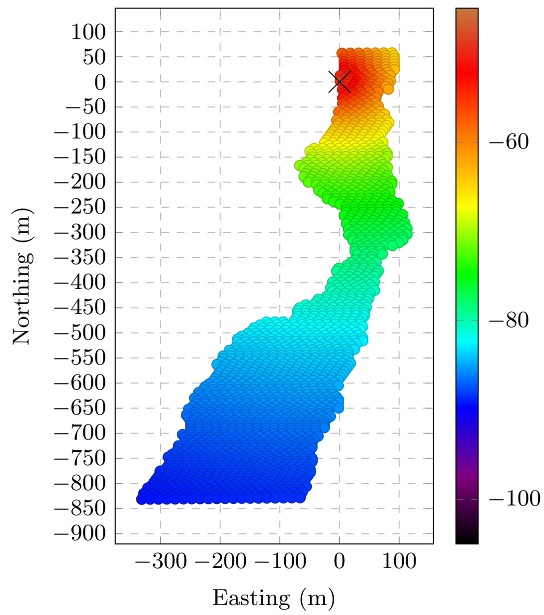
(c) 1.1 m depth

(d) 1.6 m depth

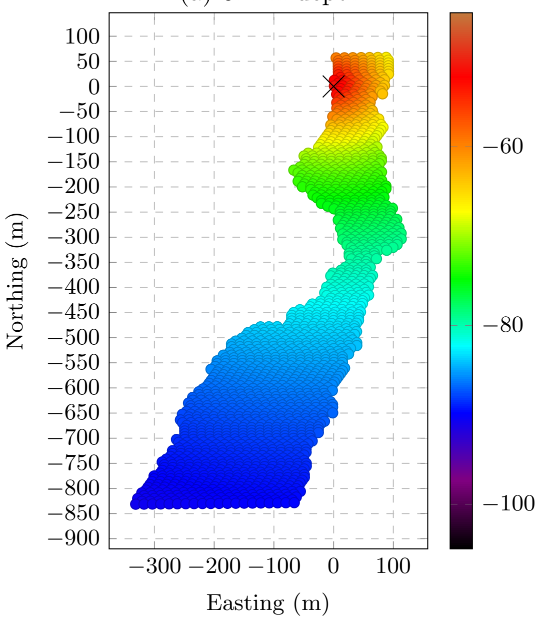
Figure A.7: Total system Loss 0.5(TE+TM)- iBeam p1 site (dB). The receiver is located at 10U 559261.9979 km E, 15674586.02 km N.



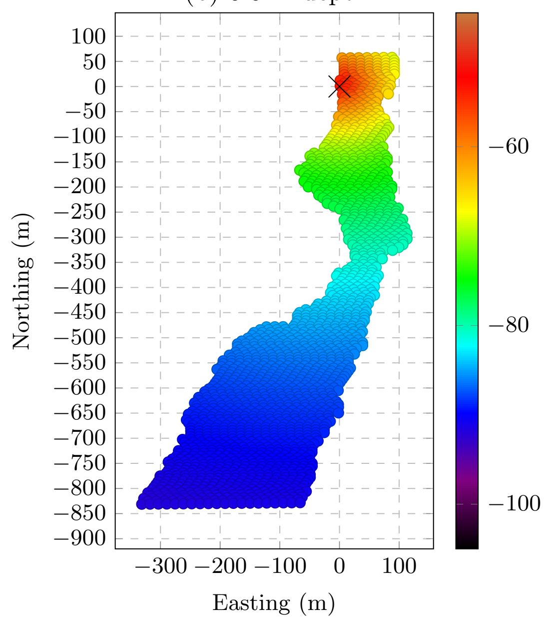
(a) 0.1 m depth



(b) 0.6 m depth

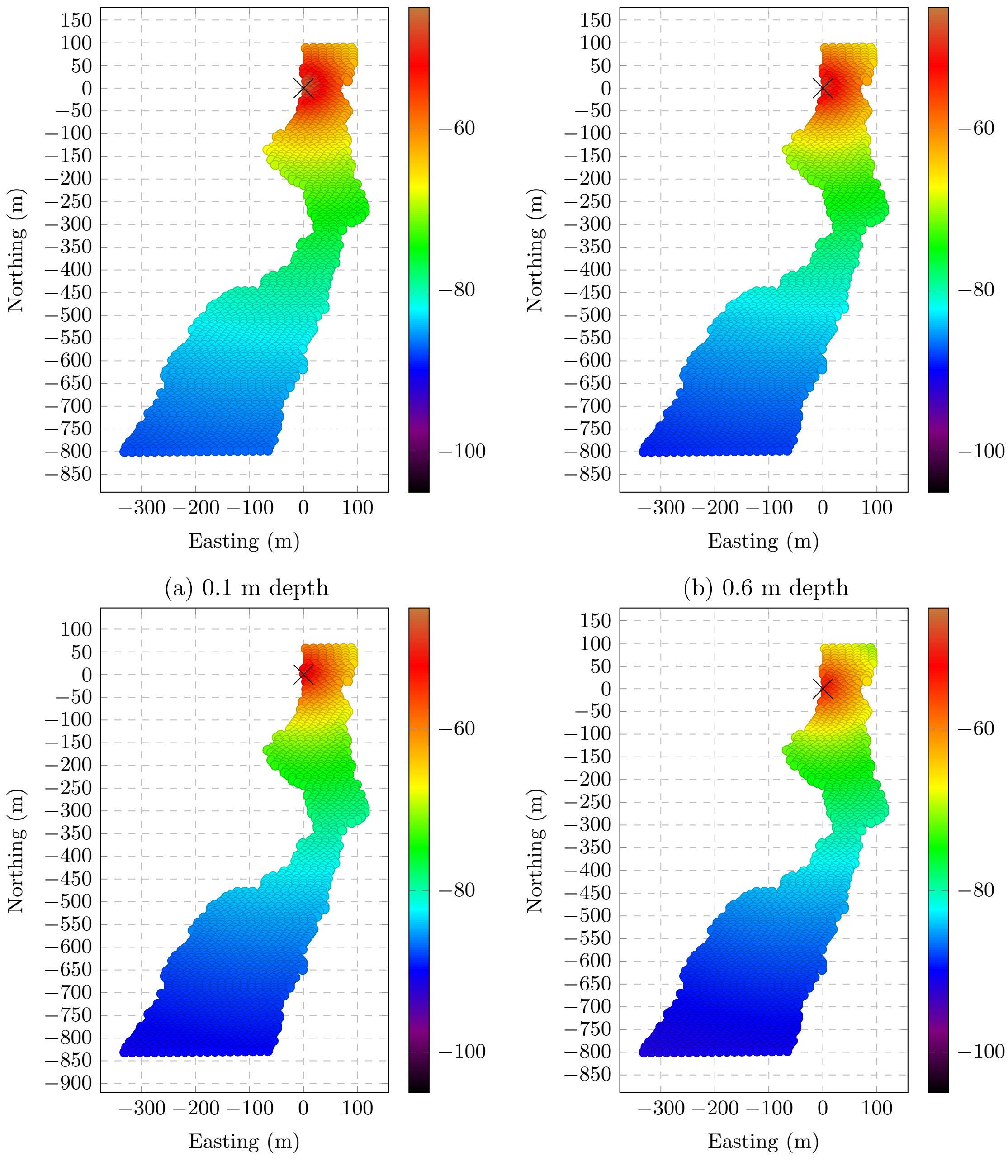


(c) 1.1 m depth



(d) 1.6 m depth

Figure A.8: Total system Loss 0.5(TE+TM)- iBeam p2 site (dB). The receiver is located at 10U 559268.0157 km E, 15674572.97 km N.



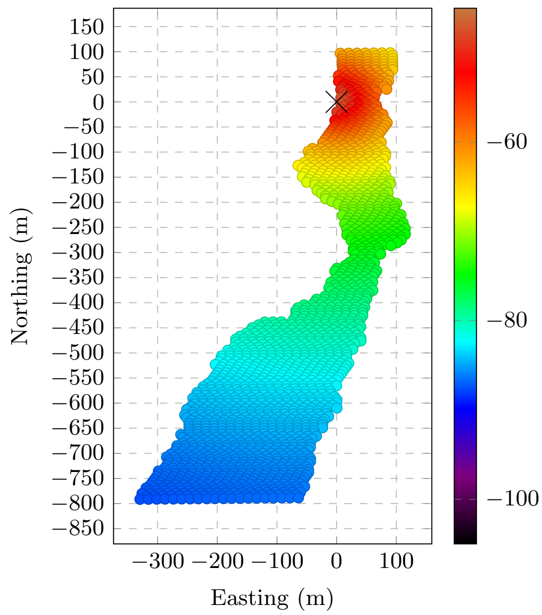
(a) 0.1 m depth

(b) 0.6 m depth

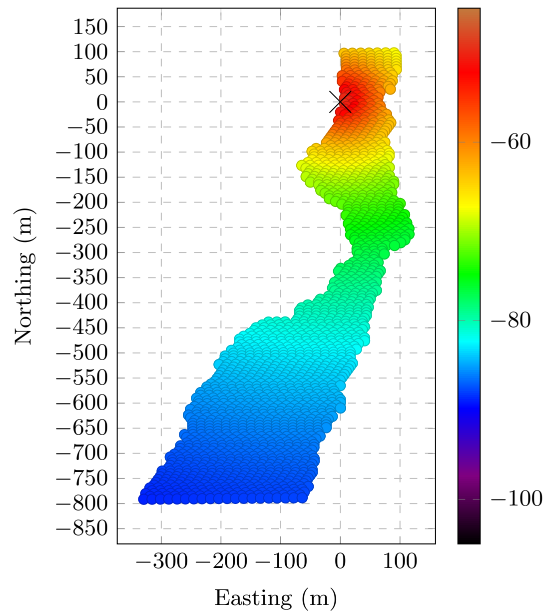
(c) 1.1 m depth

(d) 1.6 m depth

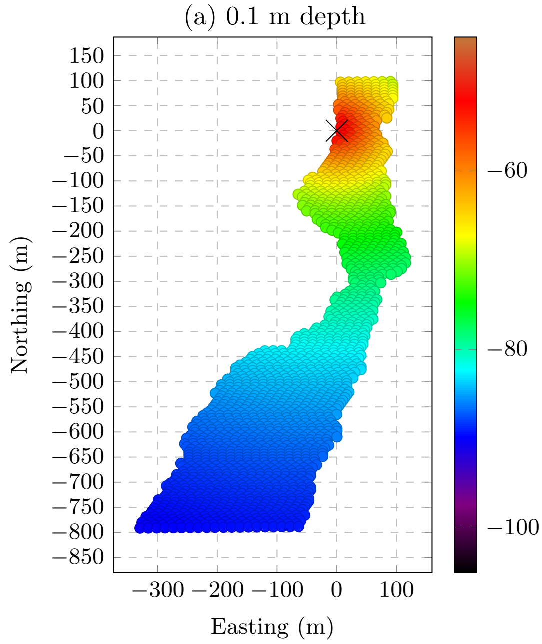
Figure A.9: Total system Loss 0.5(TE+TM)- iBeam p5 site (dB). The receiver is located at 10U 559268.0248 km E, 15674541.94 km N.



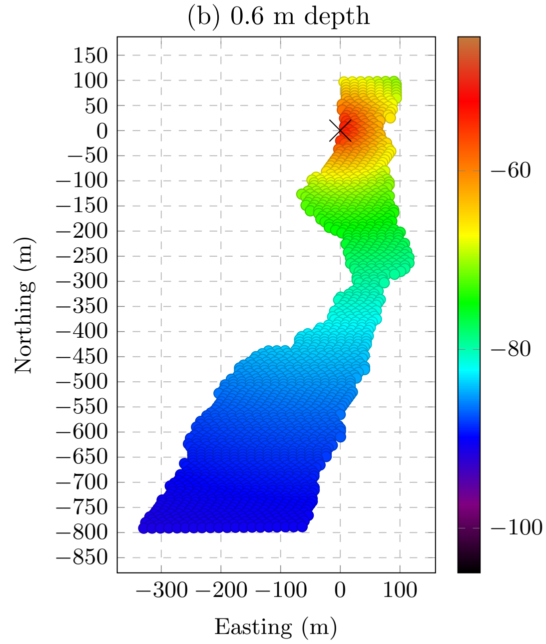
(a) 0.1 m depth



(b) 0.6 m depth

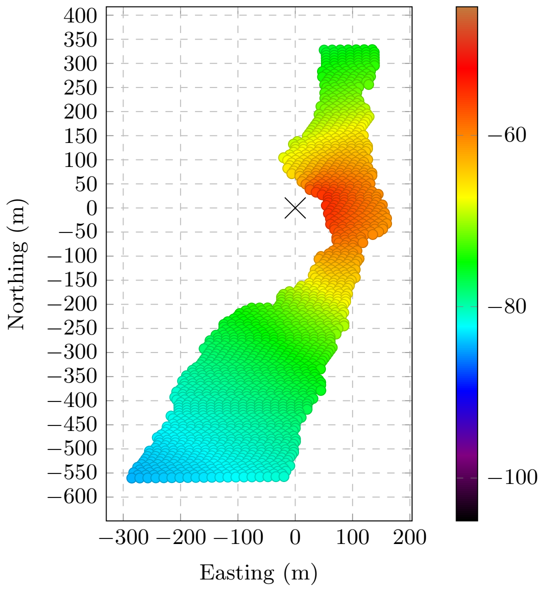


(c) 1.1 m depth

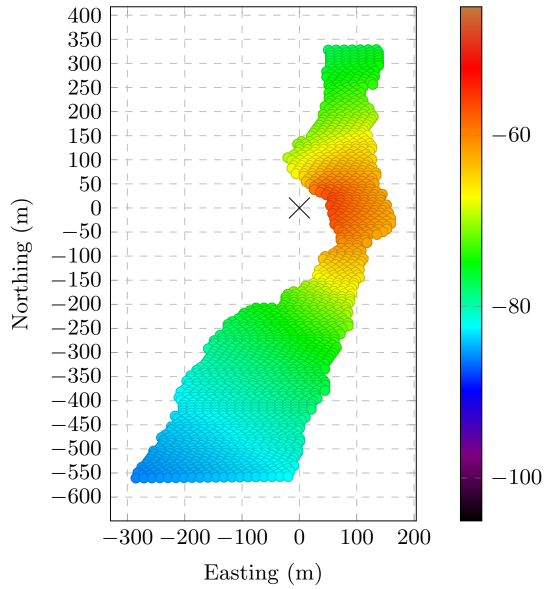


(d) 1.6 m depth

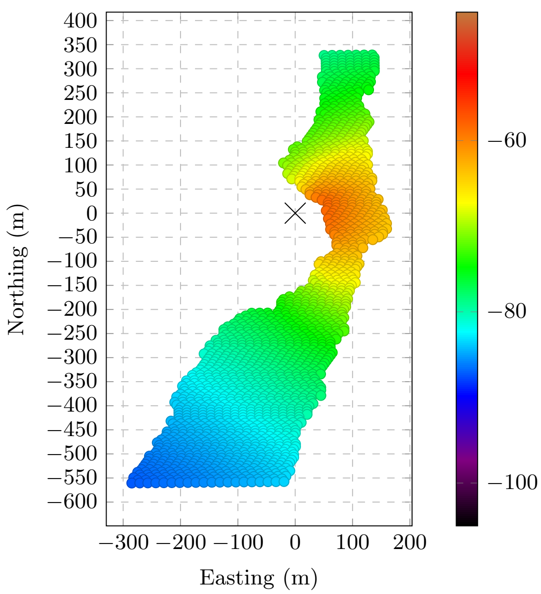
Figure A.10: Total system Loss 0.5(TE+TM)- iBeam p6 site (dB). The receiver is located at 10U 559266.0324 km E, 15674533.02 km N.



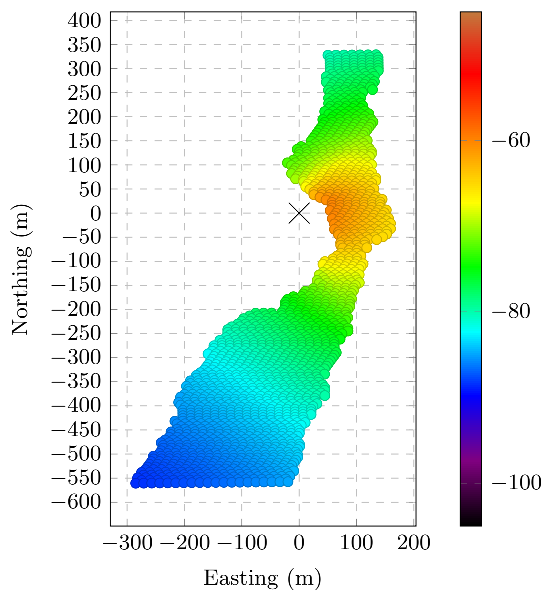
(a) 0.1 m depth



(b) 0.6 m depth

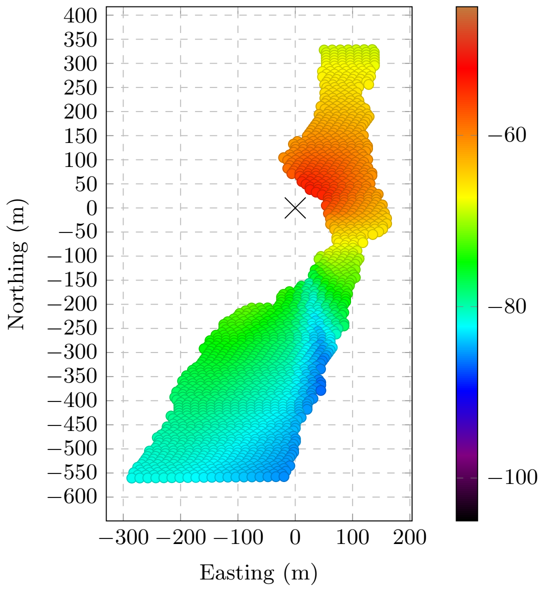


(c) 1.1 m depth

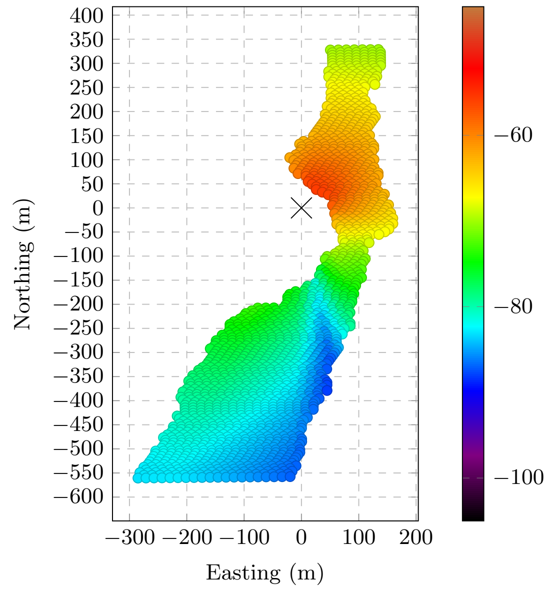


(d) 1.6 m depth

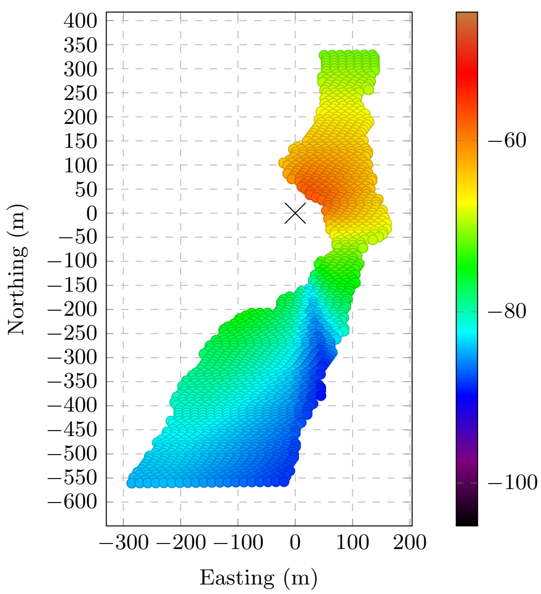
Figure A.11: Total system Loss 0.5(TE+TM)- Jenny Downstream site (dB). The receiver is located at 10U 559221.7604 km E, 15674302.06 km N.



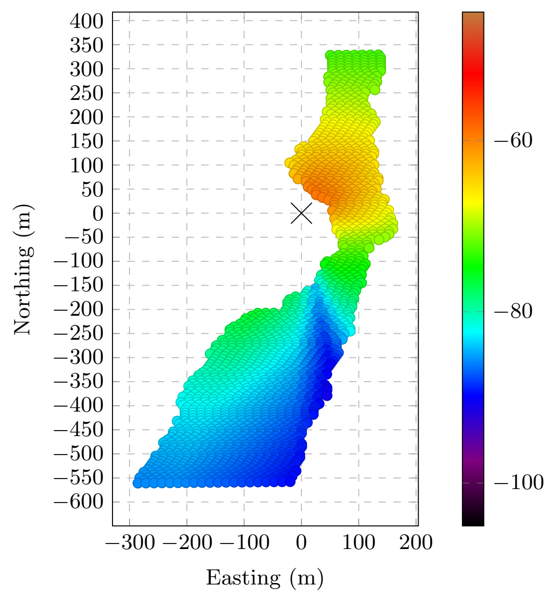
(a) 0.1 m depth



(b) 0.6 m depth

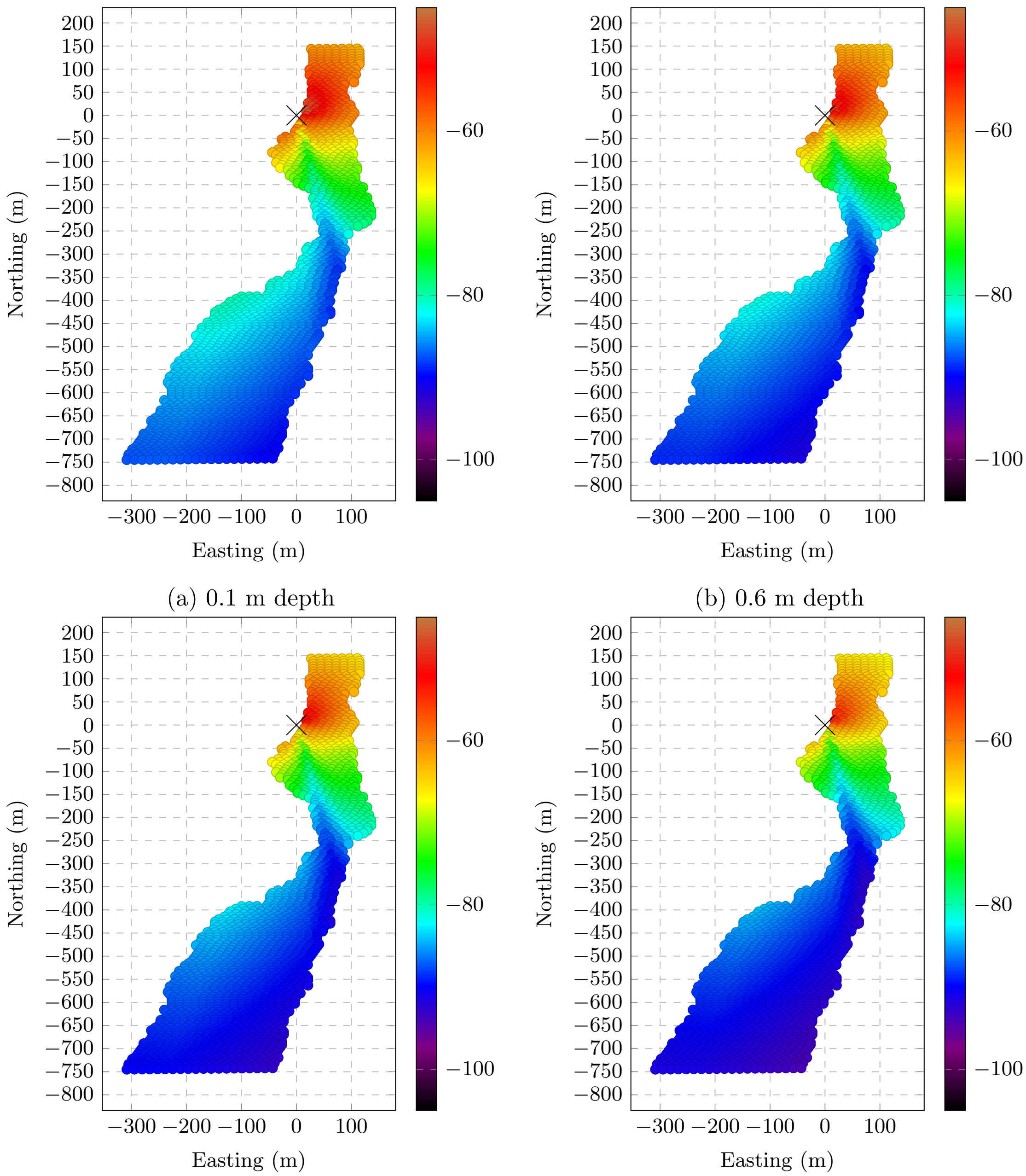


(c) 1.1 m depth



(d) 1.6 m depth

Figure A.12: Total system Loss 0.5(TE+TM)- Jenny Upstream site (dB). The receiver is located at 10U 559221.7604 km E, 15674302.06 km N.



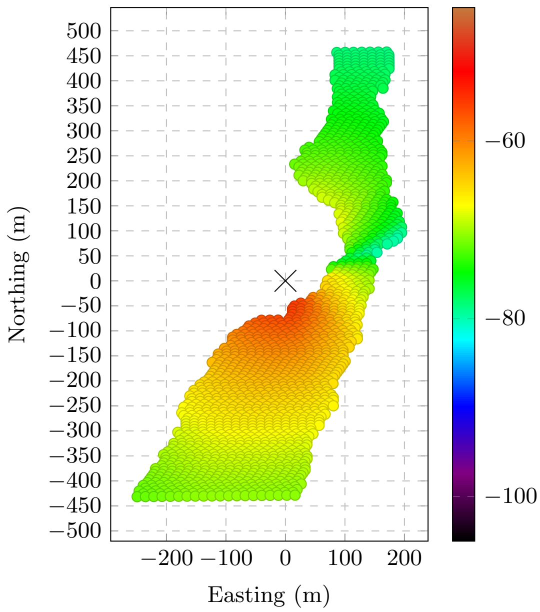
(a) 0.1 m depth

(b) 0.6 m depth

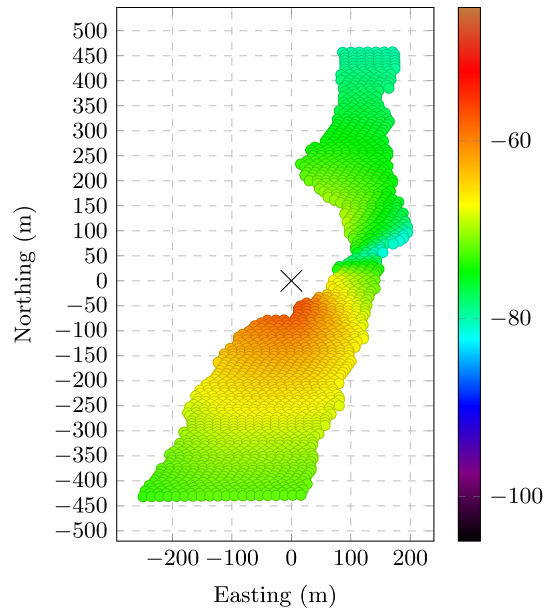
(c) 1.1 m depth

(d) 1.6 m depth

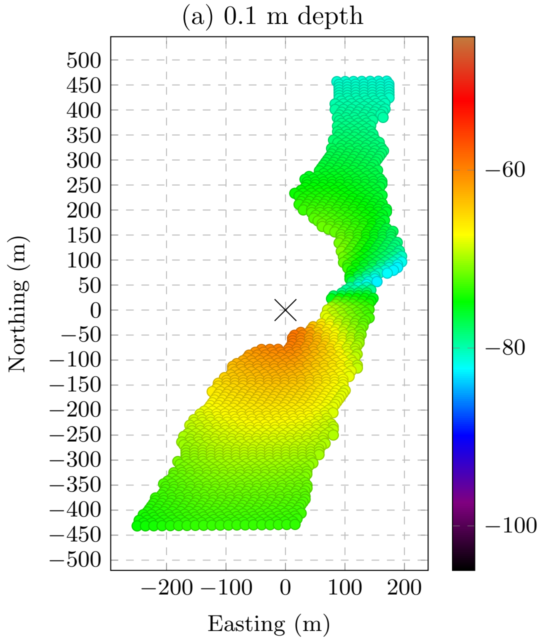
Figure A.13: Total system Loss 0.5(TE+TM)- Nose site (dB). The receiver is located at 10U 559245.1976 km E, 15674486.4 km N.



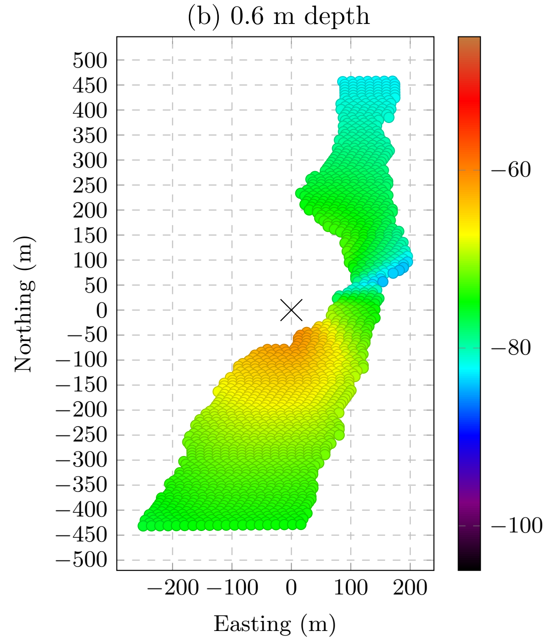
(a) 0.1 m depth



(b) 0.6 m depth

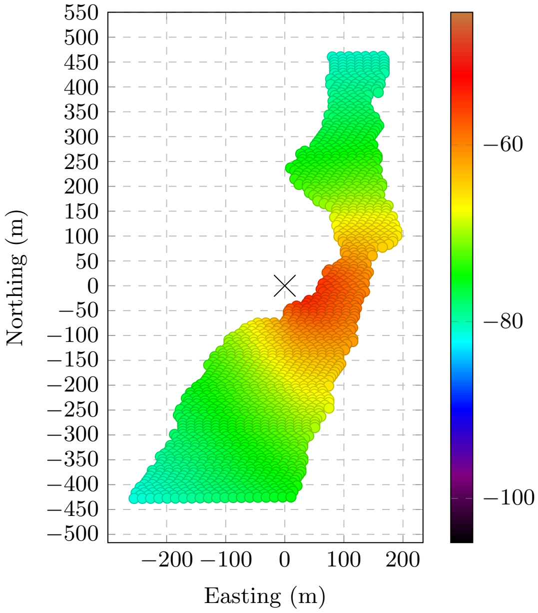


(c) 1.1 m depth

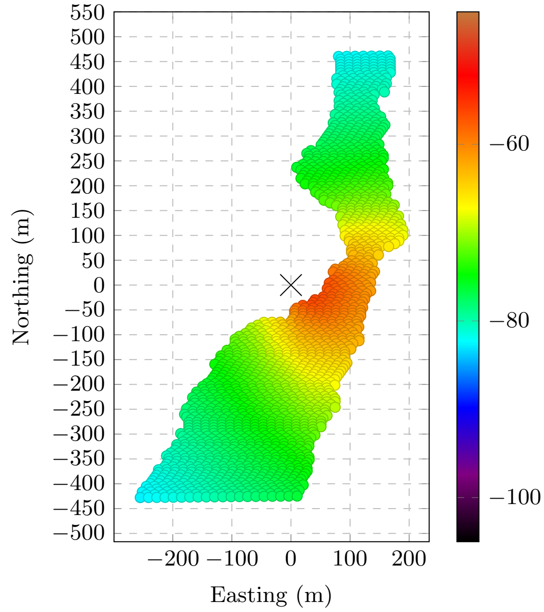


(d) 1.6 m depth

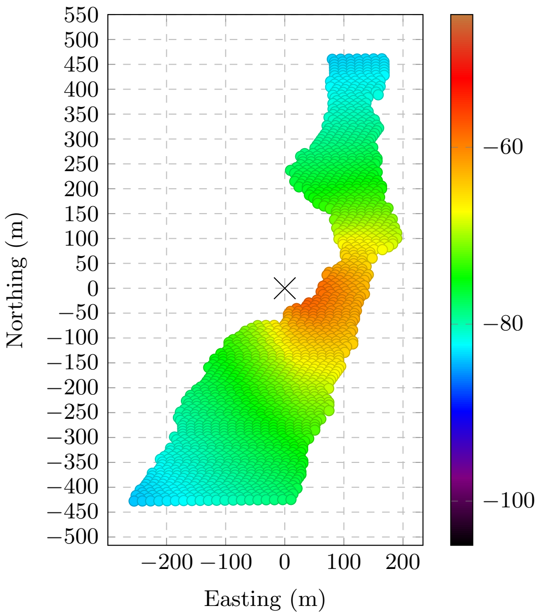
Figure A.14: Total system Loss 0.5(TE+TM)- Razorback Downstream site (dB). The receiver is located at 10U 559185.8782 km E, 15674173.07 km N.



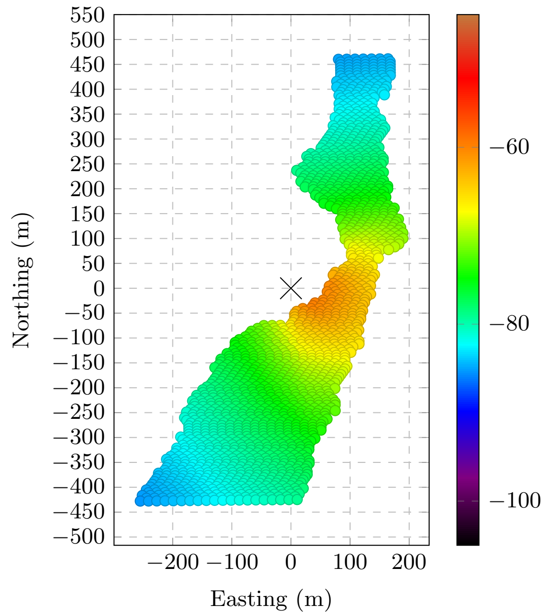
(a) 0.1 m depth



(b) 0.6 m depth



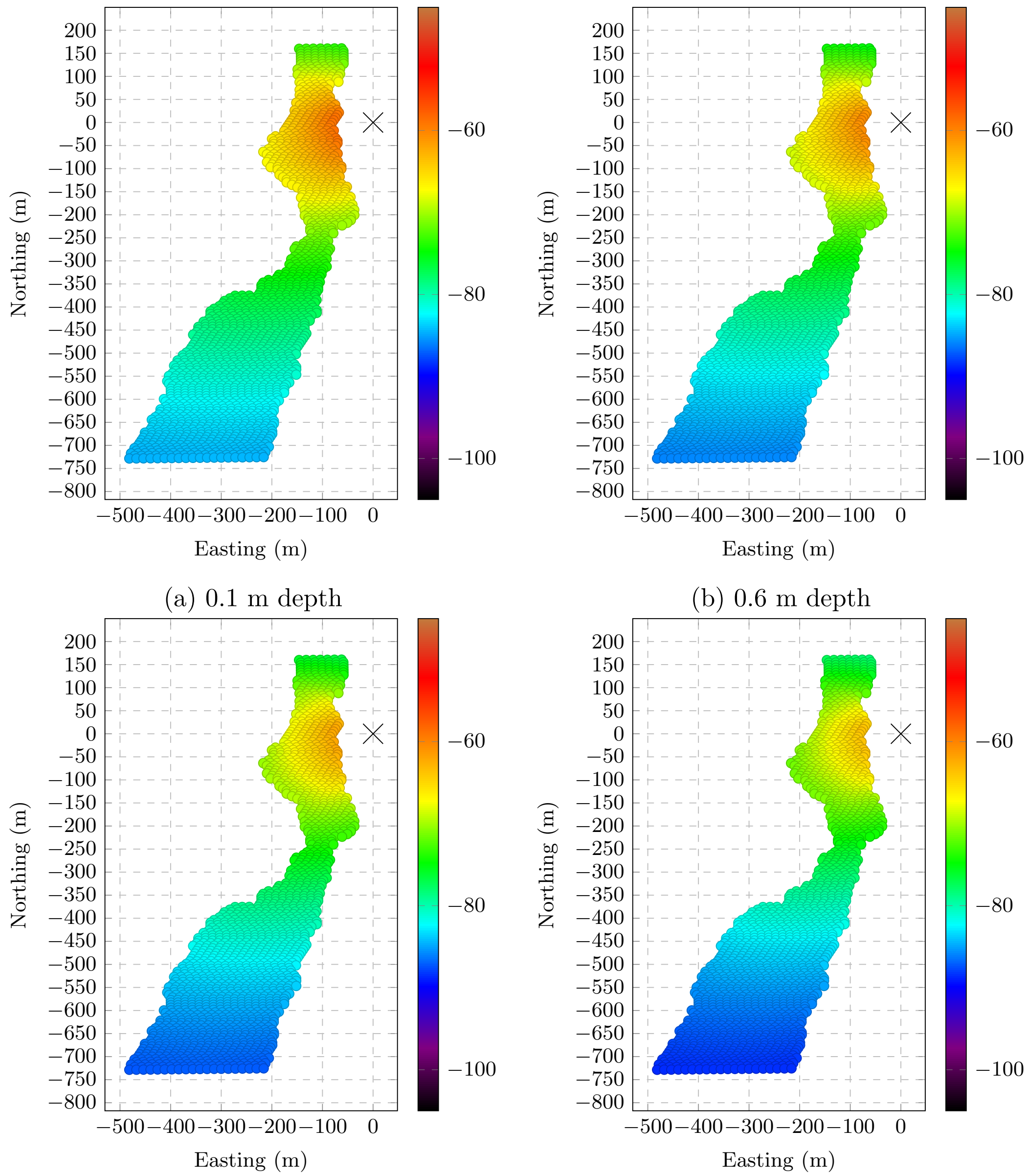
(c) 1.1 m depth



(d) 1.6 m depth

Figure A.15: Total system Loss 0.5(TE+TM)- Razorback Upstream site (dB). The receiver is located at 10U 559191.6489 km E, 15674169.36 km N.

A.2.2 TE Gain



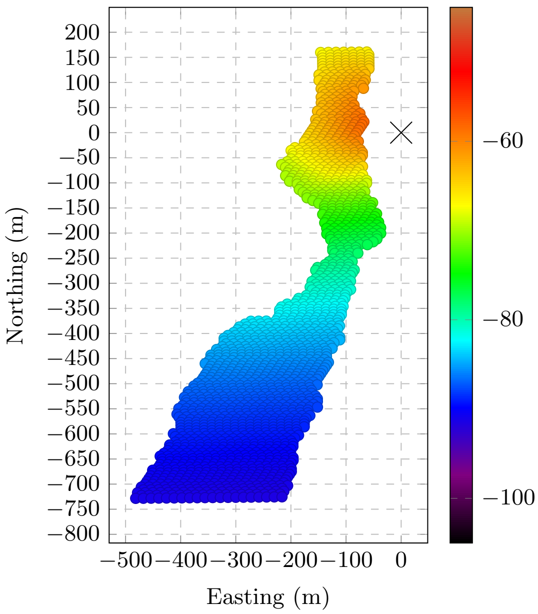
(a) 0.1 m depth

(b) 0.6 m depth

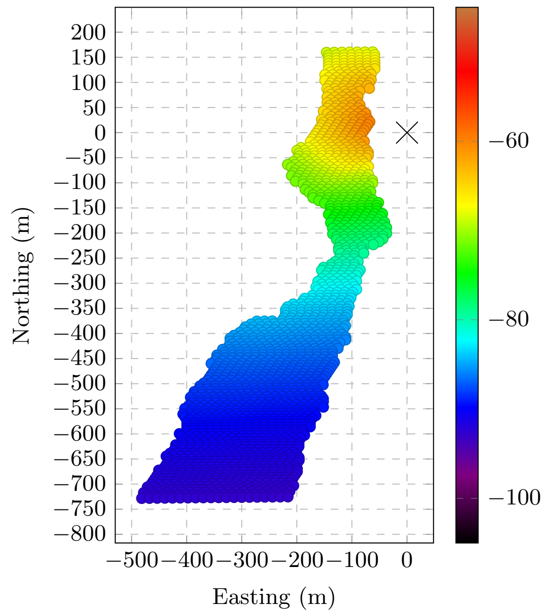
(c) 1.1 m depth

(d) 1.6 m depth

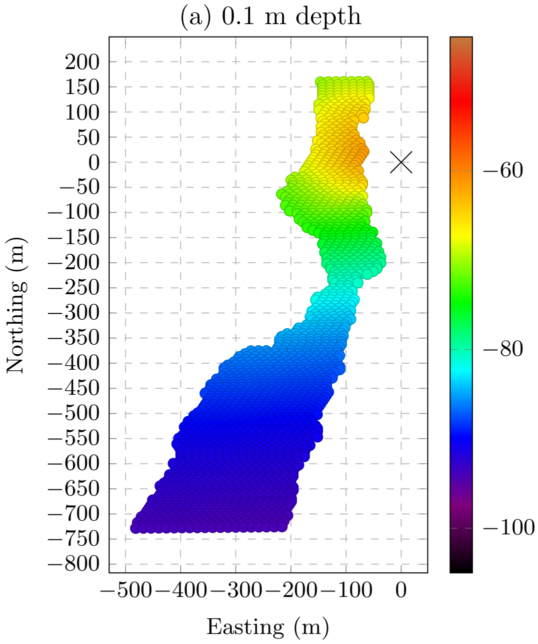
Figure A.16: Total system loss TE- Eastside Downstream site (dB).



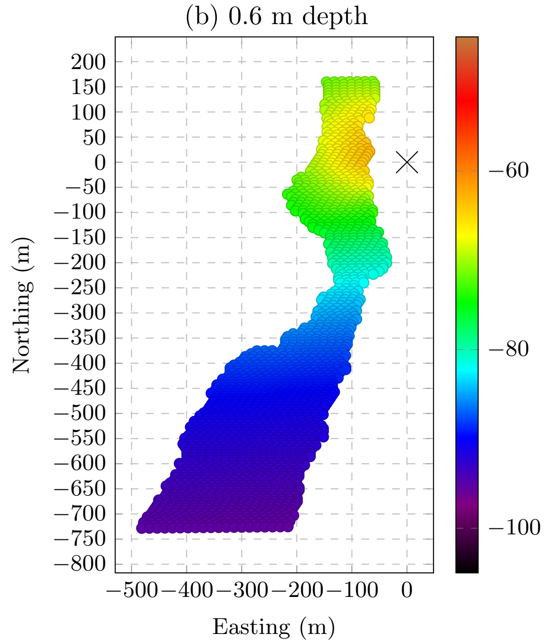
(a) 0.1 m depth



(b) 0.6 m depth

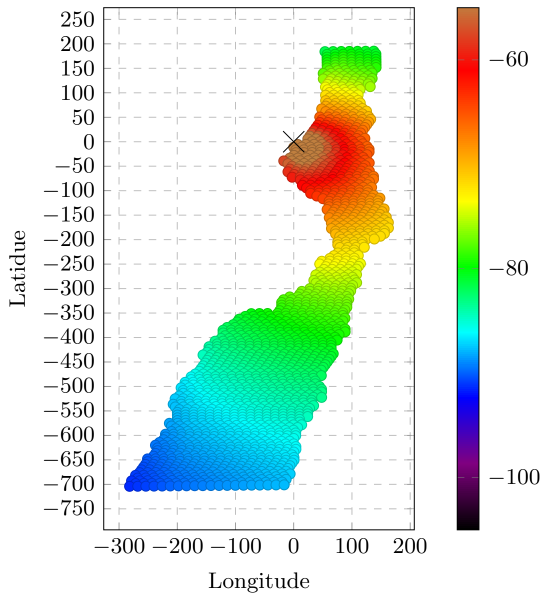


(c) 1.1 m depth

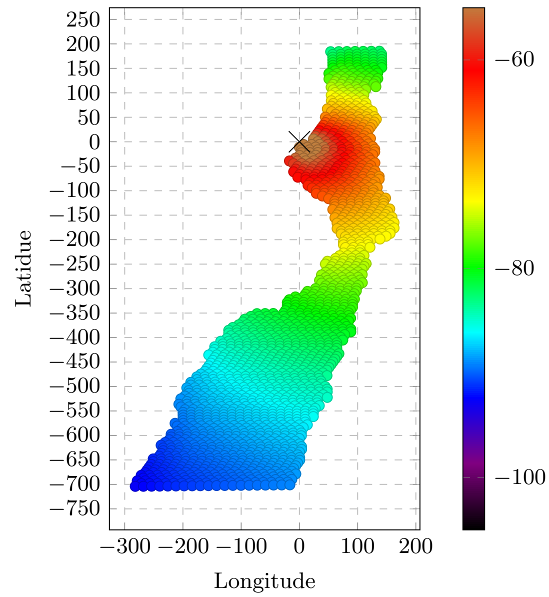


(d) 1.6 m depth

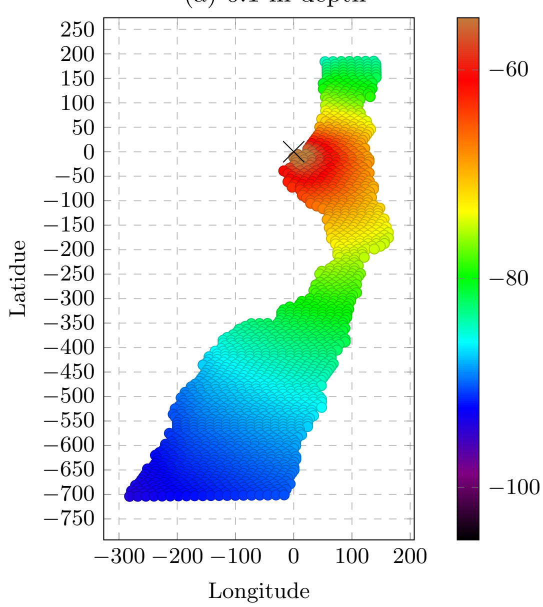
Figure A.17: Total system loss TE- Eastside Upstream site (dB).



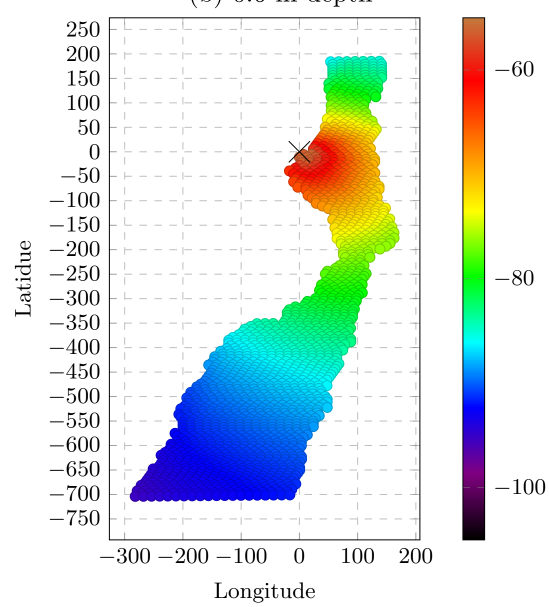
(a) 0.1 m depth



(b) 0.6 m depth

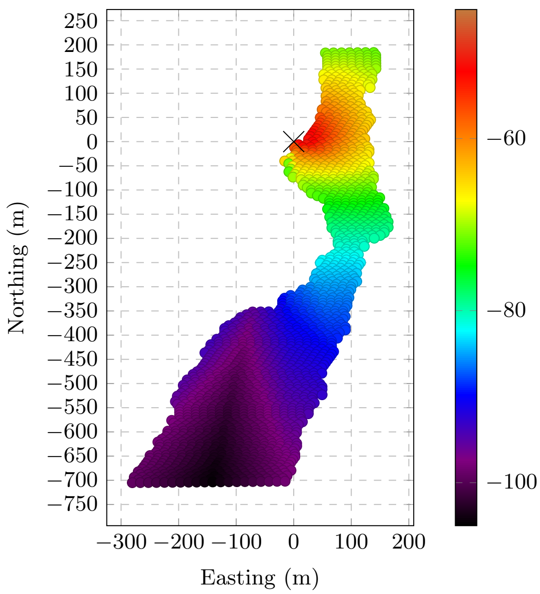


(c) 1.1 m depth

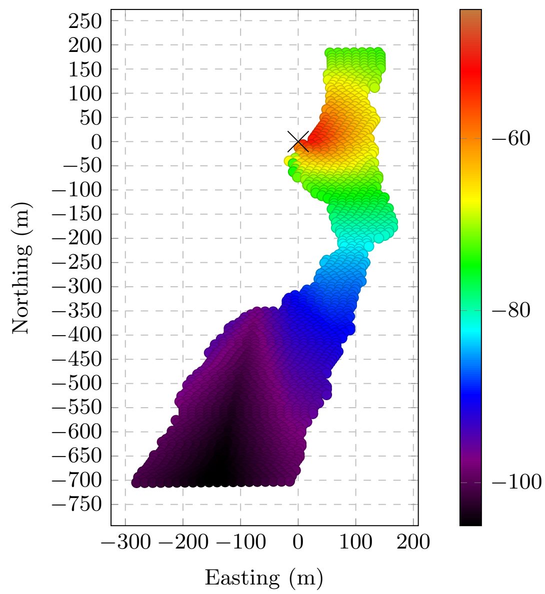


(d) 1.6 m depth

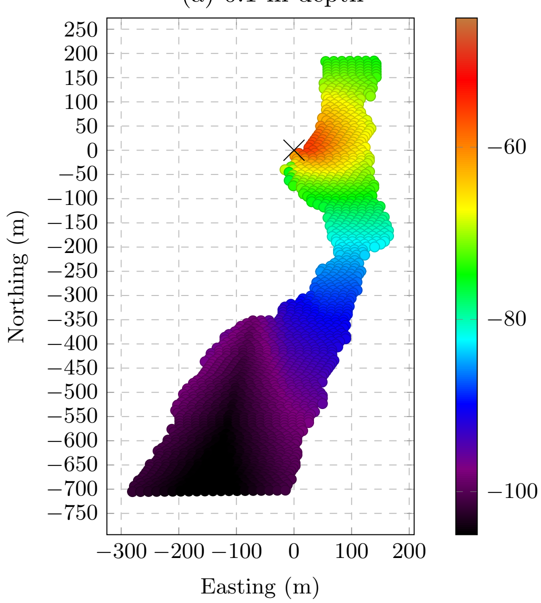
Figure A.18: Total system loss TE- Eddy Downstream site (dB).



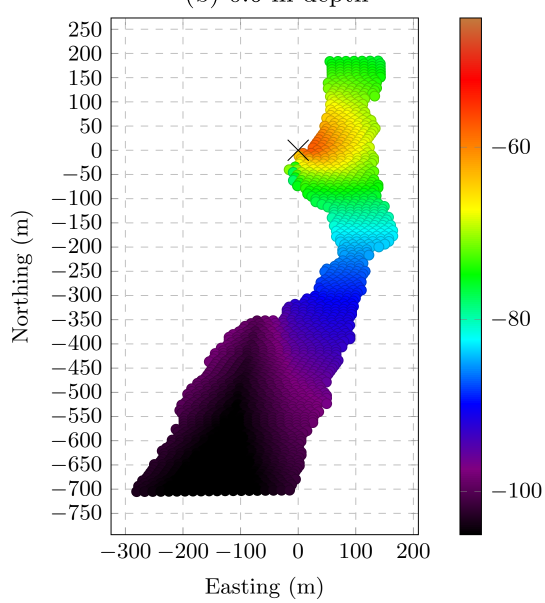
(a) 0.1 m depth



(b) 0.6 m depth

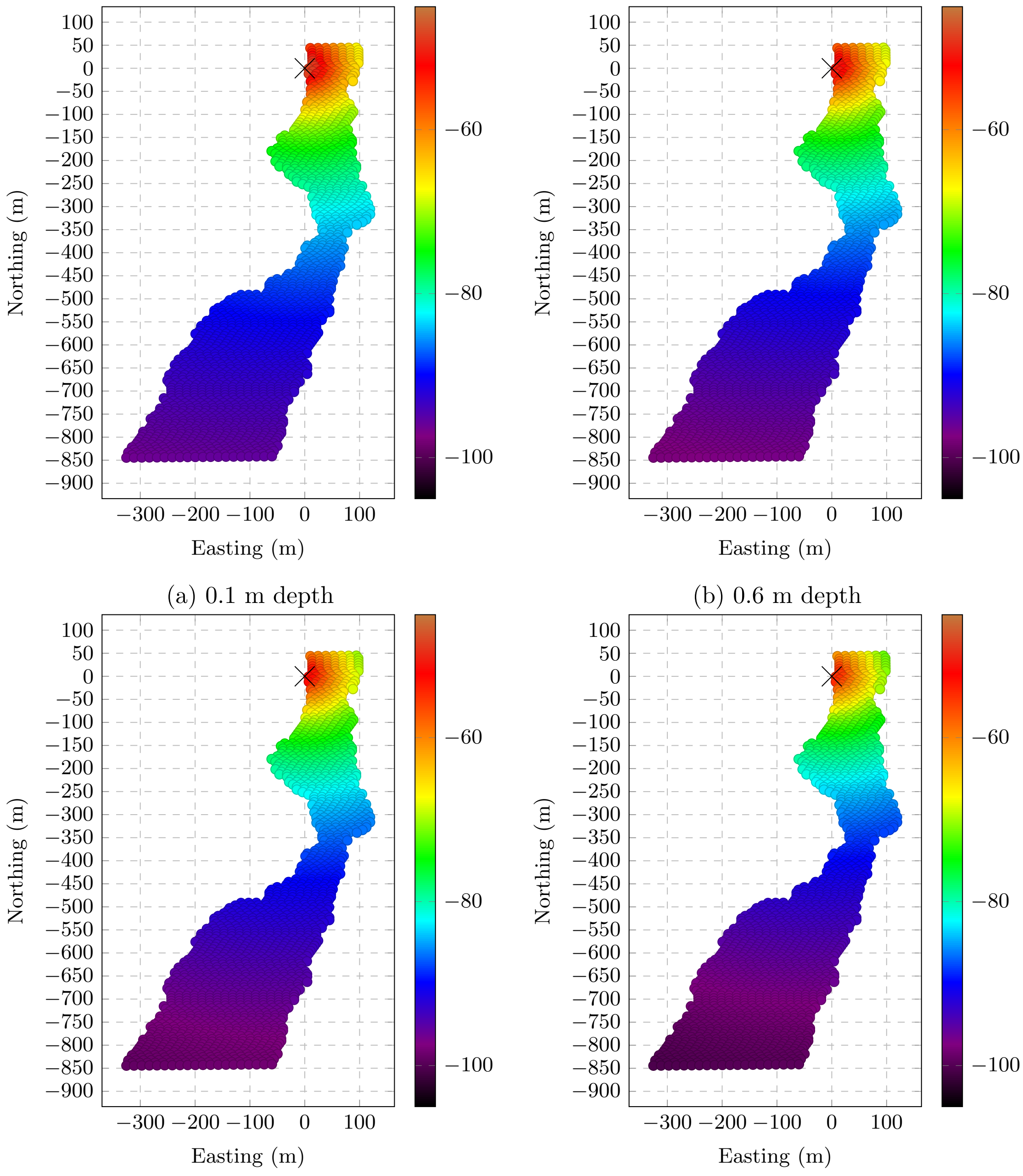


(c) 1.1 m depth



(d) 1.6 m depth

Figure A.19: Total system loss TE- Eddy Upstream site (dB).



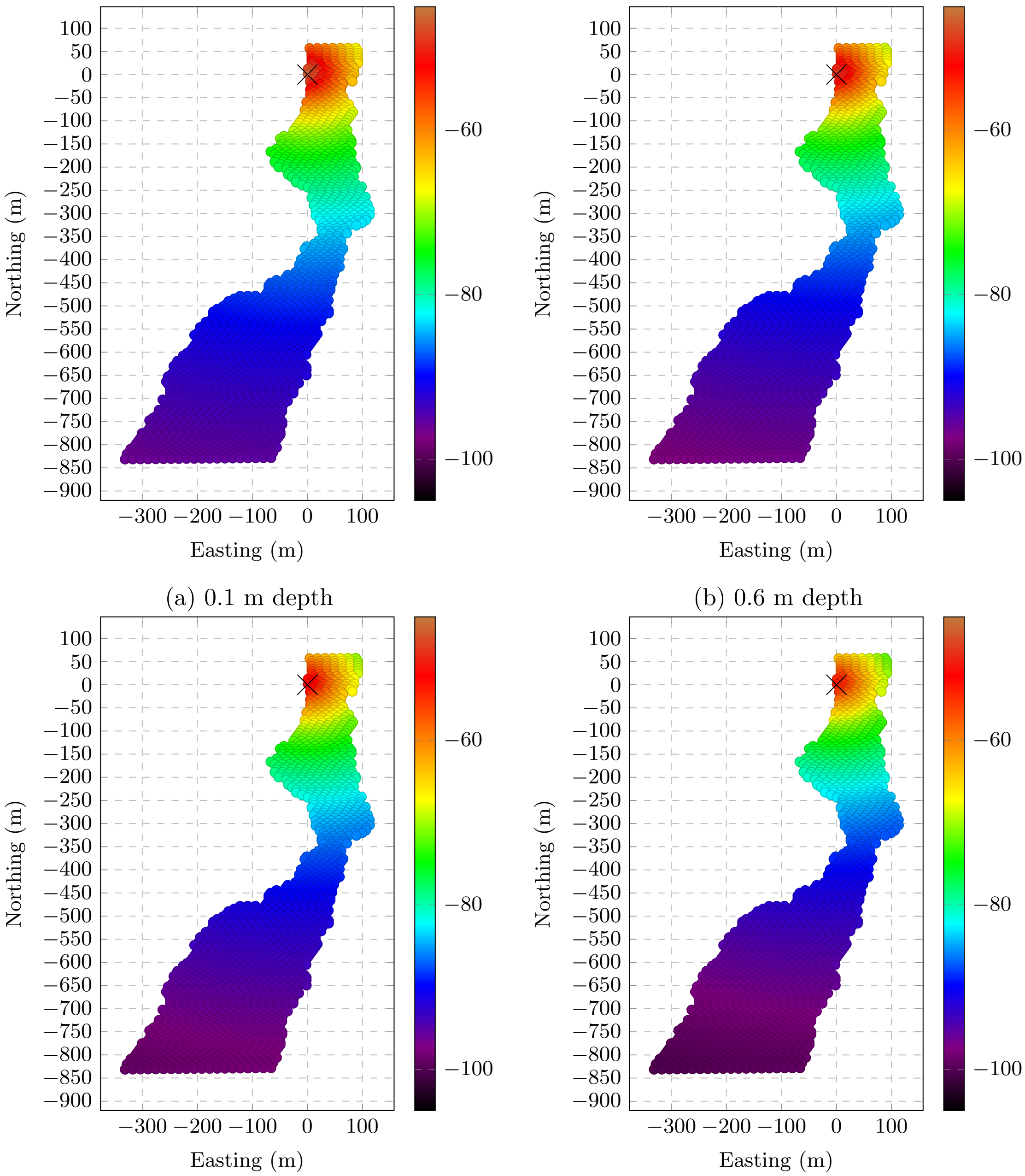
(a) 0.1 m depth

(b) 0.6 m depth

(c) 1.1 m depth

(d) 1.6 m depth

Figure A.20: Total system loss TE- iBeam p1 site (dB).



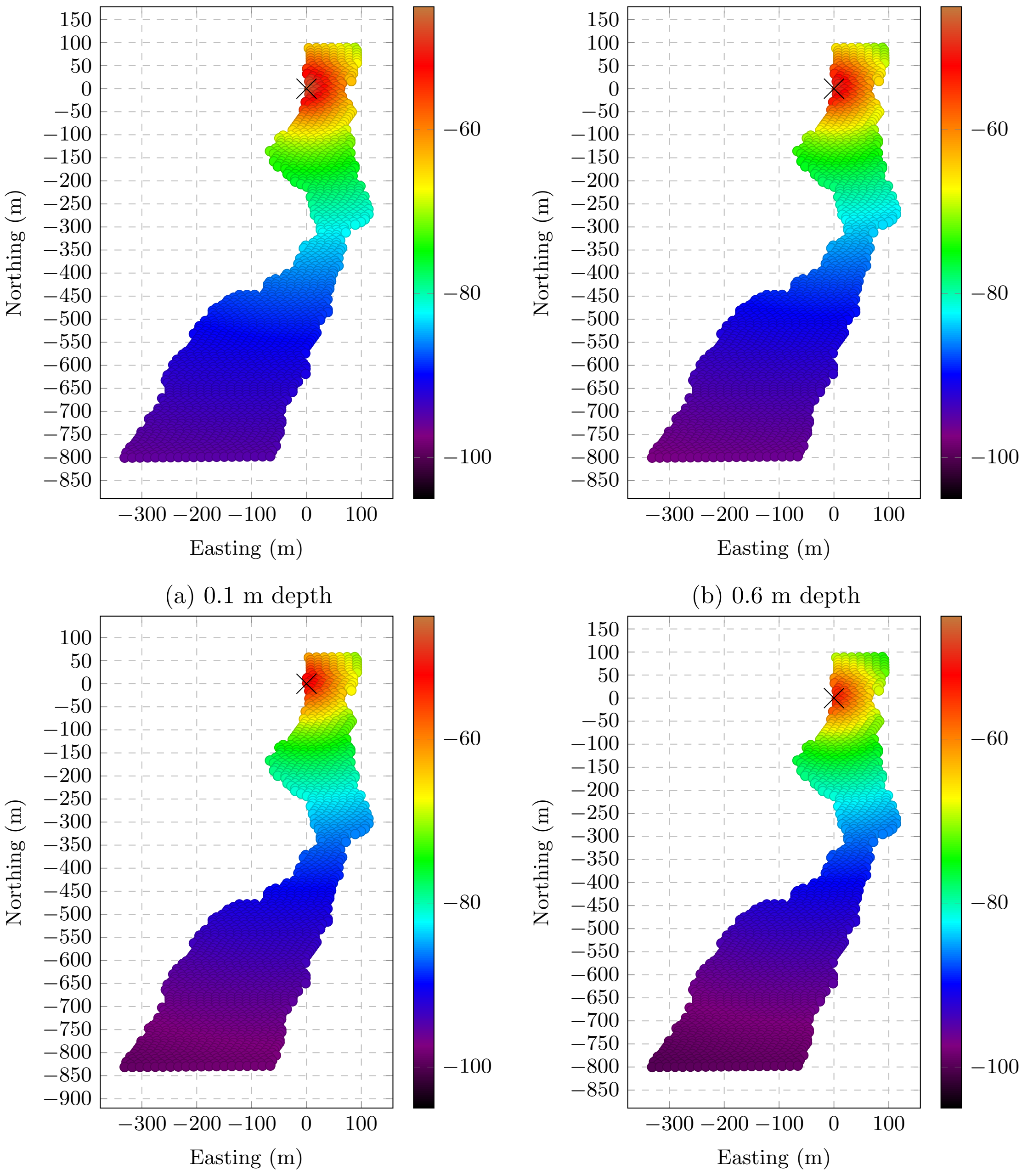
(a) 0.1 m depth

(b) 0.6 m depth

(c) 1.1 m depth

(d) 1.6 m depth

Figure A.21: Total system loss TE- iBeam p2 site (dB).



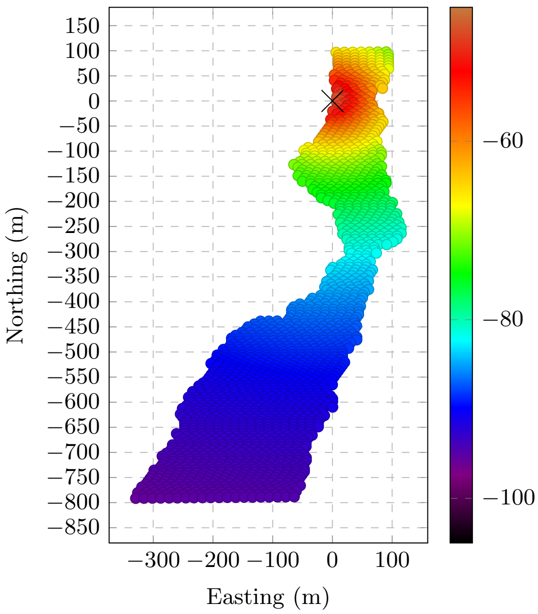
(a) 0.1 m depth

(b) 0.6 m depth

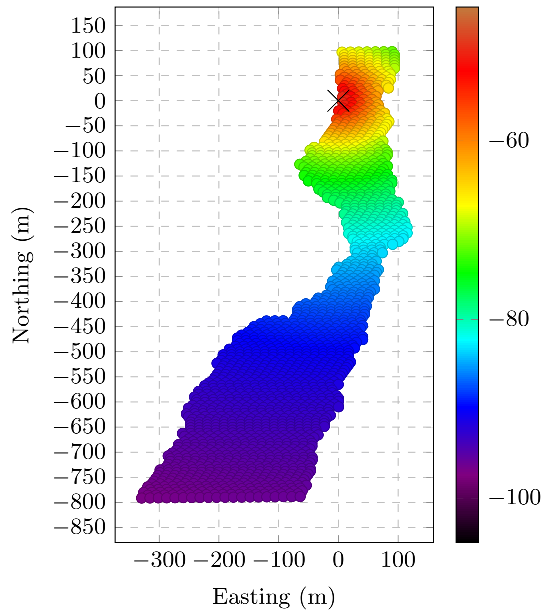
(c) 1.1 m depth

(d) 1.6 m depth

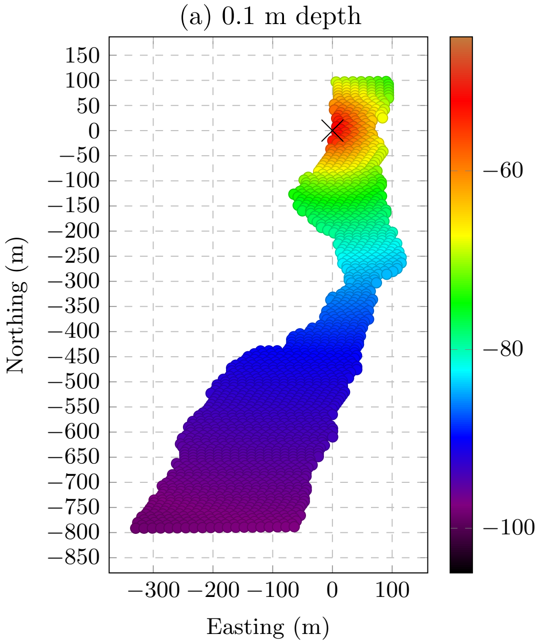
Figure A.22: Total system loss TE- iBeam p5 site (dB).



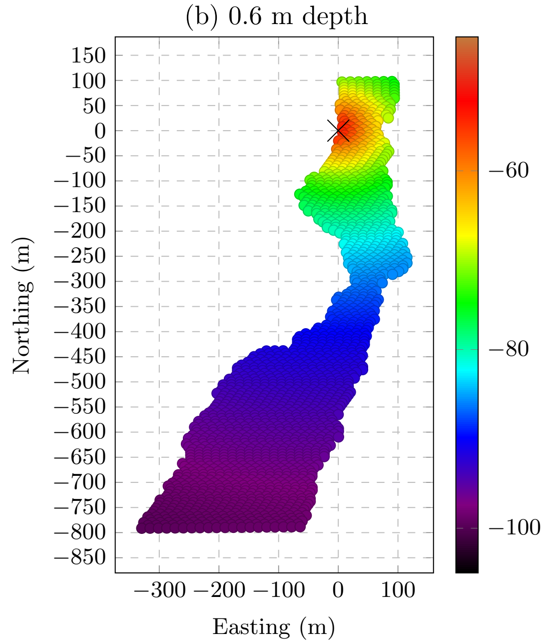
(a) 0.1 m depth



(b) 0.6 m depth

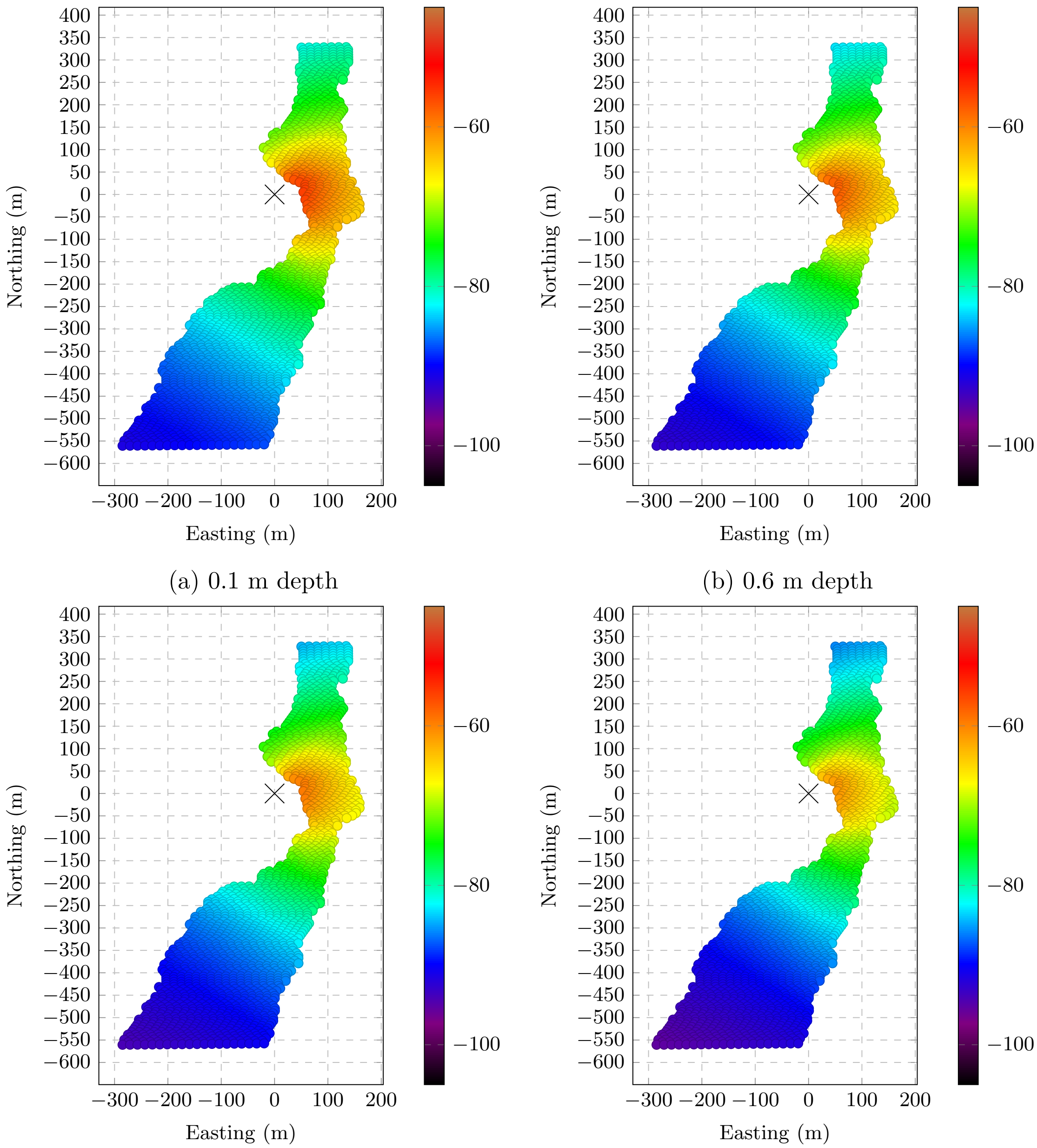


(c) 1.1 m depth



(d) 1.6 m depth

Figure A.23: Total system loss TE- iBeam p6 site (dB).



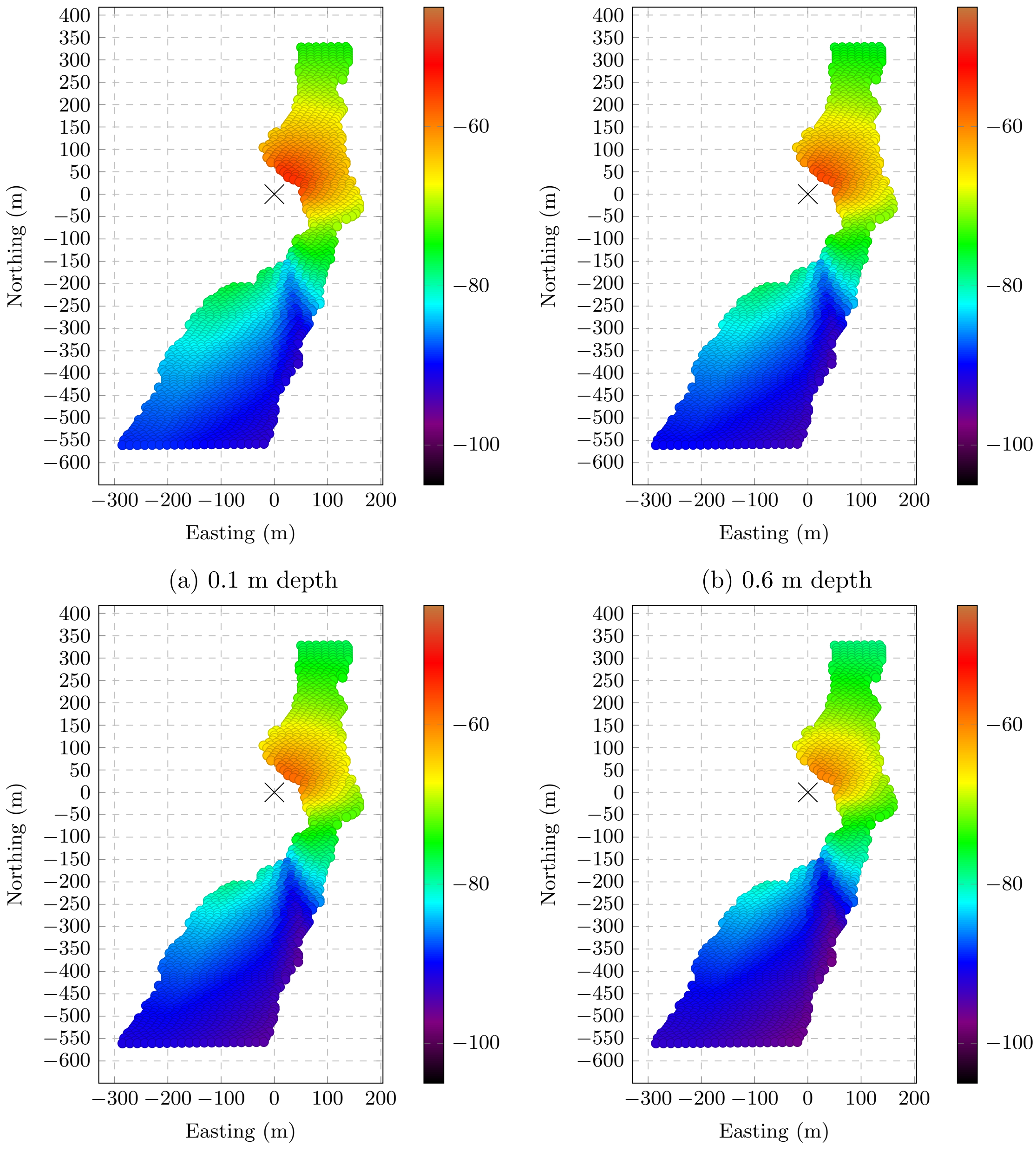
(a) 0.1 m depth

(b) 0.6 m depth

(c) 1.1 m depth

(d) 1.6 m depth

Figure A.24: Total system loss TE- Jenny Downstream site (dB).



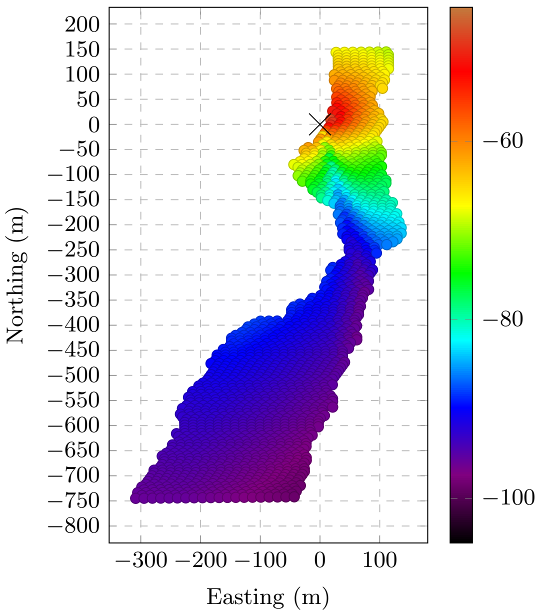
(a) 0.1 m depth

(b) 0.6 m depth

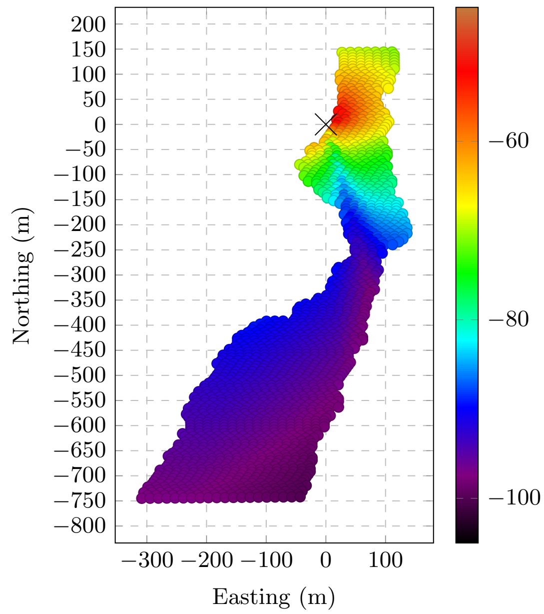
(c) 1.1 m depth

(d) 1.6 m depth

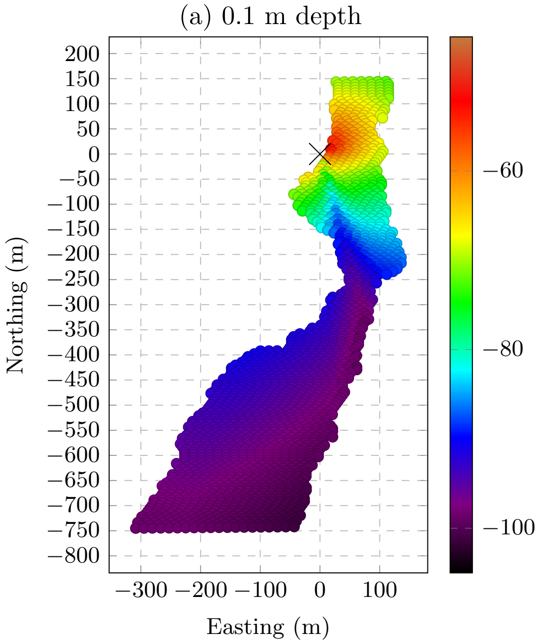
Figure A.25: Total system loss TE- Jenny Upstream site (dB).



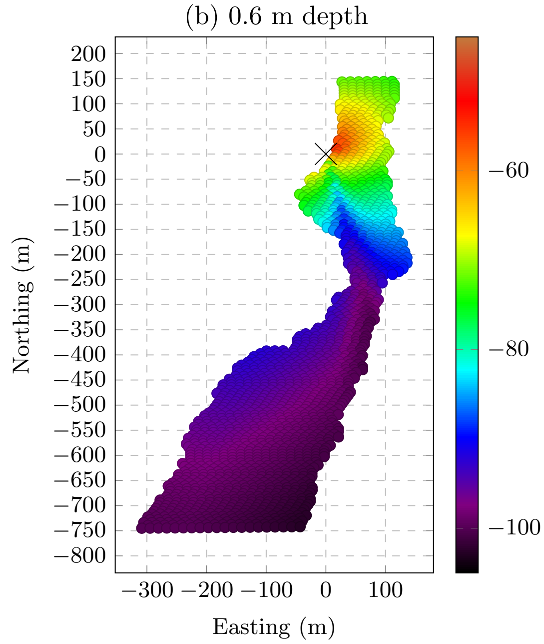
(a) 0.1 m depth



(b) 0.6 m depth

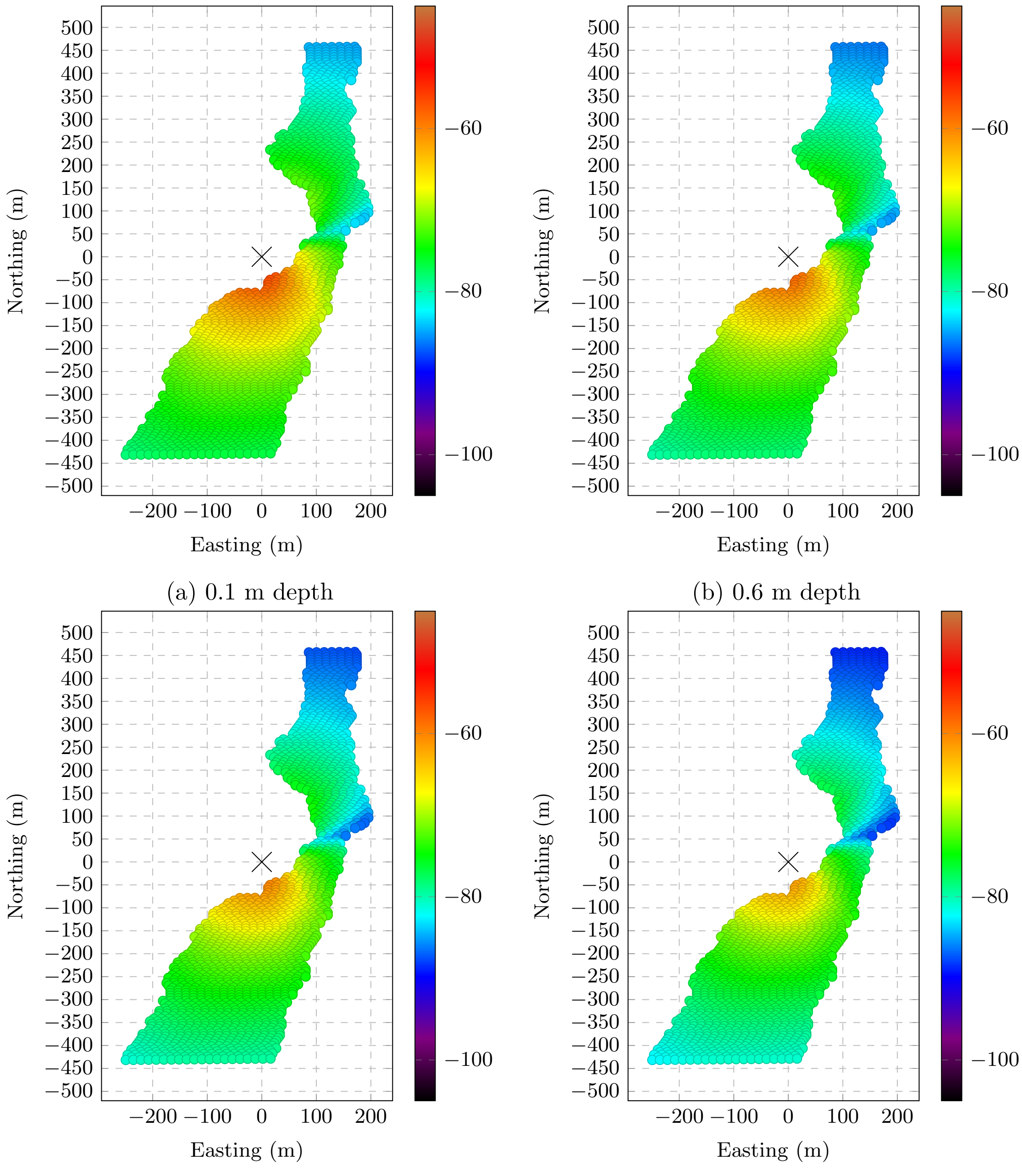


(c) 1.1 m depth



(d) 1.6 m depth

Figure A.26: Total system loss TE- Nose site (dB).



(a) 0.1 m depth

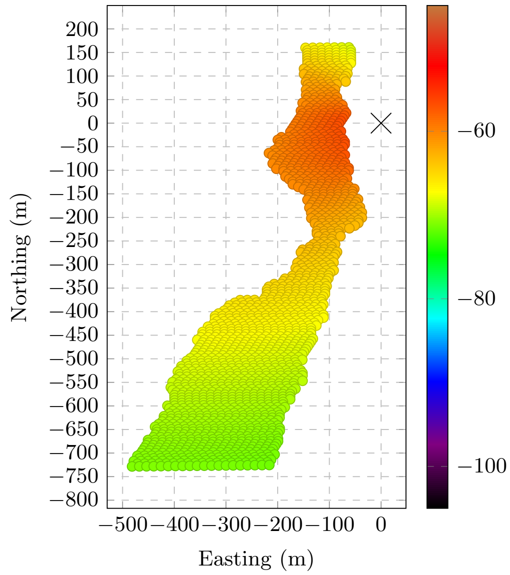
(b) 0.6 m depth

(c) 1.1 m depth

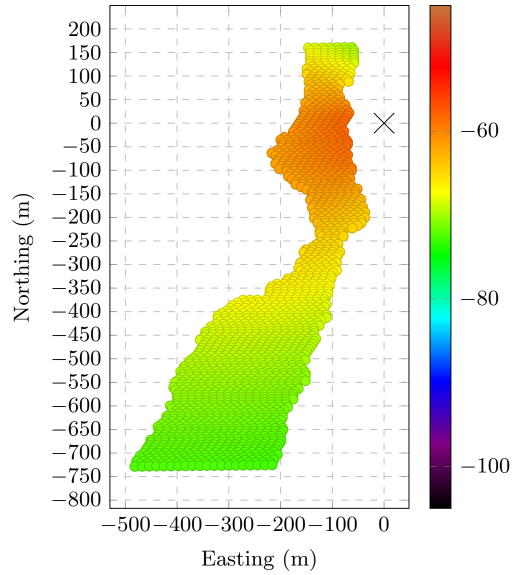
(d) 1.6 m depth

Figure A.27: Total system loss TE- Razorback Downstream site (dB).

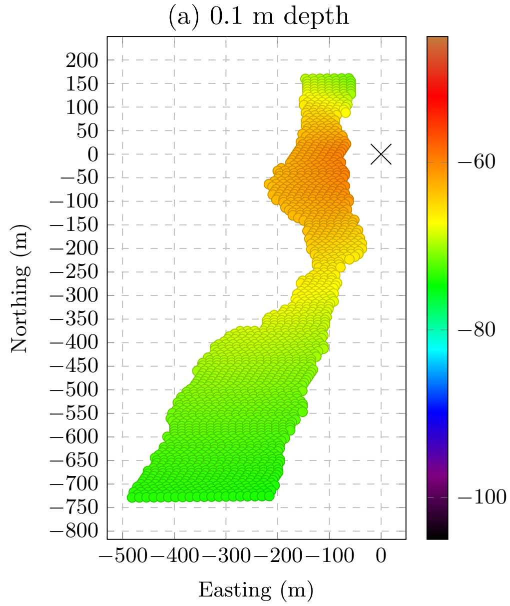
A.2.3 TM Gain



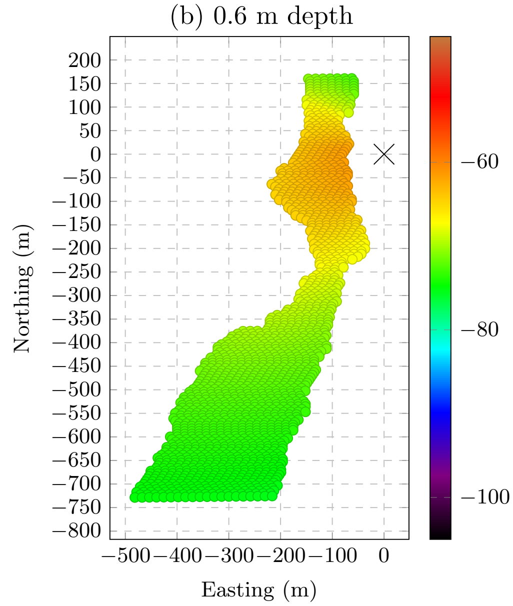
(a) 0.1 m depth



(b) 0.6 m depth

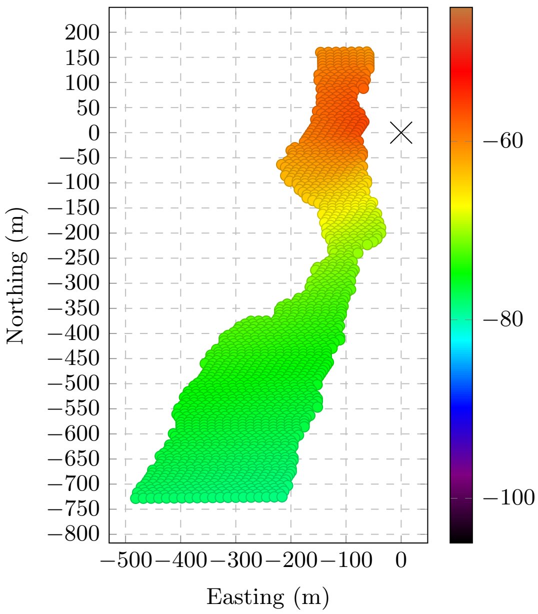


(c) 1.1 m depth

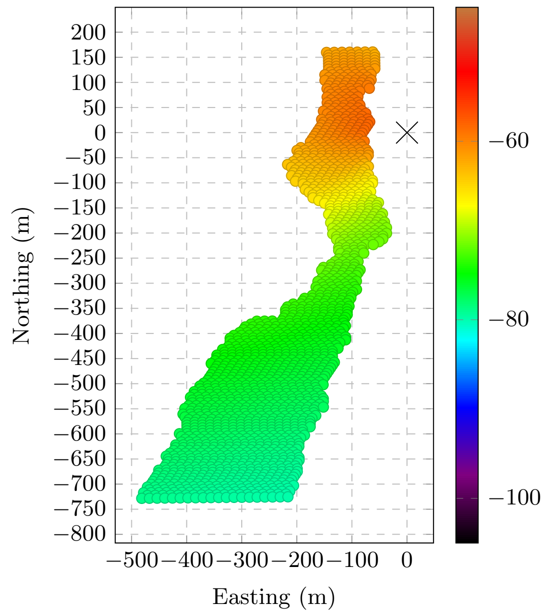


(d) 1.6 m depth

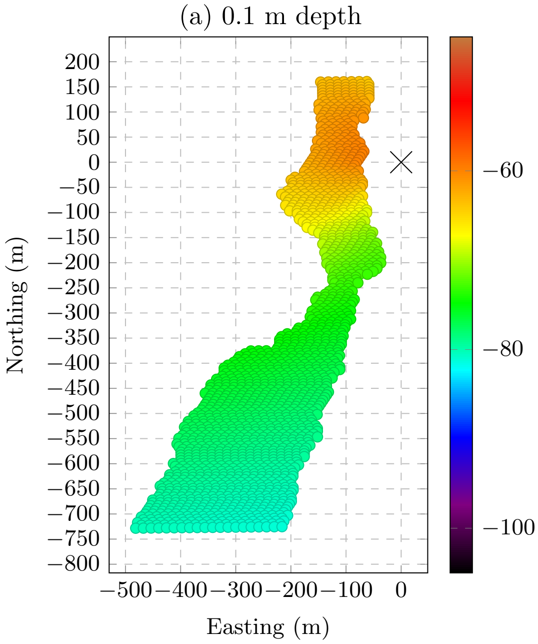
Figure A.28: Total system Loss TM- Eastside Downstream site (dB).



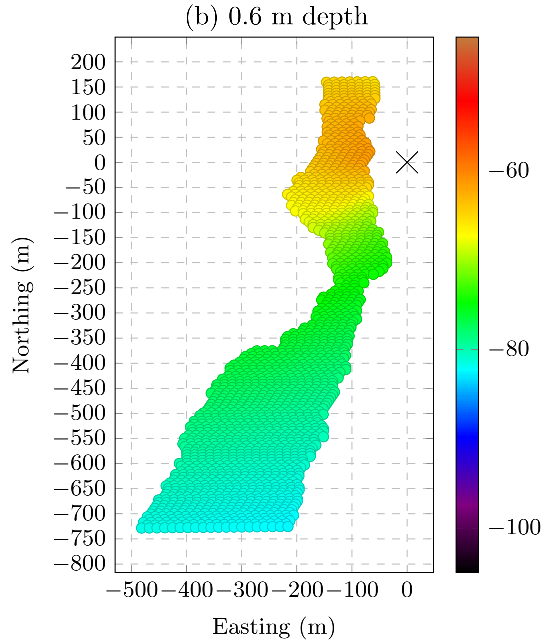
(a) 0.1 m depth



(b) 0.6 m depth

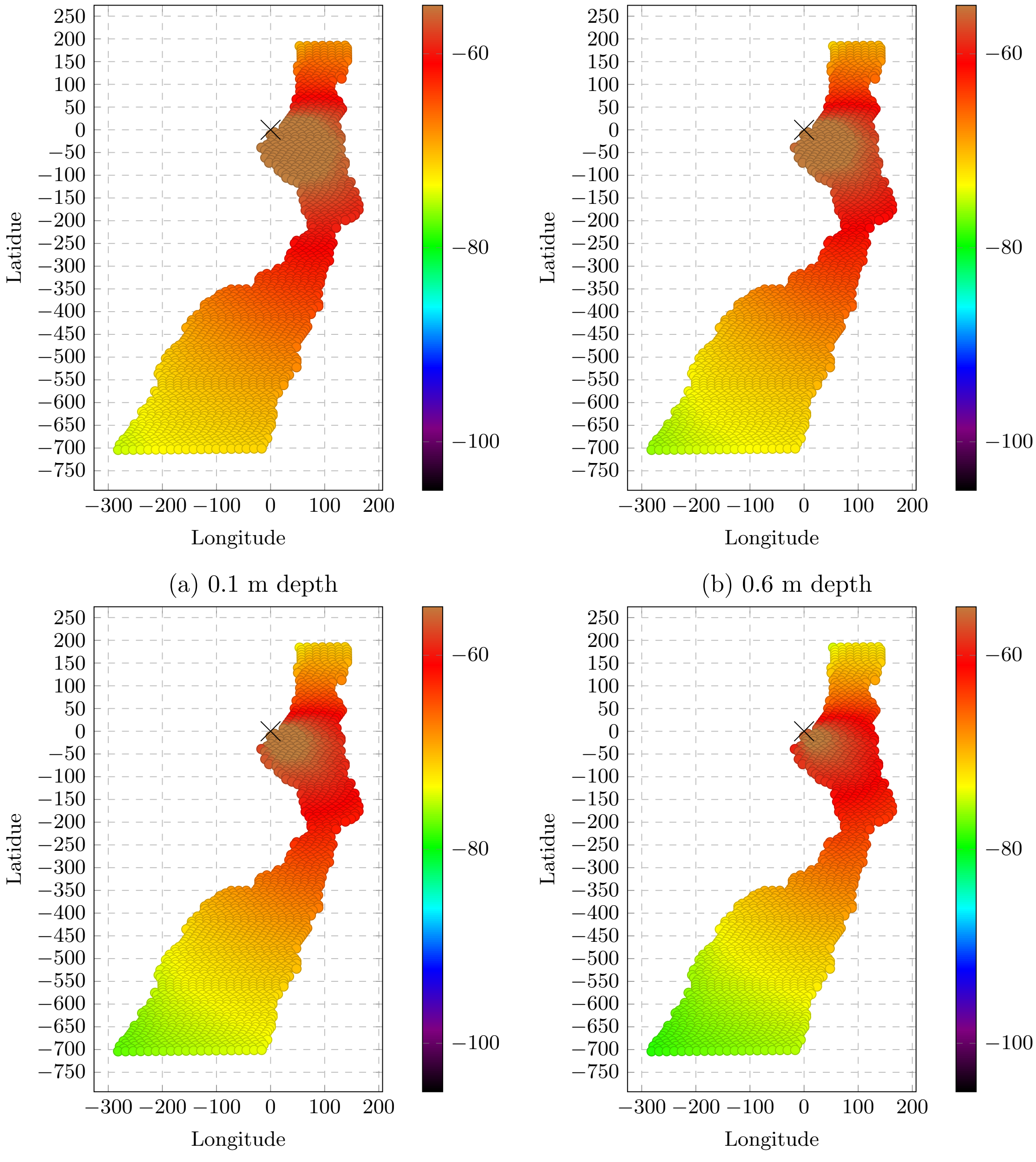


(c) 1.1 m depth



(d) 1.6 m depth

Figure A.29: Total system Loss TM- Eastside Upstream site (dB).



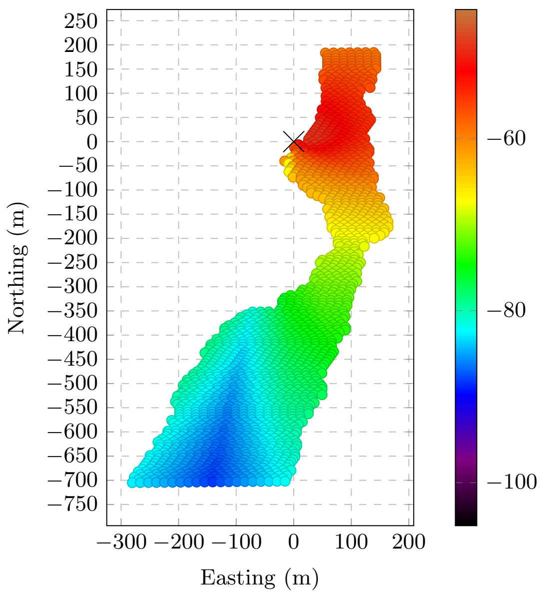
(a) 0.1 m depth

(b) 0.6 m depth

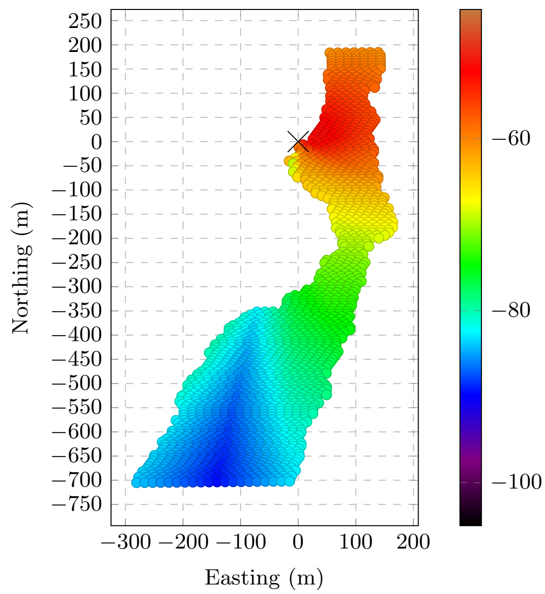
(c) 1.1 m depth

(d) 1.6 m depth

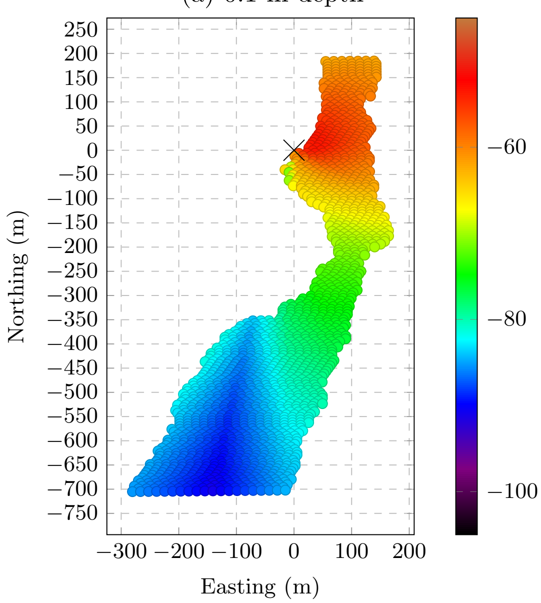
Figure A.30: Total system Loss TM- Eddy Downstream site (dB).



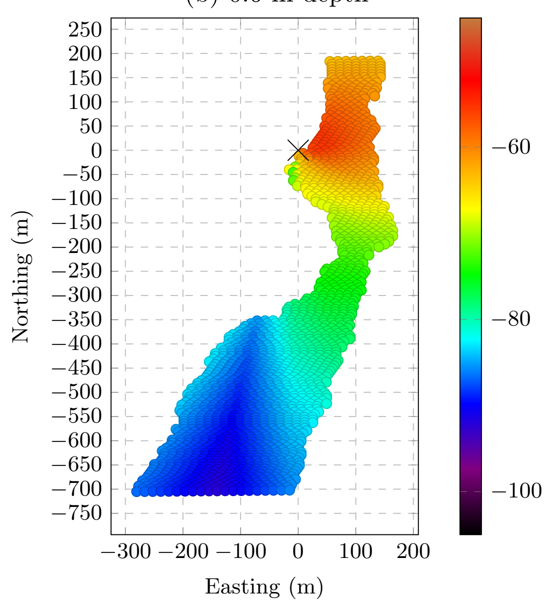
(a) 0.1 m depth



(b) 0.6 m depth

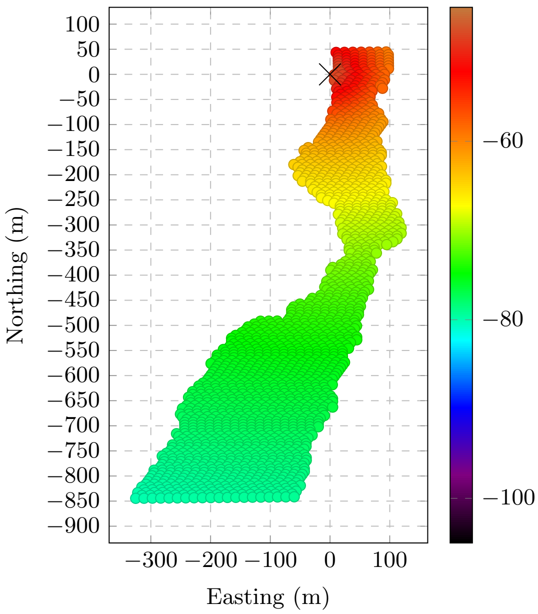


(c) 1.1 m depth

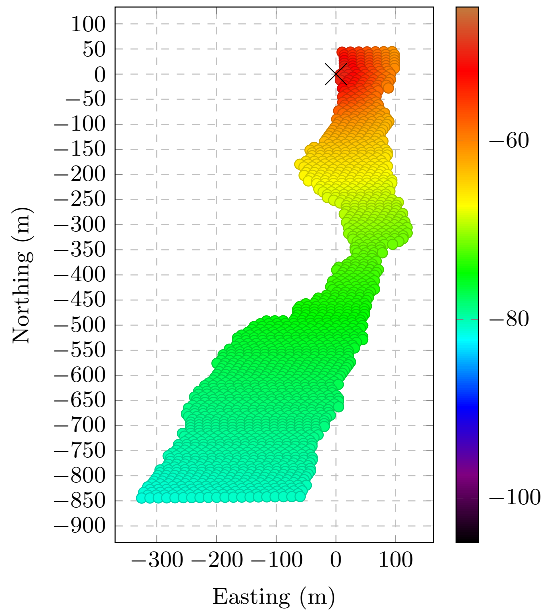


(d) 1.6 m depth

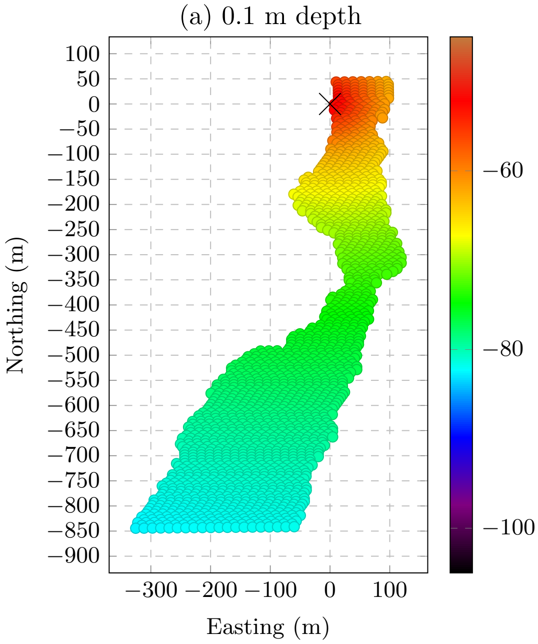
Figure A.31: Total system Loss TM- Eddy Upstream site (dB).



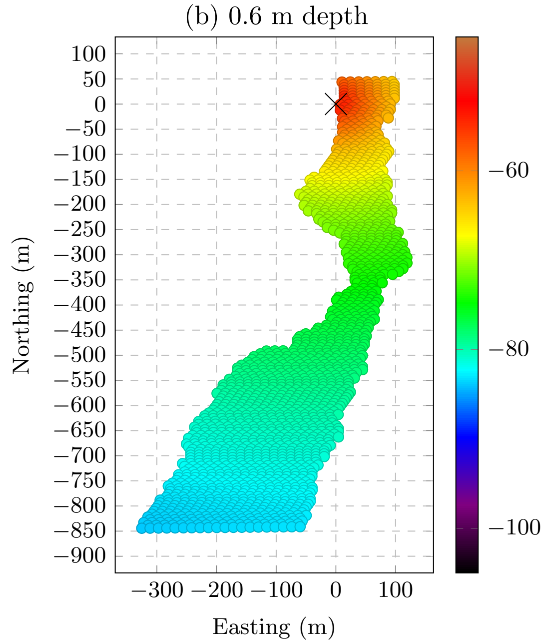
(a) 0.1 m depth



(b) 0.6 m depth

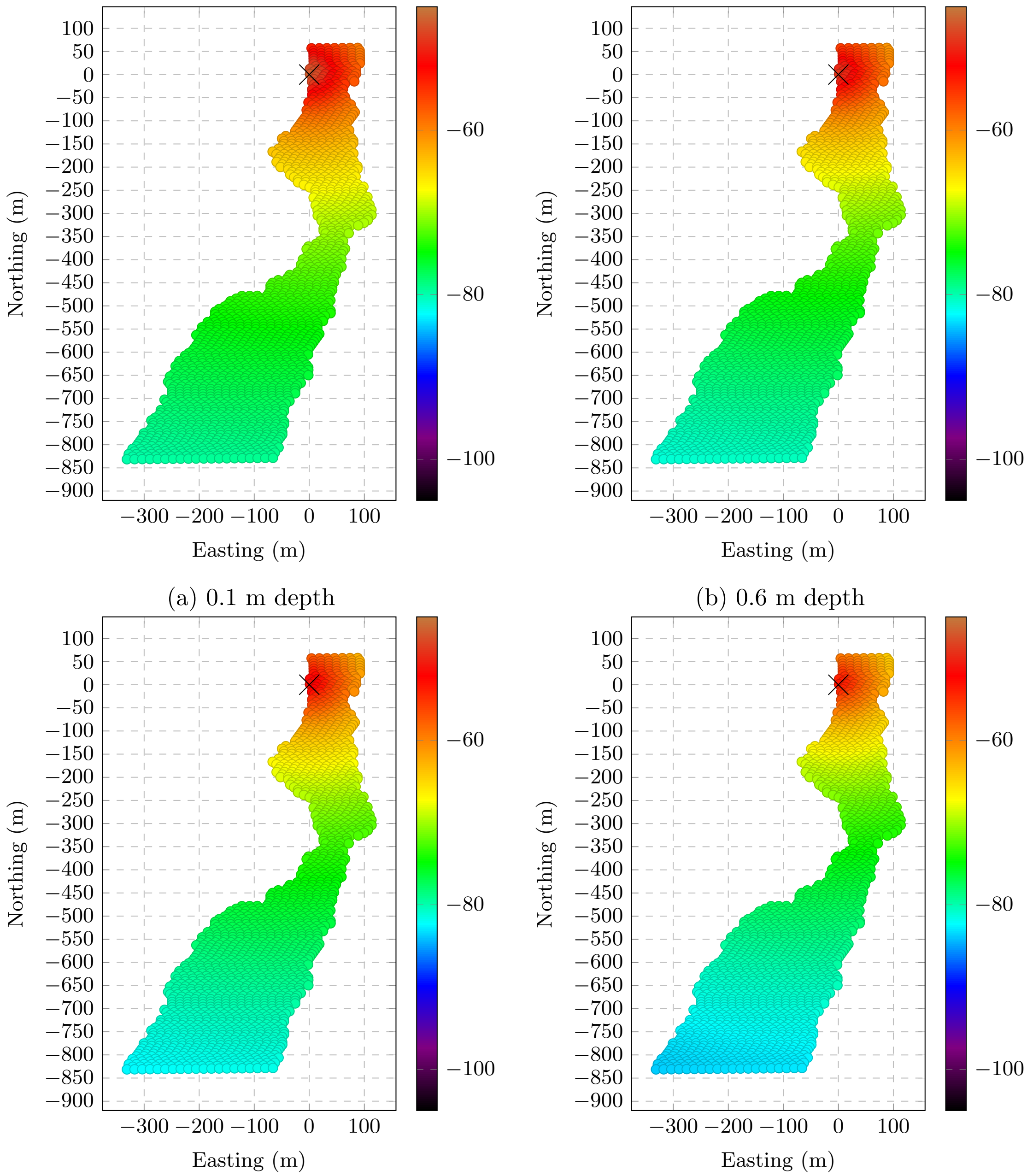


(c) 1.1 m depth



(d) 1.6 m depth

Figure A.32: Total system Loss TM- iBeam p1 site (dB).



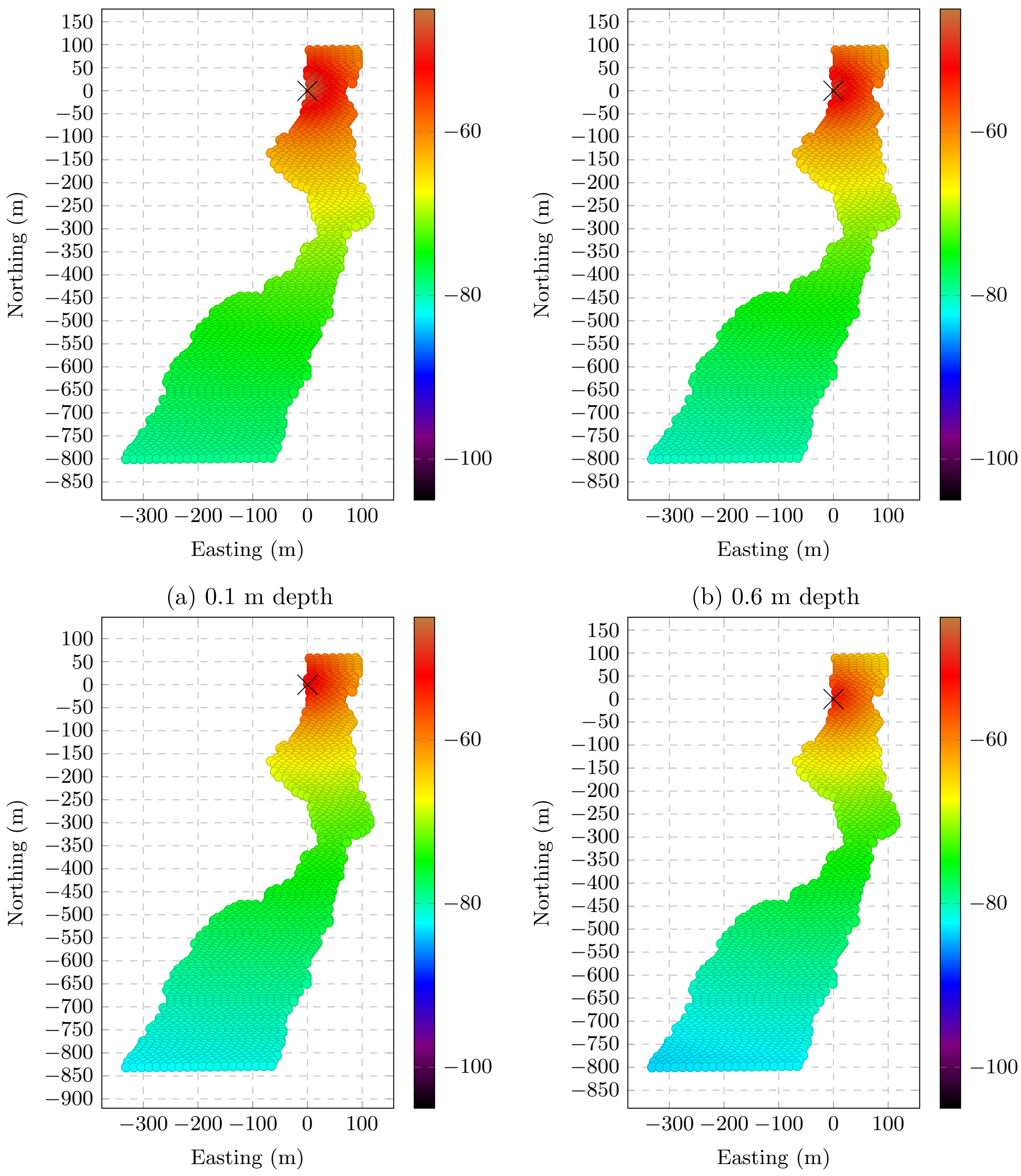
(a) 0.1 m depth

(b) 0.6 m depth

(c) 1.1 m depth

(d) 1.6 m depth

Figure A.33: Total system Loss TM- iBeam p2 site (dB).



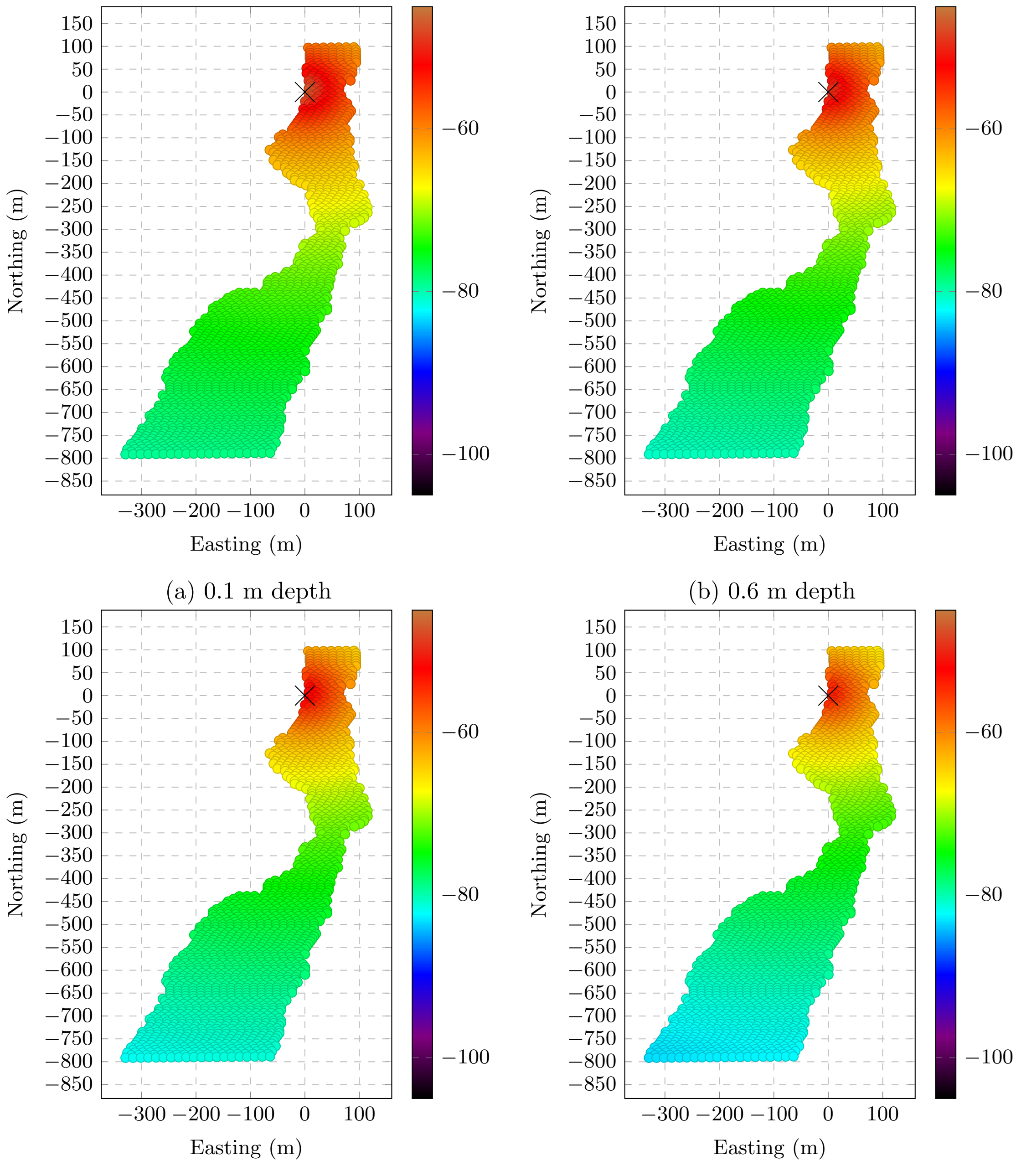
(a) 0.1 m depth

(b) 0.6 m depth

(c) 1.1 m depth

(d) 1.6 m depth

Figure A.34: Total system Loss TM- iBeam p5 site (dB).



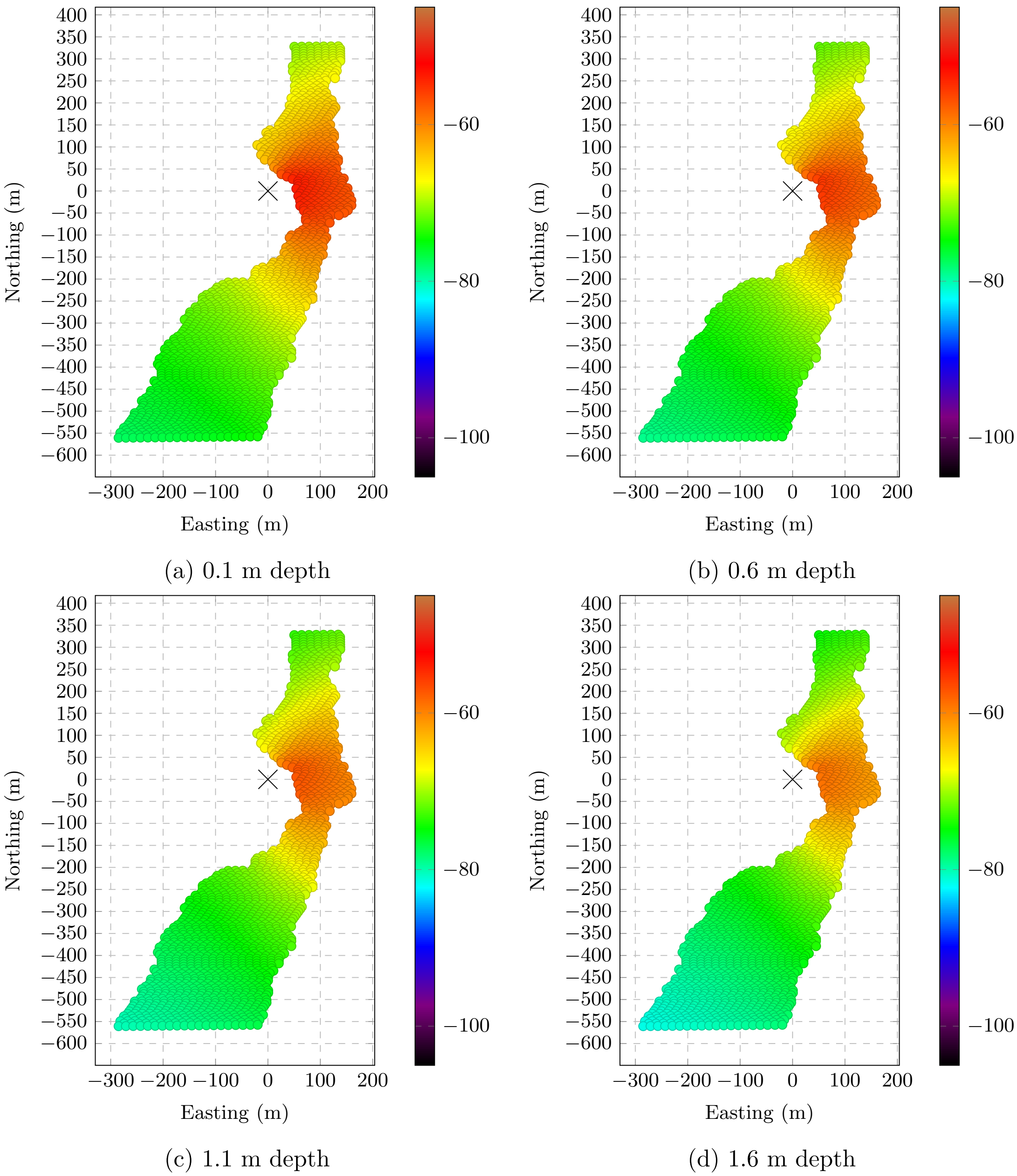
(a) 0.1 m depth

(b) 0.6 m depth

(c) 1.1 m depth

(d) 1.6 m depth

Figure A.35: Total system Loss TM- iBeam p6 site (dB).



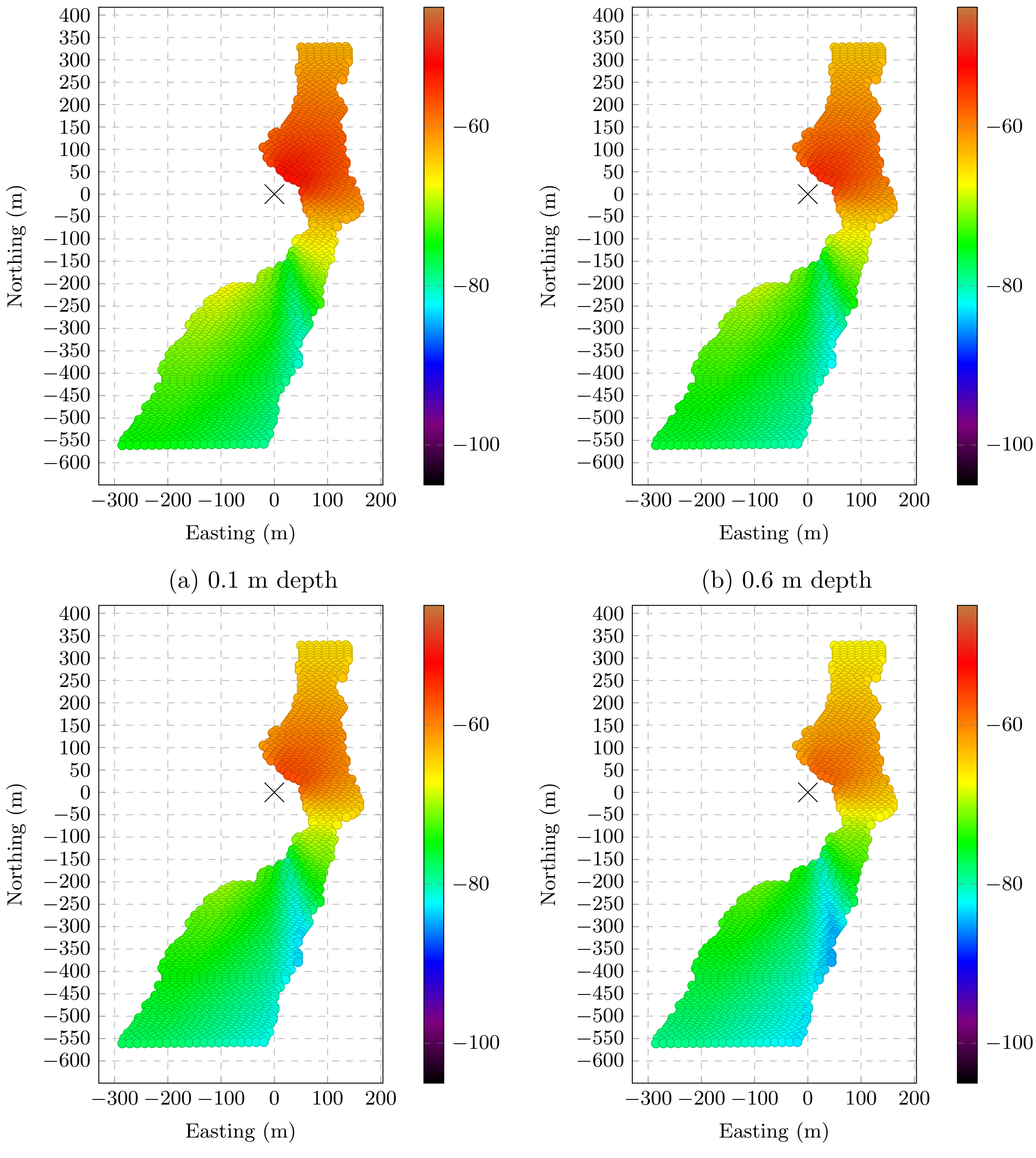
(a) 0.1 m depth

(b) 0.6 m depth

(c) 1.1 m depth

(d) 1.6 m depth

Figure A.36: Total system Loss TM- Jenny Downstream site (dB).



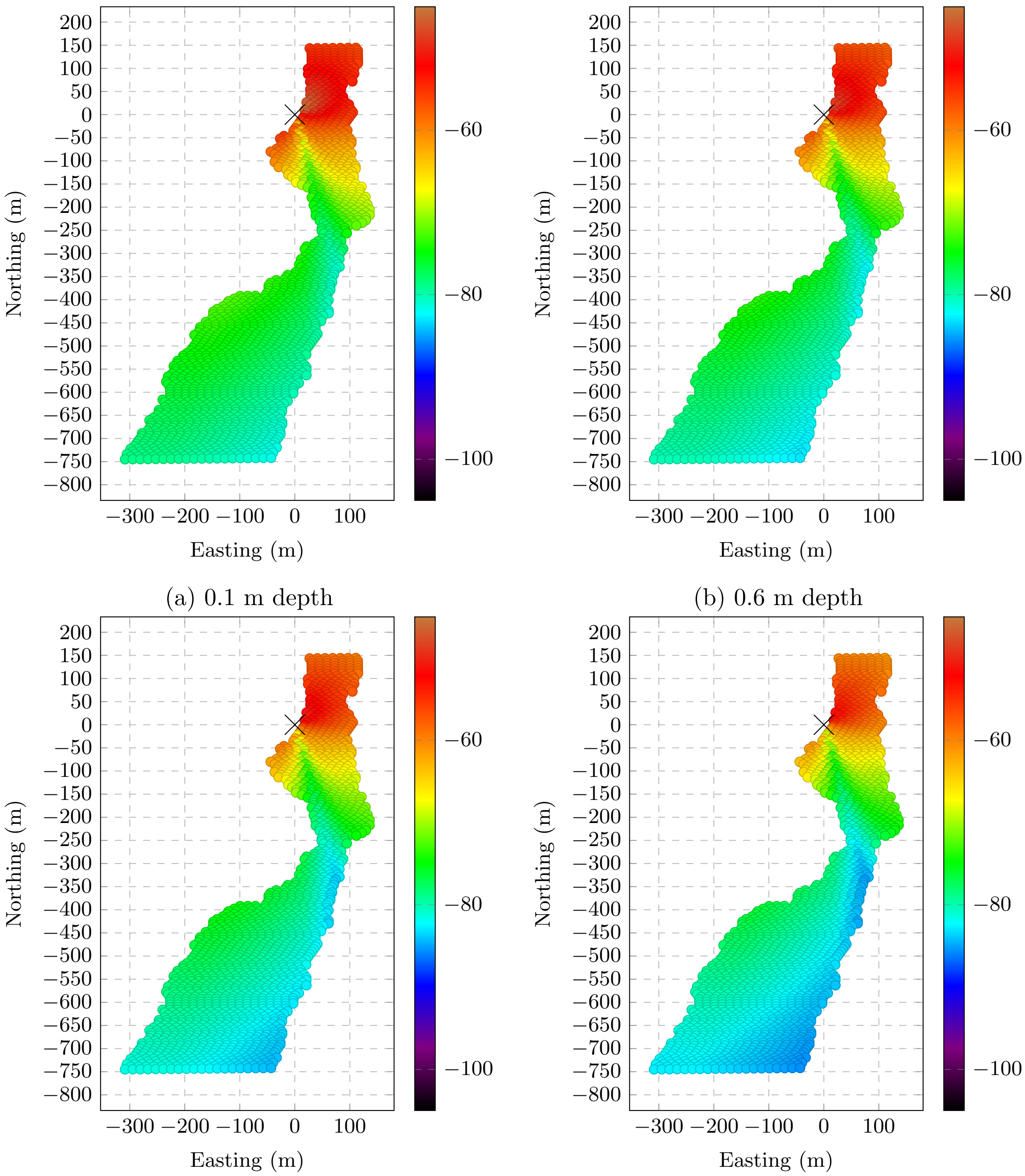
(a) 0.1 m depth

(b) 0.6 m depth

(c) 1.1 m depth

(d) 1.6 m depth

Figure A.37: Total system Loss TM- Jenny Upstream site (dB).



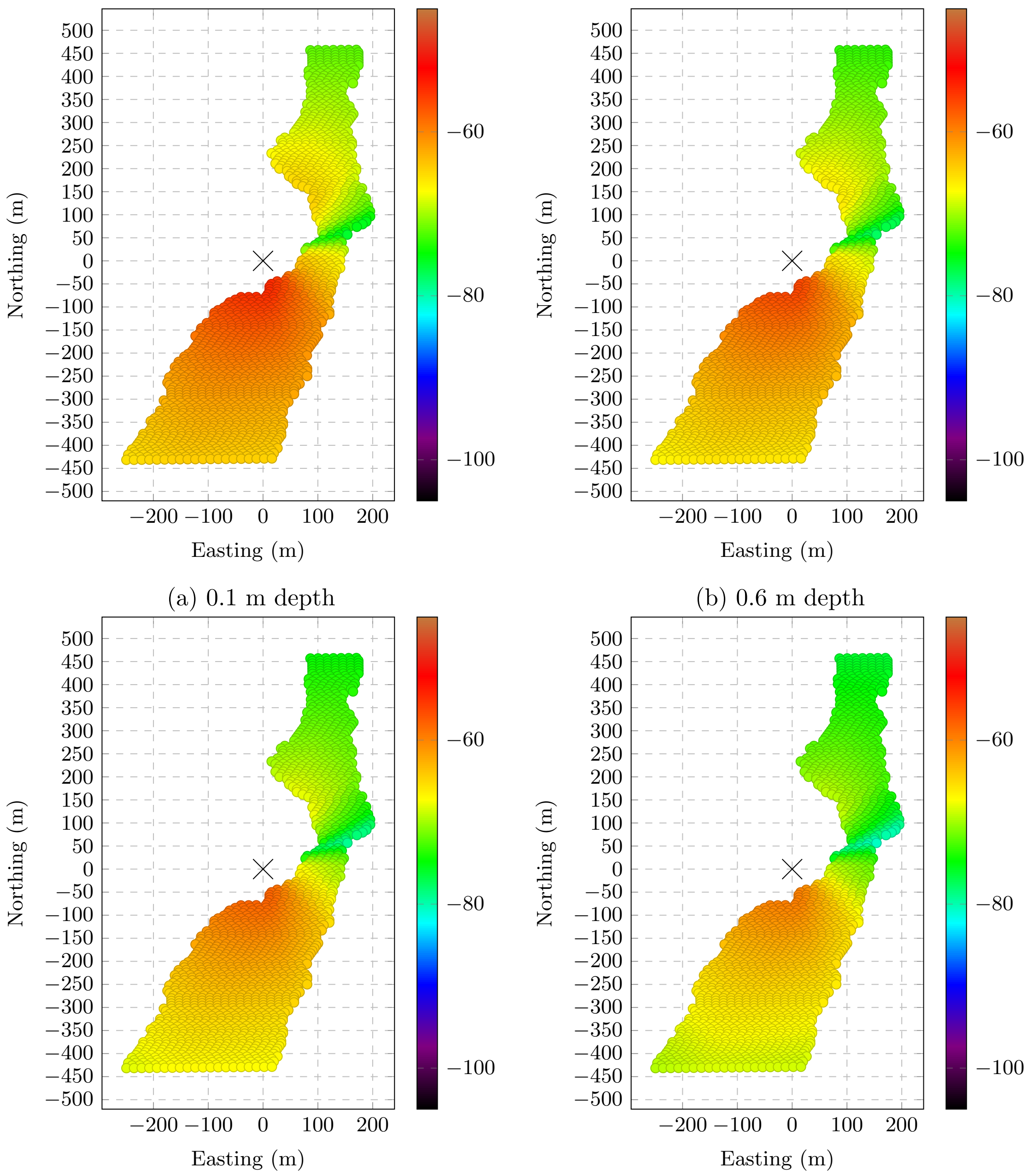
(a) 0.1 m depth

(b) 0.6 m depth

(c) 1.1 m depth

(d) 1.6 m depth

Figure A.38: Total system Loss TM- Nose site (dB).



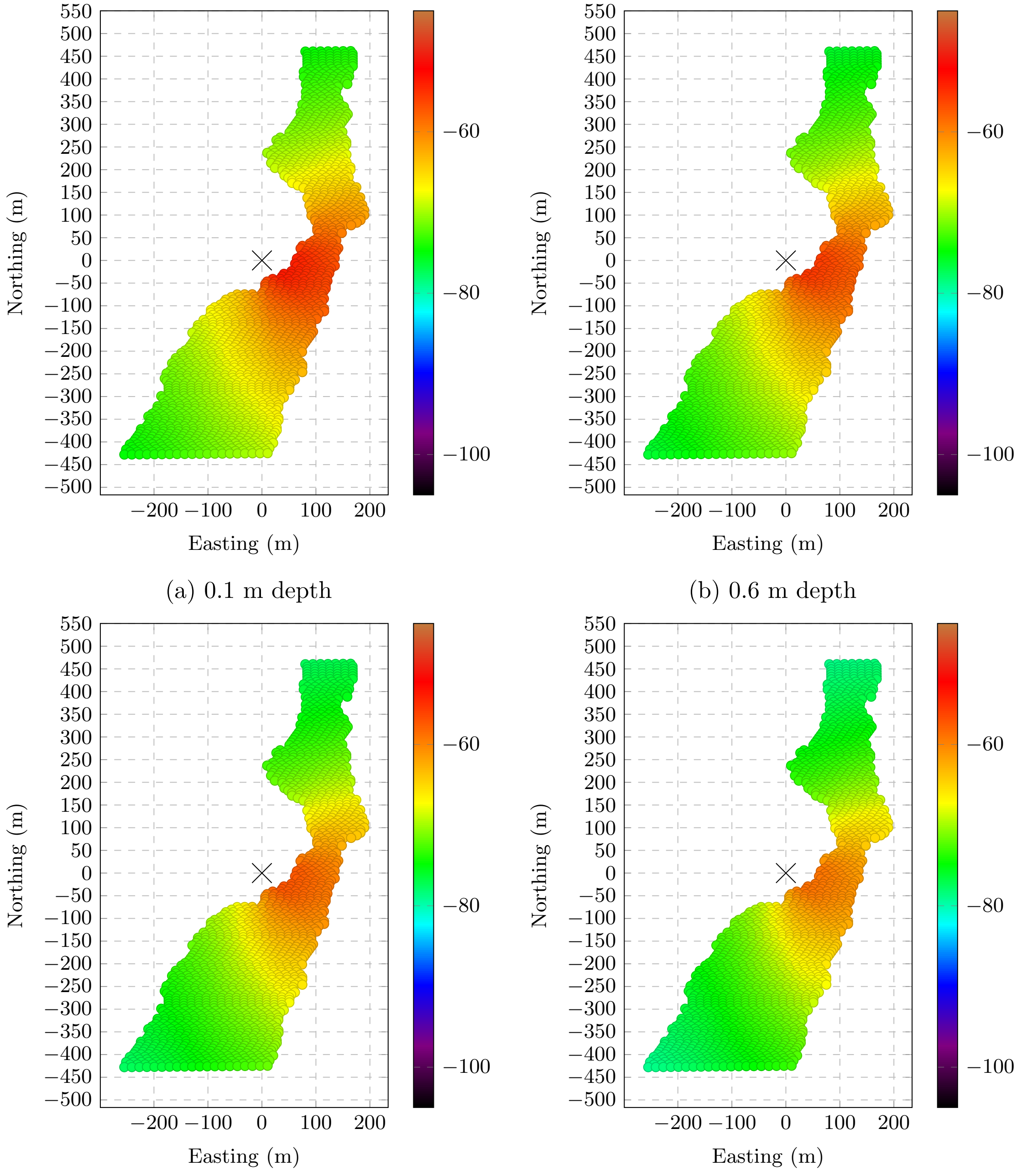
(a) 0.1 m depth

(b) 0.6 m depth

(c) 1.1 m depth

(d) 1.6 m depth

Figure A.39: Total system Loss TM- Razorback Downstream site (dB).



(a) 0.1 m depth

(b) 0.6 m depth

(c) 1.1 m depth

(d) 1.6 m depth

Figure A.40: Total system Loss TM- Razorback Upstream site (dB).

Appendix B

Code

B.1 Fish Propagation

B.1.1 Fish Propagation Model

```
%Author: Elias Bircher
%Last Edited 10/18/23

%Provides colour coded map of the data

%Treats each latitude and longitude point separately and does the
%calculations like that. THis is the most up to date file for the full
%river. It includes a path loss calculation that encompasses both air time
%as well as river time. It also has functions.
clear
close all
clc

%% Writing Constants
ep0 = 8.854e-12;
mu0 = 4*pi*1e-7;
sigma = 0.014; %S/m
f = 1.5e8;
w = 2*pi*f;

ep1 = ep0;
ep2 = 81*ep0 - 1i*sigma/w;
k1 = w*sqrt(mu0*ep1);
k2 = w*sqrt(mu0*ep2);

c=2.99792458e8;

lambda1 = c./f;
vwater = 1/(sqrt(81*ep0*mu0));
```

```
lambda2 = vwater./f;

E0 = 100; %Arbitrary - Makes no difference what value it is

TGain = -4; %Transmitter gain for unbalanced dipole (in dB)
etaPol = -3; %Polarisation Mismatch (in dB)

NumWaterPoints = 4; %Describe how many depths you want a slice of
NumAirPoints = 1; %Only calculates one value in air

%% If you want to do one file: Multifile = 0
Multifile = 1;

%% File Management

% File Management should follow the following order:
% Base Directory: ~/Documents/University/Thesis/FishPropagation/
% Input CSV:
% ~/Documents/University/Thesis/FishPropagation/AntennaLocations/
% Format of Input File: antenna_data_NameOfLocation.csv
% Output an empty directory has to be created: ModelLocations/
% Pattern of receiving antenna needs to be in FishPropagation/ with the
% name AntennaPattern.csv
cd ~/Documents/University/Thesis/FishPropagation/
files = dir('AntennaLocations/*.csv');

file = strings(size(files));
fileRead = strings(size(files));
fileWrite = strings(size(files));
fileWrite2 = strings(size(files));

AntennaLocations = "AntennaLocations/";
ModelLocations = "ModelLocations/";

for i=1:length(files)
    file = convertCharsToStrings(files(i).name);
    fileRead(i) = AntennaLocations+file;
    fileWrite(i) = ModelLocations+strrep(file,'data','model');
    fileWrite2(i) = ModelLocations+strrep(file,'data','model2');
end


if Multifile == 1
    disp("Locked and Loaded")
elseif Multifile == 0
    fileRead = fileRead(10);
    fileWrite = fileWrite(10);
end


numFiles = 1;
%% Main loop that does all of the files at once
```

```
for file = 1:length(fileRead)

Site1 = readmatrix(fileRead(file));
TextSite1 =
    readtable(fileRead(file),"VariableNamingRule","preserve");

%Antenna Radiation Profile
AntennaGainFile = 'AntennaPattern.csv';


%% Initialize Empty Arrays
x = [];
y=[];

ywater = zeros(NumWaterPoints,1);
xwater = zeros(NumWaterPoints,1);
zwater = zeros(NumWaterPoints,1);

latwater = zeros(NumWaterPoints,1);
longwater = zeros(NumWaterPoints,1);

xair = [];
z = [];
zair = [];

PtotTE3 = [];
PtotTM3 = [];
Pinit = [];

PWaterTE = zeros(NumWaterPoints,1);
PWaterTM = zeros(NumWaterPoints,1);
PWaterTE_Engineering = zeros(NumWaterPoints,1);
PWaterTM_Engineering = zeros(NumWaterPoints,1);

YagiGains = zeros(NumAirPoints,1,length(Site1));
TransmitterGains = zeros(NumAirPoints,1,length(Site1));
polarisationMismatches = zeros(NumAirPoints,1,length(Site1));

MagAngleGains = zeros(NumAirPoints,1,length(Site1));

xvals = [];
yvals = [];
zvals = [];

xwaters = zeros(NumWaterPoints,1,length(Site1));
ywaters = zeros(NumWaterPoints,1,length(Site1));
zwaters = zeros(NumWaterPoints,1,length(Site1));

latwaters = zeros(NumWaterPoints,1,length(Site1));
longwaters = zeros(NumWaterPoints,1,length(Site1));

PinitsTE = zeros(NumAirPoints,1,length(Site1));
PinitsTM = zeros(NumAirPoints,1,length(Site1));
```

```
Pwaters = zeros(NumWaterPoints,1,length(Site1));
PwatersTE = zeros(NumWaterPoints,1,length(Site1));
PwatersTM = zeros(NumWaterPoints,1,length(Site1));
PwatersTE_Engineering = zeros(NumWaterPoints,1,length(Site1));
PwatersTM_Engineering = zeros(NumWaterPoints,1,length(Site1));

Transmission_Coefficient_te = zeros(NumAirPoints,1,length(Site1));
Transmission_Coefficient_tm = zeros(NumAirPoints,1,length(Site1));

Reflection = [];
Transmission = [];
Pstarter = [];

AllAngles = zeros(NumAirPoints,1,length(Site1));
AllAttenuationsdB = zeros(NumWaterPoints,1,length(Site1));
AllPathLossesdB = zeros(NumWaterPoints,1,length(Site1));

AttenuationsdB = zeros(NumWaterPoints,1);
PathLossesdB = zeros(NumWaterPoints,1);

Pinitial = 0;
Ptransmitted = 0;
Preflected = 0;


%% Following section can be altered if the input csv has a
    different format to the one used

Angle = Site1(:,13); %Offset Directional
Hypotenuse = Site1(:,12); %Hypotenuse
HorizontalDist = Site1(:,11); %Horizontal Distance to River
Latitude = Site1(:,9); %Latitude of River Piece
Longitude = Site1(:,10); %Longitude of River Piece
AntLat = Site1(:,2); %Antenna Latitude
AntLong = Site1(:,3); %Antenna Longitude
Bearing = Site1(1,6); %Bearing of Antenna: 0 indicates downward
Pitch = abs(Site1(1,7)); %Antenna tilt off xy plane
zantenna = Site1(1,8); %Height of the antenna
siteName = TextSite1{:,1};

i = 1; %Index to go over every single raster point

Lengthy = length(Angle); %Go through each lat and long coordinate
indexAir = 1; %How many points are calculated in the air

while i<=(Lengthy)

%Each of these points will be the lat and long in the file
%i = 0 is the first latitude and longitude point.

%Angle in xy plane
phir = deg2rad(Angle(i)); %radian
```

```
phi = Angle(i); %degrees

% Creating distances: This would be if the bearing is pointing
% along the x axis.
xpos = cos(phir)*HorizontalDist(i);
ypos = sin(phir)*HorizontalDist(i);

%Theta Value - Angle of Incidence: From river to sky
thetar = atan(HorizontalDist(i)/zantenna); %radians
theta = rad2deg(thetar); %degrees

thetar_p = asin(k1.*sin(thetar)./k2); %Angle of transmission into
    water

[Gain,MaxAngleFromMaxGain] =
    AntennaGain(theta,phi,Pitch,Bearing,AntennaGainFile); %Calculate
    the Antenna Gain based on angle in xy and with z plane

[k1x,k2x,k1z,k2z] = waveNumber(thetar,w,mu0,ep1,ep2);

[rte,tte,rtm,ttm,rte_coeff,tte_coeff,rtm_coeff,ttm_coeff] =
    Coefficients(k1z,k2z,ep1,ep2);

[eta,eta_Prime,etaTE,etaTE_Prime,etaTM,etaTM_Prime] =
    EtaValues(thetar,w,mu0,k1z,k2z,ep1,ep2); %TE and TM have cosines
    baked inside

Betaz_p = real(k2z);
alphaz_p = -1.*imag(k2z);

dair = Hypotenuse(i); %Distance travelled in the air

[Pz,Pz_incoming,Pz_reflected] = PowerAirZ(E0,w,mu0,k1z,rte);

[E,H,Ein,Hin] =
    TE_Field(E0,k1z,k1x,zantenna,HorizontalDist(i),rte_coeff,etaTE);

[ETM,HTM,ETMin,HTMin] =
    TM_Field(E0,k1z,k1x,zantenna,HorizontalDist(i),rtm_coeff,etaTM);

PowerTEin = FieldPower(Ein,Hin).*real(cos(thetar)); %Z-direction
FieldsPowerIncident2 =
    0.5.*real((abs(E0).^2)./eta).*real(cos(thetar)); %Gives the Same
    Answer (Z-direction)

PowerTMin = FieldPower(ETMin,HTMin).*real(cos(thetar)); %Z-direction
FieldsPowerIncidentTM2 =
    0.5.*real((abs(E0).^2)./(eta.*cos(thetar).^2)).*real(cos(thetar));
    %Gives the Same Answer (Z-Direction)

PinitsTE(:,:,i) = PowerTEin;
PinitsTM(:,:,i) = PowerTMin;

```

```
YagiGain = Gain;
TransmitterGain = TGain;

MagAngleGain = MaxAngleFromMaxGain;

%Latitude and Longitude at the surface of the water
LatitudeInterface = Latitude(i);
LongitudeInterface = Longitude(i);

% In the water area
indexWater = 1;
for z1 = 0.1:0.5:2
    % In the water there is a slight offset in the latitude and
    % longitude measurements due to the fact that the ray is
    % travelling at an angle
    %z1 is a depth in the river

    XYwater = z1.*tan(thetar_p); %Distance in xy direction in water - horizontal distance

    % Creating distances: This would be if the bearing is pointing
    % along the x axis. Not general to all antennas
    xwater(indexWater,:) = cos(phir).*XYwater;
    ywater(indexWater,:) = sin(phir).*XYwater;

    %Note with Compass: 0 degree and 360 bearing (N)
    %In compass coordinate with (y = N/S and x = E/W)
    %Getting correct x and y variables based on the bearing of the
    %antenna
    xwaterref = cos(phir+(deg2rad(Bearing))).*XYwater;
    ywaterref = sin(phir+(deg2rad(Bearing))).*XYwater;

    %Decaying portion - attenuation due to conductive losses
    Attenuation = exp(-2*alphaz_p*z1);
    AttenuationdB = 10.*log10(Attenuation);

    dwater = sqrt((z1.^2)+(XYwater.^2)); %Distance travelled in the water.

    PathLoss_Total = pathLoss(dair,lambda1,dwater,lambda2); %Calculate Path loss of air and water

    [ETE_Prime,HTE_Prime] = TE_Prime_Field(E0,k2z,k2x,z1,XYwater,tte_coeff,etaTE_Prime); %TE fields in water

    [ETM_Prime,HTM_Prime] = TM_Prime_Field(E0,k2z,k2x,z1,XYwater,ttm_coeff,etaTM_Prime); %TM fields in water

    PowerTEin_Prime = FieldPower(ETE_Prime,HTE_Prime).*real(cos(thetar_p))...
     .*PathLoss_Total;
```

```
    FieldsPowerTransmitted2 = 0.5.*real(((abs(tte_coeff).^2).*(abs(E0).^2).*Attenuation)./...
        eta_Prime).*real(cos(thetar_p)).*PathLoss_Total; %Gives same answer (z-component)

    PowerTMin_Prime = FieldPower(ETM_Prime,HTM_Prime).*real(cos(thetar_p))...
        .*PathLoss_Total; %Check
    FieldsPowerTransmittedTM2 = 0.5.*real(((abs(ttm_coeff).^2).*(abs(E0).^2).*Attenuation)./...
        (eta_Prime.*cos(thetar_p).^2)).*real(cos(thetar_p))...
        .*PathLoss_Total; %Gives same answer

    xwater(indexWater,:) = xpos+xwater(indexWater,:);
    ywater(indexWater,:) = ypos+ywater(indexWater,:);
    zwater(indexWater,:) = -z1.*ones(1,length(thetar),'double');

    [latnew,longnew] = OffsetLatitudeLongitudeCalculator(LatitudeInterface...
        ,LongitudeInterface,...
        xwaterref(end,:),ywaterref(end,:)); %Need to specify Lat and Long
    latwater(indexWater,:) = latnew(:,:);
    longwater(indexWater,:) = longnew(:,:);

    AttenuationsdB(indexWater,:) = AttenuationdB(:,:);
    PathLossesdB(indexWater,:) = 10.*log10(PathLoss_Total(:,:));

    PWaterTE(indexWater,:) = (PowerTEin_Prime(:,:));
    PWaterTM(indexWater,:) = (PowerTMin_Prime(:,:));
    PWaterTE_Engineering(indexWater,:) = (tte).*Attenuation.*PathLoss_Total;
    PWaterTM_Engineering(indexWater,:) = (ttm).*Attenuation.*PathLoss_Total;

    indexWater = indexWater+1;
end
% Save the water values of the waves at a certain incoming
% coordinate position.
xvals(:,:,i) = x;
yvals(:,:,i) = y;
zvals(:,:,i) = z;

xwaters(:,:,i) = xwater;
ywaters(:,:,i) = ywater;
zwaters(:,:,i) = zwater;

latwaters(:,:,i) = latwater;
longwaters(:,:,i) = longwater;

PwatersTE(:,:,i)= PWaterTE;
PwatersTM(:,:,i)= PWaterTM;
PwatersTE_Engineering(:,:,i)= PWaterTE_Engineering;
```

```
PwatersTM_Engineering(:,:,i)= PWaterTM_Engineering;

YagiGains(:,:,i) = YagiGain;
TransmitterGains(:,:,i) = TransmitterGain;
polarisationMismatches(:,:,i) = etaPol;

MagAngleGains(:,:,i) = MagAngleGain;

AllAngles(:,:,i) = theta;
AllAttenuationsdB(:,:,i) = AttenuationsdB;
AllPathLossesdB(:,:,i) = PathLossesdB;


Transmission_Coefficient_te(:,:,i) = tte;
Transmission_Coefficient_tm(:,:,i) = ttm;

i = i+1;

x = [];
y=[];

xwater = zeros(NumWaterPoints,1);
ywater = zeros(NumWaterPoints,1);

latwater = zeros(NumWaterPoints,1);
longwater = zeros(NumWaterPoints,1);

xair = [];
z = [];
zwater = zeros(NumWaterPoints,1);
zair = [];

Pinit = [];
YagiGain = [];
TransmitterGain = [];

MagAngleGain = [];
AttenuationsdB =zeros(NumWaterPoints,1);
PathLossesdB = zeros(NumWaterPoints,1);

PWaterTE = zeros(NumWaterPoints,1);
PWaterTM = zeros(NumWaterPoints,1);
PWaterTE_Engineering = zeros(NumWaterPoints,1);
PWaterTM_Engineering = zeros(NumWaterPoints,1);

end

%Initializing more variables

PAirInitTE = zeros(NumAirPoints,1,length(Site1));
PAirInitTM = zeros(NumAirPoints,1,length(Site1));

Gain_angles = [];
```

```
Gain_anglesTE = zeros(NumWaterPoints,1,length(Site1));
Gain_anglesTM = zeros(NumWaterPoints,1,length(Site1));
Gain_anglesTE_Engineering = zeros(NumWaterPoints,1,length(Site1));
Gain_anglesTM_Engineering = zeros(NumWaterPoints,1,length(Site1));

Gain_angles_Air = zeros(NumAirPoints,1,length(Site1));
Gain_angles_AirTE = zeros(NumAirPoints,1,length(Site1));
Gain_angles_AirTM = zeros(NumAirPoints,1,length(Site1));
Gain_angles_AirTE3 = [];
Gain_angles_AirTM3 = [];

Gains =[];

%Performing the total path loss calculation
%For Fields equations need to divide the water power/ the air power
%For Engineering Equation just need to take 10*log10 of the value
% Note: Path Loss is already included
for m = 1:size(xwaters,3)

PAirInitTE(:,:,m) = PinitsTE(1,:,m);
Gain_anglesTE(:,:,m) = 10.*log10(PwatersTE(:,:,m)./PAirInitTE(:,:,m))+YagiGains(:,:,m)+...
 TransmitterGains(:,:,m)+polarisationMismatches(:,:,m);

PAirInitTM(:,:,m) = PinitsTM(1,:,m);
Gain_anglesTM(:,:,m) = 10*log10(PwatersTM(:,:,m)./PAirInitTM(:,:,m))+YagiGains(:,:,m)+...
 TransmitterGains(:,:,m)+polarisationMismatches(:,:,m);

Gain_anglesTE_Engineering(:,:,m) = 10*log10(PwatersTE_Engineering(:,:,m))+YagiGains(:,:,m)+...
 TransmitterGains(:,:,m)+polarisationMismatches(:,:,m);

Gain_anglesTM_Engineering(:,:,m) = 10*log10(PwatersTM_Engineering(:,:,m))+YagiGains(:,:,m)+...
 TransmitterGains(:,:,m)+polarisationMismatches(:,:,m);

end

FresnelTE = 10.*log10(Transmission_Coefficient_te);
FresnelTM = 10.*log10(Transmission_Coefficient_tm);

validInputs = [0,1,2,3,4,5,6,7,8,9,10];
meaningInputs = ["Yagi Gain","Transmission Coefficient TE","Transmission Coefficient TM","Angle of Incidence","Attenuation - Water","Path Loss","Overall TE","Overall TE Eng","Overall TM","Overall TM Eng","No Plot"];

% Provides a table for a user to select what type of plot is required
% or if they do not want any plot they can select 10 and it will save to a csv file.
%    TABLE = [validInputs',meaningInputs']
```

```
%     plottype = input('Enter a number: ');
plottype=10;

switch plottype
case 0
    %Yagi Gain - Using longitude and latidue axis
    n=1*numFiles+1;
    figure(n);
    for l = 1:size(xwaters,3)
        hold on;
        for s = 1:size(xwaters,2)
        scatter3(real(longwaters(1,s,l)),real(latwaters(1,s,l)),...
            real(zwaters(1,s,l)),40,(YagiGains(1,s,l)),'filled');
        xlabel("Longitude")
        ylabel("Latitude")
        zlabel("Height (m)")
        title("Three Element Yagi Antenna Gain (dB)")
        end
    end
    cb = colorbar;
    scatter(AntLong(1,1),AntLat(1,1),100,'r','x')
    % xlim([-100 100]);
    % ylim([-100 100]);
    % zlim([-20 0]);
    hold off;
case 1
    %Transmission Gain Coefficient TE - Using longitude and latidue
       axis
    n=1*numFiles+1;
    figure(n);
    for l = 1:size(xwaters,3)
        hold on;
        for s = 1:size(xwaters,2)
        scatter3(real(longwaters(1,s,l)),real(latwaters(1,s,l)),...
            real(zwaters(1,s,l)),40,(FresnelTE(1,s,l)),'filled');
        xlabel("Longitude")
        ylabel("Latitude")
        zlabel("Height (m)")
        title("Transmission Gain TE (dB)")
        end
    end
    cb = colorbar;
    scatter(AntLong(1,1),AntLat(1,1),100,'r','x')
    % xlim([-100 100]);
    % ylim([-100 100]);
    % zlim([-20 0]);
    hold off;
case 2
    %Transmission Gain Coefficient TM - Using longitude and latidue
       axis
    n=1+1*numFiles;
    figure(n);
    for l = 1:size(xwaters,3)
```

```
        hold on;
        for s = 1:size(xwaters,2)
        scatter3(real(longwaters(1,s,l)),real(latwaters(1,s,l)),...
            real(zwaters(1,s,l)),40,(FresnelTM(1,s,l)),'filled');
        xlabel("Longitude")
        ylabel("Latitude")
        zlabel("Height (m)")
        title("Transmission Gain TM (dB)")
        end
    end
    cb = colorbar;
    scatter(AntLong(1,1),AntLat(1,1),100,'r','x')
    % xlim([-100 100]);
    % ylim([-100 100]);
    % zlim([-20 0]);
    hold off;
case 3
    % %Angle of Incidence - Using longitude and latidue axis
    n=1*numFiles;
    figure(n);
    for l = 1:size(xwaters,3)
        hold on;
        for s = 1:size(xwaters,2)
        scatter3(real(longwaters(1,s,l)),real(latwaters(1,s,l)),...
            real(zwaters(1,s,l)),40,(AllAngles(1,s,l)),'filled');
        xlabel("Longitude")
        ylabel("Latitude")
        zlabel("Height (m)")
        title("Transmission Gain TE (dB)")
        end
    end
    cb = colorbar;
    scatter(AntLong(1,1),AntLat(1,1),100,'r','x')
    % xlim([-100 100]);
    % ylim([-100 100]);
    % zlim([-20 0]);
    hold off;
case 4
    % %Attenuation in dB - Using longitude and latidue axis
    n=1*numFiles;
    figure(n);
    for l = 1:size(xwaters,3)
        hold on;
        for s = 1:size(xwaters,2)
        scatter3(real(longwaters(:,s,l)),real(latwaters(:,s,l)),...
            real(zwaters(:,s,l)),40,(AllAttenuationsdB(:,s,l))...
            ,'filled');
        xlabel("Longitude")
        ylabel("Latitude")
        zlabel("Height (m)")
        title("Attenuation Gain (dB)")
        end
    end
```

```
    cb = colorbar;
    scatter(AntLong(1,1),AntLat(1,1),100,'r','x')
    % xlim([-100 100]);
    % ylim([-100 100]);
    % zlim([-20 0]);
    hold off;
case 5
    %Path Loss in dB - Using longitude and latidue axis
    n=1*numFiles;
    figure(n);
    for l = 1:size(xwaters,3)
        hold on;
        for s = 1:size(xwaters,2)
        scatter3(real(longwaters(:,s,l)),real(latwaters(:,s,l)),...
            real(zwaters(:,s,l)),40,(AllPathLossesdB(:,s,l))...
            ,'filled');
        xlabel("Longitude")
        ylabel("Latitude")
        zlabel("Height (m)")
        title("Path Loss Gain (dB)")
        end
    end
    cb = colorbar;
    scatter(AntLong(1,1),AntLat(1,1),100,'r','x')
    % xlim([-100 100]);
    % ylim([-100 100]);
    % zlim([-20 0]);
    hold off;
case 6
    %Overall System (TE) - lat long
    n=1*numFiles+1;
    figure(n);
    for l = 1:size(xwaters,3)
        hold on;
        for s = 1:size(xwaters,2)
        scatter3(real(longwaters(:,s,l)),real(latwaters(:,s,l)),...
            real(zwaters(:,s,l)),10,real(Gain_anglesTE(:,s,l))...
            ,'filled');
        end
    end
    xlabel("Longitude")
    ylabel("Latitude")
    zlabel("Depth (m)")
    title("TE Link Budget Fraser River (dB) - Fields Approach")
    cb = colorbar;
    scatter(AntLong(1,1),AntLat(1,1),100,'r','x')
    hold off;
case 7
    %Overall System (TE) Engineering - Latitude and Longitude
    n=1*numFiles+1;
    figure(n);
    for l = 1:size(xwaters,3)
        hold on;
```

```
        for s = 1:size(xwaters,2)
        scatter3(real(longwaters(:,s,l)),real(latwaters(:,s,l)),...
            real(zwaters(:,s,l)),10,real(...
            Gain_anglesTE_Engineering(:,s,l)),'filled');
        end
    end
    xlabel("Longitude")
    ylabel("Latitude")
    zlabel("Depth (m)")
    title("TE Link Budget Fraser River (dB) - Engineering Approach")
    cb = colorbar;
    scatter(AntLong(1,1),AntLat(1,1),100,'r','x')
    hold off;
case 8
    %Overall System (TM) - Latitude and Longitude
    n=1*numFiles+1;
    figure(n);
    for l = 1:size(xwaters,3)
        hold on;
        for s = 1:size(xwaters,2)
        scatter3(real(longwaters(:,s,l)),real(latwaters(:,s,l)),...
            real(zwaters(:,s,l)),10,real(Gain_anglesTM(:,s,l))...
            ,'filled');
        end
    end
    xlabel("Longitude")
    ylabel("Latitude")
    zlabel("Depth (m)")
    title("TM Link Budget Fraser River (dB) - Fields Approach")
    cb = colorbar;
    scatter(AntLong(1,1),AntLat(1,1),100,'r','x')
    hold off;
case 9
    %Overall System (TM) Eng - Latitude and Longitude
    n=numFiles*1+1;
    figure(n);
    for l = 1:size(xwaters,3)
        hold on;
        for s = 1:size(xwaters,2)
        scatter3(real(longwaters(:,s,l)),real(latwaters(:,s,l)),...
            real(zwaters(:,s,l)),10,real(...
            Gain_anglesTM_Engineering(:,s,l)),'filled');
        end
    end
    xlabel("Longitude")
    ylabel("Latitude")
    zlabel("Depth (m)")
    title("TM Link Budget Fraser River (dB) - Engineering Approach")
    cb = colorbar;
    scatter(AntLong(1,1),AntLat(1,1),100,'r','x')
    hold off;
case 10
    disp("Skipping Plotting and saving directly");
```

```
otherwise
    disp('Incorrect Entry')
end


AntLat2 = AntLat'.*[1;1;1;1];
AntLong2 = AntLong'.*ones(4,1);


%% Comment out if you don't want to write to a file
% %Write the data to an excel sheet
ToWriteData(:,1) = reshape(longwaters,[],1);
ToWriteData(:,2) = reshape(latwaters,[],1);
ToWriteData(:,3) = reshape(zwaters,[],1);
ToWriteData(:,4) = reshape(real(Gain_anglesTE),[],1);
ToWriteData(:,5) = reshape(AntLat2,[],1);
ToWriteData(:,6) = reshape(AntLong2,[],1);
ToWriteData(:,7) = reshape(real(zantenna),[],1);
ToWriteData(:,8) = reshape(AllAttenuationsdB,[],1);
ToWriteData(:,9) = reshape(AllPathLossesdB,[],1);
ToWriteData(:,10) = reshape(real(Gain_anglesTE_Engineering),[],1);
ToWriteData(:,11) = reshape(real(Gain_anglesTM),[],1);
ToWriteData(:,12) = reshape(real(Gain_anglesTM_Engineering),[],1);
ToWriteTitle = {'Longitude' 'Latitude' 'Depth (m)' 'Gain Value TE - Fields (dB)' 'Antenna Latitude' 'Antenna Longitude' 'Height Antenna' 'AllAttenuations' 'AllPathLoss' 'TE-Eng' 'TM-Fields' 'TM-Eng'};
ToWrite1 = array2table(ToWriteData,"VariableNames",ToWriteTitle);

siteName2 = [siteName;siteName;siteName;siteName];

ToWrite = [siteName2 ToWrite1];
writetable(ToWrite,fileWrite(numFiles));

longwatersurf = longwaters(1,1,:);
latwatersurf = latwaters(1,1,:);
zantennasurf = zantenna(1,1,:);

%For the data that has no depth variables to them
ToWriteData2(:,1) = reshape(longwatersurf,[],1);
ToWriteData2(:,2) = reshape(latwatersurf,[],1);
ToWriteData2(:,3) = reshape(AntLat,[],1);
ToWriteData2(:,4) = reshape(AntLong,[],1);
ToWriteData2(:,5) = reshape(real(zantennasurf),[],1);
ToWriteData2(:,6) = reshape(YagiGains,[],1);
ToWriteData2(:,7) = reshape(FresnelTE,[],1);
ToWriteData2(:,8) = reshape(FresnelTM,[],1);
ToWriteData2(:,9) = reshape(AllAngles,[],1);
ToWriteTitle2 = {'Longitude' 'Latitude' 'Antenna Latitude' 'Antenna Longitude' 'Height Antenna' ' YagiGains' 'FresnelTE' ' FresnelTM' 'AllAngles'};
ToWrite2 = array2table(ToWriteData2,"VariableNames",ToWriteTitle2);

```

```
ToWrite = [siteName ToWrite2];
writetable(ToWrite,fileWrite2(numFiles));

numFiles = numFiles + 1;
end


function [k1x,k2x,k1z,k2z] = waveNumber(angle,w,mu0,ep1,ep2)
    % Wave number
    % 1 indicates in air
    % 2 indicates in water
    k1 = w*sqrt(mu0*ep1);
    k2 = w*sqrt(mu0*ep2); % Eq. (7.9.2)
    k1x = k1*sin(angle);
    k2x = k1x;
    k1z = k1*cos(angle);
    k2z = sqrt(w^2*mu0*ep2 - k1x.^2); % Eq. (7.9.6)
end

function [rte,tte,rtm,ttm,rte_coeff,tte_coeff,rtm_coeff,ttm_coeff]
    = Coefficients(k1z,k2z,ep1,ep2)
    % Calculate the Fresnel coefficients
    %rte,tte,rtm,ttm are power coefficients
    %rte_coeff and all other _coeff are the complex conjugates
    rte_coeff = ((k1z - k2z)./(k1z + k2z));
    rtm_coeff = ((k2z.*ep1 - k1z.*ep2)./(k2z.*ep1 + k1z.*ep2));

    ttm_coeff = (2*k2z*ep1)./(k2z*ep1+k1z*ep2);
    tte_coeff = (2*k1z./(k1z+k2z));

    %Power Values
    rte = abs(rte_coeff).^2;
    rtm = abs(rtm_coeff).^2;
    ttm = 1-rtm;
    tte = 1-rte;

end

function [eta,eta_Prime,etaTE,etaTE_Prime,etaTM,etaTM_Prime] =
    EtaValues(thetar,w,mu0,k1z,k2z,ep1,ep2)
    %Calculate the various wave impedances
    etaTE = w.*mu0./k1z;
    etaTE_Prime = w.*mu0./k2z;
    etaTM = k1z./(w.*ep1);
    etaTM_Prime = k2z./(w.*ep2);
    eta = sqrt(mu0./ep1);
    eta_Prime = sqrt(mu0./ep2);
end

function PL = pathLoss(d1,lambda1,d2,lambda2)
    %Calculates the path loss in air and water
    if d1 == 0
        PL = 1;
```

```
    else
        PL = (lambda1./(4.*pi.*d1)).^2.*(lambda2./(4.*pi.*d2)).^2;
    end
end

function [Pz,Pz_incoming,Pz_reflected] = PowerAirZ(E0,w,mu0,k1z,rte)
        %Calculates the incoming, reflected and total power in the
            air
        Pz = abs(E0)^2./(2.*w.*mu0).*k1z.*(1-(rte));
        Pz_incoming = abs(E0)^2./(2.*w.*mu0).*k1z;
        Pz_reflected = abs(E0)^2./(2.*w.*mu0).*k1z.*(rte);
end

function [Gain,MaxAngleFromMaxGain] =
    AntennaGain(theta,phi,pitch,bearing,AntennaGainFile)
    %Calculates the yagi gain
    alpha = 90-theta-pitch;
    % Theta measurement

    phiPrime = phi; %Offset from antenna to water location

    MaxAngleFromMaxGain = max(abs(alpha),abs(phiPrime));
    %Calculate the maximum angle

    data = readmatrix(AntennaGainFile);
    Angle = data(:,1); %Offset Directional
    AntGain = data(:,2);

    Gain = interp1(Angle,AntGain,MaxAngleFromMaxGain);
    %Interpolate based on manufacturers gain
end


function [E,H,Ein,Hin] = TE_Field(E0,k1z,k1x,z0,x0,rte_coeff,etaTE)
    % TE Fields: In First medium
    Ey = E0.*(exp(-1i.*k1z.*z0)+rte_coeff.*exp(1i.*k1z.*z0))...
        .*exp(-1i.*k1x.*x0);
    Hx = E0.*(-1.*exp(-1i.*k1z.*z0)+rte_coeff.*exp(1i.*k1z.*z0))...
        .*exp(-1i.*k1x.*x0)./etaTE;
    Hz = E0.*((k1x./k1z).*exp(-1i.*k1z.*z0)+rte_coeff.*(k1x./k1z)...
        .*exp(1i.*k1z.*z0)).*exp(-1i.*k1x.*x0)./etaTE;

    E = [0,Ey,0];
    H = [Hx,0,Hz];

    Eyin = E0.*(exp(-1i.*k1z.*z0)).*exp(-1i.*k1x.*x0);
    Hxin = E0.*(-1.*exp(-1i.*k1z.*z0)./etaTE).*exp(-1i.*k1x.*x0);
    Hzin =
       E0.*((k1x./k1z).*exp(-1i.*k1z.*z0)./etaTE).*exp(-1i.*k1x.*x0);

    Ein = [0,Eyin,0];
    Hin = [Hxin,0,Hzin];
end
```

```
function [ETM,HTM,ETMin,HTMin] = TM_Field(E0,k1z,k1x,z0,x0,rtm_coeff,etaTM)
    % TM Fields: In First medium
    Hy_TM = E0.*(exp(-1i.*k1z.*z0)+rtm_coeff.*exp(1i.*k1z.*z0))...
         .*exp(-1i.*k1x.*x0)./etaTM;
    Ex_TM = E0.*(exp(-1i*k1z.*z0)+rtm_coeff.*exp(1i.*k1z.*z0))...
         .*exp(-1i.*k1x.*x0);
    Ez_TM = E0.*(-1.*(k1x./k1z).*exp(-1i.*k1z*z0)+rtm_coeff.*(k1x./k1z)...
         .*exp(1i.*k1z.*z0)).*exp(-1i.*k1x.*x0);

    ETM = [Ex_TM,0,Ez_TM];
    HTM = [0,Hy_TM,0];

    Hy_TMin = E0.*(exp(-1i.*k1z.*z0).*exp(-1i.*k1x.*x0))./etaTM;
    Ex_TMin = E0.*(exp(-1i*k1z.*z0).*exp(-1i.*k1x.*x0));
    Ez_TMin = E0.*(-1.*(k1x./k1z).*exp(-1i.*k1z*z0).*exp(-1i.*k1x.*x0));

    ETMin = [Ex_TMin,0,Ez_TMin];
    HTMin = [0,Hy_TMin,0];
end

function [ETE_Prime,HTE_Prime] = TE_Prime_Field(E0,k2z,k2x,z1,x1,tte_coeff,etaTEPrime)
    % TE Fields: In second medium
    EyPrime = E0.*tte_coeff.*(exp(-1i.*k2z.*z1).*exp(-1i.*k2x.*x1));
    HxPrime = E0.*tte_coeff.*(-1.*exp(-1i.*k2z.*z1).*exp(-1i.*k2x.*x1))...
         ./etaTEPrime;
    HzPrime = E0.*tte_coeff.*((k2x./k2z).*exp(-1i.*k2z.*z1)...
         .*exp(-1i.*k2x.*x1))./etaTEPrime;

    ETE_Prime = [0,EyPrime,0];
    HTE_Prime = [HxPrime,0,HzPrime];
end

function [ETM_Prime,HTM_Prime] = TM_Prime_Field(E0,k2z,k2x,z1,x1,ttm_coeff,etaTMPrime)
    % TM Fields: In second medium
    HyPrime_TM = E0.*ttm_coeff.*(exp(-1i.*k2z.*z1).*exp(-1i.*k2x.*x1))...
         ./etaTMPrime;
    ExPrime_TM = E0.*ttm_coeff.*(exp(-1i.*k2z.*z1).*exp(-1i.*k2x.*x1));
    EzPrime_TM = E0.*ttm_coeff.*(-1.*(k2x./k2z).*exp(-1i.*k2z.*z1)...
         .*exp(-1i.*k2x.*x1))./etaTMPrime;

    ETM_Prime = [ExPrime_TM,0,EzPrime_TM];
    HTM_Prime = [0,HyPrime_TM,0];
end
```

```
function [Power] = FieldPower(E,H)
    %Calculate the poynting vector of E&H Fields
    Power = 0.5.*real(sqrt(sum(cross(E,conj(H)).^2)));
end


function [latnew,longnew] =
   OffsetLatitudeLongitudeCalculator(Lat,Long,xoffset,yoffset)
    rearth = 6378.137;  %radius of the earth in kilometers
    m = (1 / ((2 * pi / 360) * rearth)) / 1000;  %1 meter in degree

    latnew = Lat + (real(yoffset) * m);
    longnew = Long + (real(xoffset) * m) / cos(Lat * (pi / 180));
end
```

B.1.2 Fresnel Equations

TE Polarisation

```
%Comparison of Multiple different textbooks for TE Oblique incidence
% Up to Date: NO Issues all results agree
% November 30th 2023 last edited

%parallel == TM == P polarization
%Perpendicular == TE == S polarization


close all;
clear all;
clc;

%% Declaring Constants
f = 1.5e8; %150 MHz
w = 2*pi*f;

%Conductivity
sigmaAir = 0;
sigmaWater = 0.014;

%Declare Permitivities epsilon_r = epsilon/epsilon_o
epsilonrAir = 1;
epsilonrWater = 80.10;
epsilon0 = 8.85418782e-12;

%Declare Permeability mu_r = mu/mu_0
murAir = 1;
murWater = 0.999992;
mu0 = pi*4e-7;

% Declare values that do not depend on angle

```

```
%Calculate specific permitivity: epsilon = epsilonr*epsilon0
epsilonAir = epsilonrAir * epsilon0;
epsilonWater = epsilonrWater * epsilon0;

%Calculate specific permeability: mu = mur*mu0
muAir = murAir * mu0;
muWater = murWater * mu0;

%% Determine Input Angle Stuff
thetarAir = linspace(0,pi/2,100);


%% James Wait Textbook

%Perpendicular
gammaWater = sqrt(1i.*muWater.*w.*(sigmaWater+1i.*epsilonWater.*w));  %Water
gammaAir = sqrt(1i.*muAir.*w.*(sigmaAir+1i.*epsilonAir.*w));  %Air

thetarWater2 = (asin((gammaAir.*sin(thetarAir))./gammaWater));

uWater = gammaWater.*cos(thetarWater2);
uAir = gammaAir.*cos(thetarAir);
N0 = (uAir)./(1i.*mu0.*w);
N1 = (uWater)./(1i.*mu0.*w);

%Coefficients
rJWTE = (N0-N1)./(N0+N1);
tJWTE = 1+rJWTE; %Since this is perpendicular should be able to do t = 1+r
tJWTE2 = 2.*N0./(N0+N1);

%Power
RJWTE = abs(rJWTE).^2;
TJWTE = abs(tJWTE).^2.*real(N1)./real(N0);
TJWTE2 = 1-RJWTE; %Verification


%% Pozar
epswater = epsilonWater-1i*sigmaWater/w;
epsair = epsilonAir-1i*sigmaAir/w;

thetarWater = asin(sin(thetarAir).*sqrt(epsair.*mu0./(epswater.*mu0)));
gammzWater = 1i*w*sqrt(muWater*epswater);
etaWater = (1i*w*muAir)/gammzWater; %Same: sqrt(mu0/epswater);
gammzAir = 1i*w*sqrt(muAir*epsair);
etaAir = (1i*w*muAir)/gammzAir;%Same: etaAir2 = sqrt(mu0/epsair);

%Perpendicular coefficients
rPozarPerp = (etaWater.*cos(thetarAir)-cos(thetarWater).*etaAir)./...
    (etaWater.*cos(thetarAir)+cos(thetarWater).*etaAir);
```

```
tPozarPerp =
    (2.*etaWater.*cos(thetarAir))./(etaWater.*cos(thetarAir)+...
     cos(thetarWater).*etaAir);
tPozarPerp2 = 1+rPozarPerp; %Verification - GOOD

%Power values
RPozarPerp = abs(rPozarPerp).^2;
TPozarPerp = abs(tPozarPerp).^2.*real(etaAir.*cos(thetarWater))./...
     real(etaWater.*cos(thetarAir));
TPozarPerp2 = 1-RPozarPerp; %Verification - GOOD


%% MIT
Ni = cos(thetarAir)./etaAir;
Nt = cos(thetarWater)./etaWater;

%Coefficients
te = 2.*Ni./(Ni+Nt);
re=(Ni-Nt)./(Ni+Nt);
te2 = re+1; %Verification - GOOD

%Power Values
Te = abs(te).^2.*real(Nt)./real(Ni);
Re = abs(re).^2; % Perpendicular Power
Te2 = 1-Re;   %Verification - GOOD

%% Ch7 Rutgers Oblique Incidence from Textbook
ep1 = epsilonAir;
ep2 = epsilonWater - 1i*sigmaWater/w;
k1 = w*sqrt(mu0*ep1); %Wave numbers
k2 = w*sqrt(mu0*ep2);

k1x = k1*sin(thetarAir);
k1z = k1*cos(thetarAir);
k2z = sqrt(w^2*mu0*ep2 - k1x.^2);
k2z2 = k2.*cos(thetarWater);
thetar_p = asin(k1.*sin(thetarAir)./k2);

% Coefficients
rte = ((k1z - k2z)./(k1z + k2z));
tte = (2*k1z./(k1z+k2z));
tte2 = 1+rte;

%Power Values
Rte = abs(rte).^2;
Tte = abs(tte).^2.*(real(k2z)./real(k1z));
Tte2 = 1-Rte;


%% Perpendicular Coefficient Plots
n = 1;
figure(n)
hold on
```

```
plot(rad2deg(thetarAir),(rJWTE),rad2deg(thetarAir),(tJWTE));
xlabel("Angle of Incidence (deg)");
ylabel("Transmission and Reflection Coefficients");
title("Coefficient-Transmission and Reflection (James Wait)");
legend('Reflection - RTE','Transmission - TTE');
hold off

n=n+1;
figure(n)
plot(rad2deg(thetarAir),(rte),rad2deg(thetarAir),(tte));
xlabel("Angle of Incidence (deg)");
ylabel("Transmission and Reflection Coefficients");
title("Coefficient-Transmission and Reflection (Rutgers Textbook)")
legend('Reflection - RTE','Transmission - TTE');
saveas(gcf,'../FishPropagation/Figures/Fresnel/TE/RutgersCoeff.jpg')

n=n+1;
figure(n)
plot(rad2deg(thetarAir),(rPozarPerp),rad2deg(thetarAir),tPozarPerp);
xlabel("Angle of Incidence (deg)");
ylabel("Transmission and Reflection Coefficients");
title("Coefficient-Transmission and Reflection (Pozar)")
legend('Reflection - RTE','Transmission - TTE');
saveas(gcf,'../FishPropagation/Figures/Fresnel/TE/PozarCoeff.jpg')

n=n+1;
figure(n)
plot(rad2deg(thetarAir),(re),rad2deg(thetarAir),(te));
xlabel("Angle of Incidence (deg)");
ylabel("Transmission and Reflection Coefficients");
title("Coefficient-Transmission and Reflection (MIT)")
legend('Reflection - RTE','Transmission - TTE');
saveas(gcf,'../FishPropagation/Figures/Fresnel/TE/MITCoeff.jpg')


%% Perpendicular Power Plots
n = n+1;
figure(n)
plot(rad2deg(thetarAir),(RJWTE),rad2deg(thetarAir),...
    (TJWTE),rad2deg(thetarAir),(1-RJWTE));
xlabel("Angle of Incidence (deg)");
ylabel("Transmission and Reflection Power");
title("Power-TE Polarization Transmission and Reflection (James
    Wait)")
legend('Reflection','Transmission','Transmission 2');
saveas(gcf,'../FishPropagation/Figures/Fresnel/TE/JamesWaitPower.jpg')

n=n+1;
figure(n)
plot(rad2deg(thetarAir),(Rte),rad2deg(thetarAir),...
    (Tte),rad2deg(thetarAir),(1-Rte));
xlabel("Angle of Incidence (deg)");
ylabel("Transmission and Reflection Power");
```

```
title("Power-Transmission and Reflection (Rutgers Textbook)")
legend('Reflection','Transmission','Transmission 2');
saveas(gcf,'../FishPropagation/Figures/Fresnel/TE/RutgersPower.jpg')

n=n+1;
figure(n)
plot(rad2deg(thetarAir),(RPozarPerp),rad2deg(thetarAir),...
    TPozarPerp,rad2deg(thetarAir),(1-RPozarPerp));
xlabel("Angle of Incidence (deg)");
ylabel("Transmission and Reflection Power");
title("Power-TE Polarization Transmission and Reflection (Pozar)")
legend('Reflection','Transmission','Transmission 2');
saveas(gcf,'../FishPropagation/Figures/Fresnel/TE/PozarPower.jpg')

n=n+1;
figure(n)
plot(rad2deg(thetarAir),(Re),rad2deg(thetarAir),...
    (Te),rad2deg(thetarAir),(1-Re));
xlabel("Angle of Incidence (deg)");
ylabel("Transmission and Reflection Power");
title("Power-TE Polarization Transmission and Reflection (MIT)")
legend('Reflection','Transmission','Transmission 2');
saveas(gcf,'../FishPropagation/Figures/Fresnel/TE/MITPower.jpg')

n=n+1;
figure(n)
plot(rad2deg(thetarAir),10.*log10(Re),rad2deg(thetarAir),10.*log10(Te));
xlabel("Angle of Incidence (deg)");
ylabel("Transmission and Reflection Power");
title("Power-TE Polarization Transmission and Reflection (MIT)")
legend('Reflection - |RTE|^2','Transmission - 10*log10(|TTE|^2)');
saveas(gcf,'../FishPropagation/Figures/Fresnel/TE/MITPower10Log.jpg')



disp("Perpendicular")
TABLE = ["rJWTE","rPozar","rMIT","rRutgers"]
TABLE = [rJWTE',rPozarPerp',re',rte'] %Get all the same values
TABLE = ["tJWTE","tPozar","tMIT","tRutgers"]
TABLE = [tJWTE',tPozarPerp',te',tte']

disp("Perpendicular Power")
TABLE = ["RJWTE","RPozar","RMIT","RRutgers"]
TABLE = [RJWTE',RPozarPerp',Re',Rte'] %Get all the same values
TABLE = ["tJWTE","tPozar","tMIT","tRutgers"]
TABLE = [TJWTE',TPozarPerp',Te',Tte']


%Write to a csv file
labels =
    ["thetaAir","rJWTE","tJWTE","rChrisPerp","tChrisPerp","re",...
     "te","rte","tte","RJWTE","TJWTE","RChrisPerp","TChrisPerp","Re",...
     "Te","Rte","Tte","RdB","TdB"];
```

```
dataJWTE = [rad2deg(thetarAir)',real(rJWTE)',real(tJWTE)',...
    real(rPozarPerp)',real(tPozarPerp)',real(re)',real(te)',real(rte)',...
    real(tte)',real(RJWTE)',real(TJWTE)',real(RPozarPerp)',...
    real(TPozarPerp)',real(Re)',real(Te)',real(Rte)',real(Tte)',...
    (10.*log10((Rte)))',(10.*log10(Rte))'];
togo = [labels;dataJWTE];
writematrix(togo,'../FishPropagation/Figures/Fresnel/TE/FresnelTE.csv');
```

TM Polarisation

```
%Comparison of Multiple different textbooks for TM Oblique incidence
% UP to Date:
% November 30th 2023 last edited

%parallel == TM == P polarization
%Perpendicular == TE == S polarization

close all;
clear all;
clc;

%% Declaring Constants
f = 1.5e8;
w = 2*pi*f;

%Conductivity
sigmaAir = 0;
sigmaWater = 0.014;

%Declare Permitivities epsilon_r = epsilon/epsilon_o
epsilonrAir = 1;
epsilonrWater = 80.10;
epsilon0 = 8.85418782e-12;

%Declare Permeability mu_r = mu/mu_0
murAir = 1;
murWater = 0.999992;
mu0 = pi*4e-7;

% Declare values that do not depend on angle
%Calculate specific permitivity: epsilon = epsilonr*epsilon0
epsilonAir = epsilonrAir * epsilon0;
epsilonWater = epsilonrWater * epsilon0;

%Calculate specific permeability: mu = mur*mu0
muAir = murAir * mu0;
muWater = murWater * mu0;



%% Determine Input Angle Stuff
thetarAir = linspace(0,pi/2,100);

```

```
%% James Wait Textbook
gammaWater = sqrt(1i.*muWater.*w.*(sigmaWater+1i.*epsilonWater.*w));%Water
gammaAir = sqrt(1i.*muAir.*w.*(sigmaAir+1i.*epsilonAir.*w));  %Air

thetarWater = (asin((gammaAir.*sin(thetarAir))./gammaWater));
uWater = gammaWater.*cos(thetarWater);
uAir = gammaAir.*cos(thetarAir);
KAir = uAir./(sigmaAir+1i.*epsilonAir.*w);
KWater = uWater./(sigmaWater+1i.*epsilonWater.*w);
ZWater = KWater; %For the semi-infinite 2 layer case


%Coefficients
rJWTM = -(ZWater-KAir)./(ZWater+KAir);
tJWTM = 2*KAir./(KAir+ZWater);
tJWTM2 = (1+rJWTM);

% Power
TJWTM = abs(tJWTM).^2.*real(KWater)./real(KAir);
RJWTM = abs(rJWTM).^2;
TJWTM2 = 1-RJWTM;


%% Pozar

thetarWater = asin(sin(thetarAir).*sqrt(epsilonAir.*mu0./...
    (epsilonWater.*mu0)));

epswater = epsilonWater-1i*sigmaWater/w;
epsair = epsilonAir-1i*sigmaAir/w;
gammzWater = 1i*w*sqrt(muWater*epswater);
etaWater = (1i*w*muAir)/gammzWater; %Same: sqrt(mu0/epswater);
gammzAir = 1i*w*sqrt(muAir*epsair);
etaAir = (1i*w*muAir)/gammzAir;%Same: etaAir2 = sqrt(mu0/epsair);

%Coefficients
rPozarPara = (etaWater.*cos(thetarWater)-cos(thetarAir).*etaAir)./...
    (etaWater.*cos(thetarWater)+etaAir.*cos(thetarAir));
tPozarPara = (2.*etaWater.*cos(thetarWater))./...
    (etaWater.*cos(thetarWater)+cos(thetarAir).*etaAir);
tPozarPara2 = (1+rPozarPara);


%Power Equations
RPozarPara = abs(rPozarPara).^2;
TPozarPara = real(etaAir.*cos(thetarAir))./...
    real(etaWater.*cos(thetarWater)).*abs(tPozarPara).^2;
TPozarPara2 = 1-RPozarPara;
```

```
%% MIT
Mi = etaAir.*cos(thetarAir);
Mt = etaWater.*cos(thetarWater);

%Coefficients
th = 2.*Mi./(Mi+Mt);
rh = (Mi-Mt)./(Mi+Mt);
th2 = (1+rh);

%Power
Th = abs(th.^2).*real(Mt)./real(Mi);
Rh = abs(rh).^2;
Th2 = 1-Rh;



%% Ch7 Rutgers Oblique Incidence from Textbook
ep1 = epsilonAir;
ep2 = epsilonWater - 1i*sigmaWater/w;
k1 = w*sqrt(mu0*ep1); %Wave numbers
k2 = w*sqrt(mu0*ep2);

k1x = k1*sin(thetarAir);
k1z = k1*cos(thetarAir);
k2z = sqrt(w^2*mu0*ep2 - k1x.^2);
k2z2 = k2.*cos(thetarWater);

% Coefficients
rtm = ((k2z.*ep1 - k1z.*ep2)./(k2z.*ep1 + k1z.*ep2));
ttm = (2*k2z*ep1)./(k2z*ep1+k1z*ep2);
ttm2 = (1+rtm);


%Power Values
Rtm = abs(rtm).^2;
Ttm = abs(ttm2).^2.*(real(k1z*ep2)./real(k2z*ep1));
Ttm2 = 1-Rtm;


%% Parallel Coefficients
n= 1;
figure(n)
plot(rad2deg(thetarAir),(rJWTM),rad2deg(thetarAir),(tJWTM));
xlabel("Angle of Incidence (deg)");
ylabel("Transmission and Reflection Coefficients");
title("Coefficients-Transmission and Reflection (James Wait)")
legend('Reflection - RTM','Transmission - TTM');
saveas(gcf,'../FishPropagation/Figures/Fresnel/TM/JamesWait.jpg')


n=n+1;
figure(n)
plot(rad2deg(thetarAir),(rPozarPara),rad2deg(thetarAir),tPozarPara);
```

```
xlabel("Angle of Incidence (deg)");
ylabel("Transmission and Reflection Coefficients");
title("Coefficients-Transmission and Reflection (Pozar)")
legend('Reflection - RTM','Transmission - TTM');
saveas(gcf,'../FishPropagation/Figures/Fresnel/TM/Pozar.jpg')

n=n+1;
figure(n)
plot(rad2deg(thetarAir),(rtm),rad2deg(thetarAir),(ttm));
xlabel("Angle of Incidence (deg)");
ylabel("Transmission and Reflection Coefficients");
title("Coefficients-Transmission and Reflection (Rutgers Textbook)")
legend('Reflection - RTM','Transmission - TTM');
saveas(gcf,'../FishPropagation/Figures/Fresnel/TM/Rutgers.jpg')

n=n+1;
figure(n)
plot(rad2deg(thetarAir),(rh),rad2deg(thetarAir),(th));
xlabel("Angle of Incidence (deg)");
ylabel("Transmission and Reflection Coefficients");
title("Coefficients-Transmission and Reflection (MIT)")
legend('Reflection - RTM','Transmission - TTM');
saveas(gcf,'../FishPropagation/Figures/Fresnel/TM/MIT.jpg')

%% Parallel Power Plots
n= n+1;
figure(n)
plot(rad2deg(thetarAir),(RJWTM),rad2deg(thetarAir),(TJWTM));
xlabel("Angle of Incidence (deg)");
ylabel("Transmission and Reflection Coefficients");
title("Power-Transmission and Reflection (James Wait)")
legend('Reflection','Transmission');
saveas(gcf,'../FishPropagation/Figures/Fresnel/TM/JamesWaitPower.jpg')


n=n+1;
figure(n)
plot(rad2deg(thetarAir),(RPozarPara),rad2deg(thetarAir),TPozarPara);
xlabel("Angle of Incidence (deg)");
ylabel("Transmission and Reflection Coefficients");
title("Power-Transmission and Reflection (Pozar)")
legend('Reflection','Transmission');
saveas(gcf,'../FishPropagation/Figures/Fresnel/TM/PozarPower.jpg')

n=n+1;
figure(n)
plot(rad2deg(thetarAir),(Rtm),rad2deg(thetarAir),(Ttm));
xlabel("Angle of Incidence (deg)");
ylabel("Transmission and Reflection Coefficients");
title("Power-TM/Parallel Polarization Transmission and " + ...
    "Reflection (Rutgers)")
legend('Reflection','Transmission');
saveas(gcf,'../FishPropagation/Figures/Fresnel/TM/RutgersPower.jpg')
```

```
n=n+1;
figure(n)
plot(rad2deg(thetarAir),(Rh),rad2deg(thetarAir),(Th));
xlabel("Angle of Incidence (deg)");
ylabel("Transmission and Reflection Coefficients");
title("Power-Transmission and Reflection (MIT)")
legend('Reflection','Transmission');
saveas(gcf,'../FishPropagation/Figures/Fresnel/TM/MITPower.jpg')

n=n+1;
figure(n)
plot(rad2deg(thetarAir),10*log10(Rh),rad2deg(thetarAir),10.*log10(Th));
xlabel("Angle of Incidence (deg)");
ylabel("Transmission and Reflection Coefficients");
title("Power-Transmission and Reflection (MIT)")
legend('Reflection - 10*log10|RTM|^2','Transmission -
    10*log10|TTM|^2');
saveas(gcf,'../FishPropagation/Figures/Fresnel/TM/MITPowerdB.jpg')





%parallel == TM
%Perpendicular == TE

disp("Parallel Coefficients")
TABLE = ["rJWTM","rPozar","rMIT","rRutgers"]
TABLE = [rJWTM',rPozarPara',rh',rtm'] %A Pesky sign issue remains
TABLE = ["tJWTM","tPozar","tMIT","tRutgers"]
TABLE = [tJWTM',tPozarPara',th',ttm']


disp("Parallel Power")
TABLE = ["rJWTM","rPozar","rMIT","rRutgers"]
TABLE = [RJWTM',RPozarPara',Rh',Rtm'] %A Pesky sign issue remains
TABLE = ["tJWTM","tJW2TM","tPozar","tMIT","tRutgers"] %
TABLE = [TJWTM',TPozarPara',Th',Ttm']%
TABLE = ["tJWTM","tMIT","tRutgers"]
TABLE = [TJWTM',Th2',Ttm2']

labels =
    ["thetaAir","rJWTM","tJWTM","rChrisPara","tChrisPara","rh"...
     ,"th","rtm","ttm","RJWTM","TJWTM","RChrisPara","TChrisPara","Rh"...
     ,"Th","Rtm","Ttm","RdB","TdB"];
dataJWTE = [rad2deg(thetarAir)',real(rJWTM)',real(tJWTM)'...
     ,real(rPozarPara)',real(tPozarPara)',real(rh)',real(th)',real(rtm)'...
     ,real(ttm)',real(RJWTM)',real(TJWTM)',real(RPozarPara)',...
     real(TPozarPara)',real(Rh)',real(Th)',real(Rtm)',real(Ttm)',...
     (10.*log10((Rtm)))',(10.*log10(Ttm))'];
togo = [labels;dataJWTE];
writematrix(togo,'../FishPropagation/Figures/Fresnel/TM/FresnelTM.csv');
```

B.2 Acoustic Propagation

B.2.1 Fitting to Single-layer

```
%% Window Propagation
% Fits the averaged data obtained by multiple sources for the absorption
% coefficient and for the transmission loss to a transmission line model.
% Three different fitting approaches are used. Linear fit, polynomial fit
% and spline fit. These results can then be used in calculating other
% transmission line models that we come up with.

% Although there is more transmission loss data, we had to reduce the
% number of points to match the number of points we had for the absorption
% coefficient.

clear;
clc;

f=[125,250,500,1000,2000,4000];

%%3 mm
% Single Pane 3 mm - Sound Reduction (dB)
R = [-20.175,-21.25,-25.55,-28.9,-33.175,-26.6];

% Single Pane 3 mm - Absorption Coefficient
alpha =  [0.0702,0.04,0.03,0.03,0.02,0.02];

% %% 6 mm
% % Single Pane 6 mm - Sound Reduction (dB)
% R = [-23.4,-27.4,-31.8,-35.2,-26.8,-35.5];
%
% % Single Pane 6 mm - Absorption Coefficient
% alpha = [0.08,0.04,0.03,0.03,0.02,0.02,0.02];

ZGlasses = [];
gammaGlasses = [];

for i = 1:length(f)
    w = 2*pi*f(1);
    c = 343; %In Air
    cglass = 4540;
    rho0 = 1.293; %Density of Air
    rhoglass = 2500;

    %% Transmission Line Calculation
    ZAir = rho0.*c; %Impedance of Air (considered to be lossless)
```

```
    ZAir2 = rho0.*c;

    ZGlassRe = rhoglass.*cglass;
    syms ZGlassIm %What we are trying to solve for
    ZGlass = ZGlassRe+1i.*ZGlassIm;

    %k = Beta-1i*alpha
    %ik = gamma = alpha+iBeta
    gammaAir = 1i.*w./c; %Lossless portion of the propagation constant
    gammaGlassIm = 1i.*w./cglass;
    syms gammaGlassRe %What we are solving for (attenuation)

    %Fitting to single pane scenario where the glass is 3 mm thick
    lair = 0;
    lglass = 0.003;
    lair2 = 0;

    %Calculate the input impedance and the total Reflection
    Zin = ZGlass.*((ZAir2+ZGlass.*tanh((gammaGlassRe+gammaGlassIm)...
        .*lglass))./(ZGlass+ZAir2.*tanh((gammaGlassRe+gammaGlassIm)...
        .*lglass)));
    gammaTotal = (Zin-ZAir)./(Zin+ZAir);


    % Transmission Line
    Vs = 10;
    IncidentPower = 0.5.*abs(Vs).^2.*real(1./ZAir).*(1-abs(gammaTotal).^2);
    Pin = 0.5.*abs(Vs).^2.*real(1./ZAir);
    Pref = 0.5.*abs(Vs).^2.*real(1./ZAir).*(abs(gammaTotal).^2);

    %Equations for three layer transmission line from Bound.Cond.
    V1m = -0.5.*Vs.*((ZGlass./ZAir).*(1-gammaTotal)-(1+gammaTotal));
    V1p = 0.5.*Vs.*((ZGlass./ZAir).*(1-gammaTotal)+(1+gammaTotal));

    %Wave leaving the middle layer
    V2p = V1p.*exp(-(gammaGlassRe+gammaGlassIm).*lglass)+V1m...
        .*exp((gammaGlassRe+gammaGlassIm).*lglass);

    LoadPower = 0.5.*real(1./ZAir).*abs(V2p).^2;

    LossPower = IncidentPower-LoadPower;

    eqn1 = abs(gammaTotal).^2 == (1-alpha(i));
    eqn2 = (LoadPower./Pin) == 10^(R(i)/10); %R =10.*log10(Iout./Iin)

    eqns =[eqn1,eqn2]; %eqn3

    %Want both the variables we are solving for to be positive.
    assume(gammaGlassRe>0)
```

```
    assumeAlso(ZGlassIm>0)
    %Solve the system of equations
    S = vpasolve(eqns,[ZGlassIm,gammaGlassRe]);



    %% Check - Solving the values at each frequency and making sure right
    %% Re-do with calculated values for transmission Line Calculations
    ZAir = rho0.*c;
    ZGlasssym = S.ZGlassIm;
    dZGlassIm = double(ZGlasssym);
    ZGlass = ZGlassRe+1i.*dZGlassIm;

    gammaAir = w./c;
    gammaGlassIm = 1i.*w./cglass;
    gammaGlassRe = S.gammaGlassRe;
    dgammaGlassRe = double(gammaGlassRe);
    gammaGlass = dgammaGlassRe+gammaGlassIm;
    gammaAir2 = w./c;

    lair = 0;
    lglass = 0.003;
    lair2 = 0;

    Zin = ZGlass.*((ZAir2+ZGlass.*tanh(gammaGlass.*lglass))...
        ./(ZGlass+ZAir2.*tanh(gammaGlass.*lglass)));
    gammaTotal = (Zin-ZAir)./(Zin+ZAir);


    % Transmission Line
    Vs = 10;
    IncidentPower = 0.5.*abs(Vs).^2.*real(1./ZAir).*(1-abs(gammaTotal).^2);
    Pin = 0.5.*abs(Vs).^2.*real(1./ZAir);
    Pref = 0.5.*abs(Vs).^2.*real(1./ZAir).*(abs(gammaTotal).^2);

    V1m = -0.5.*Vs.*((ZGlass./ZAir).*(1-gammaTotal)-(1+gammaTotal));
    V1p = 0.5.*Vs.*((ZGlass./ZAir).*(1-gammaTotal)+(1+gammaTotal));

    V2p = V1p.*exp(-gammaGlass.*lglass)+V1m.*exp(gammaGlass.*lglass);

    LoadPower = 0.5.*real(1./ZAir).*abs(V2p).^2;

    LossPower = IncidentPower-LoadPower;


    if (abs(gammaTotal).^2 - (1-alpha(i)) <=1E-10) ...
            && (10.*log10(LoadPower./Pin)-R(i) <=1E-10)
        disp("Plugging solved variables back into the equation it works.")
```

```
    else
        disp("We get the wrong answer for some reason?")
        disp(abs(gammaTotal).^2 - (1-alpha(i)))
        disp(10.*log10(LoadPower./Pin)-R(i))
    end

    ZGlasses(end+1) = ZGlass;
    gammaGlasses(end+1) = gammaGlass;





end


freq = linspace(125,4000,100);


%% Polynomial Fit
%Carry out the polynomial fit
ZGlassesPoly = polyfit(f,ZGlasses,3);
gammaGlassesPoly = polyfit(f,gammaGlasses,3);

%Evaluate the polynomial fit
ZGlassesPolyVal = polyval(ZGlassesPoly,freq);
gammaGlassesPolyVal = polyval(gammaGlassesPoly,freq);

%% Linear interpolation
%Makes an array with the interpolated results immediately
ZGlassesLinInterp = interp1(f, ZGlasses, freq, 'linear');
gammaGlassesLinInterp = interp1(f, gammaGlasses, freq, 'linear');

%% Spline interpolation
%Makes an array with the interpolated results immediately
ZGlassesSplineInterp = interp1(f, ZGlasses, freq, 'spline');
gammaGlassesSplineInterp = interp1(f, gammaGlasses, freq, 'spline');

%% Uncomment if you want to run on its own

labels = ["FitFreq","ReZGlassPolyFit","ImZGlassPolyFit"...
    ,"RegammaGlassPolyFit","ImgammaGlassPolyFit","ReZGlassLinearFit"...
    ,"ImZGlassLinearFit","RegammaGlassLinearFit","ImgammaGlassLinearFit"...
    ,"ReZGlassSplineFit","ImZGlassSplineFit","RegammaGlassSplineFit"...
    ,"ImgammaGlassSplineFit"];
labels2 =
    ["Frequencies","ReZGlass","ImZGlass","RegammaGlass","ImgammaGlass"];

FittingOptions =
    [freq',real(ZGlassesPolyVal)',imag(ZGlassesPolyVal)'...
    ,real(gammaGlassesPolyVal)',imag(gammaGlassesPolyVal)'...
    ,real(ZGlassesLinInterp)',imag(ZGlassesLinInterp)'...
    ,real(gammaGlassesLinInterp)',imag(gammaGlassesLinInterp)'...
```

```
    ,real(ZGlassesSplineInterp)',imag(ZGlassesSplineInterp)'...
    ,real(gammaGlassesSplineInterp)',imag(gammaGlassesSplineInterp)'];
FittingOptions2 =
    [f',real(ZGlasses)',imag(ZGlasses)',real(gammaGlasses)'...
    ,imag(gammaGlasses)'];

togo = [labels;FittingOptions];
togo2 = [labels2;FittingOptions2];
writematrix(togo,"../../Accoustics/Figures/FittedImpedanceandWave.csv");
writematrix(togo2,"../../Accoustics/Figures/ActualImpedanceandWave.csv");

%% Polyfit comparison
figure(1)
scatter(f, real(ZGlasses))
hold on
plot(freq, real(ZGlassesPolyVal))
legend("Actual Values","Polyval")
hold off
grid
xlabel('Frequency')
ylabel('Real ZGlasses Polyval')

figure(2)
scatter(f, imag(ZGlasses))
hold on
plot(freq, imag(ZGlassesPolyVal))
legend("Actual Values","Polyval")
hold off
grid
xlabel('Frequency')
ylabel('Imag ZGlasses Polyval')

figure(3)
scatter(f, real(gammaGlasses))
hold on
plot(freq, real(gammaGlassesPolyVal))
legend("Actual Values","Polyval")
hold off
grid
xlabel('Frequency')
ylabel('Real gammaGlasses Polyval')

figure(4)
scatter(f, imag(gammaGlasses))
hold on
plot(freq, imag(gammaGlassesPolyVal))
legend("Actual Values","Polyval")
hold off
grid
xlabel('Frequency')
ylabel('Imag gammaGlasses Polyval')
```

```
%% Interp comparison
figure(5)
scatter(f, real(ZGlasses))
hold on
plot(freq, real(ZGlassesInterp))
legend("Actual Values","Interp")
hold off
grid
xlabel('Frequency')
ylabel('Real ZGlasses Interp')

figure(6)
scatter(f, imag(ZGlasses))
hold on
plot(freq, imag(ZGlassesInterp))
legend("Actual Values","Interp")
hold off
grid
xlabel('Frequency')
ylabel('Imag ZGlasses Interp')

figure(7)
scatter(f, real(gammaGlasses))
hold on
plot(freq, real(gammaGlassesInterp))
legend("Actual Values","Interp")
hold off
grid
xlabel('Frequency')
ylabel('Real gammaGlasses Interp')

figure(8)
scatter(f, imag(gammaGlasses))
hold on
plot(freq, imag(gammaGlassesInterp))
legend("Actual Values","Interp")
hold off
grid
xlabel('Frequency')
ylabel('Imag gammaGlasses Interp')
```

B.2.2 Multi-layer Transmission Line

```
% Multi layer Perpendicular Polarization
% Does the actual calculations for the multilayer tranmission line
% Reads in the impedance values from the
% AuralizationEquatingTransmissionLine

%Last Updated Oct 23 - Works well - can do multiple frequencies

```

```
clear;
close all;
clc;

AuralizationEquatingTransmissionLine;

ZGlass =
    [ZGlassesPolyVal',ZGlassesLinInterp',ZGlassesSplineInterp'];
gammaGlass = [gammaGlassesPolyVal',gammaGlassesLinInterp'...
    ,gammaGlassesSplineInterp'];
typeInterpolation = ["polynomial","linear","spline"];

numlayers = 3;
numangles = 1;
numfrequencypoints = 100;
%%
% 0 - Triple Pane: Air
% 1 - Double Pane: Air
% 2 - Single Pane
% 3 - Triple Pane: Argon
% 4 - Double Pane: Argon
windowtype = 2;

%% Values that AuralizationEquatingTransmissionLine produces
% ZGlassesPolyVal
% gammaGlassesPolyVal
% ZGlassesLinInterp
% gammaGlassesLinInterp
% ZGlassesSplineInterp
% gammaGlassesSplineInterp

lengthbetweenpane = [0.003,0.006,0.009,0.03,0.06,0.09,0.3,0.6,0.9];
InterpolationStyles = 3;
for a=1:InterpolationStyles
for q = 1:length(lengthbetweenpane)

    lspacing = lengthbetweenpane(q);
    [freq,w,theta,etaT,nT,Z,l,smallgamma,smallgamma2,del,u,N] = ...
        InitializeVariables(numlayers, numangles,...
        numfrequencypoints,ZGlass(:,a),gammaGlass(:,a),...
        lspacing,windowtype);

    thetaAir = theta(1,:,:);

    %% Rutgers Stuff
    etaT_in = ImpedanceCalculatorRut(etaT,del,numlayers);
    etaT_end = etaT_in(end,:,:);
    etaTAir = etaT(1,:,:);
    gammaT1 = (etaT_end-etaTAir)./(etaT_end+etaTAir);


    %% Transmission Line
```

```
    ZAir = Z(1,:,:);

    Zin = ImpedanceCalculatorTLin(Z,smallgamma,l,numlayers);
    ZinEnd = Zin(end,:,:);

    gammaTotal = (ZinEnd-ZAir)./(ZinEnd+ZAir);

    %% Power

    %% Rutgers Stuff
    E0 = 10;
    E=[];
    H =[];
    Power = [];
    AbsPower = [];

    ETa = E0.*(1+gammaT1);
    HTa = (E0./etaTAir).*(1-gammaT1);
    E = ETa;
    H = HTa;

    Pinc = 1/2.*real(ETa.*conj(HTa)); %1-|gammaT1|^2
    Pins = 1/2.*real(abs(E0).^2./etaTAir);
    Power = Pinc;

    for i = 1:numlayers %Calculate ET2 and ET3
        deli = del(i,:,:);
        etaTi = etaT(i,:,:);
        HTi = H(i,:,:);
        ETi = E(i,:,:);
        ETi_1 = cos(deli).*ETi-1i.*etaTi.*sin(deli).*HTi;
        HTi_1 = -1i.*(1./etaTi).*sin(deli).*ETi+cos(deli).*HTi;
        E(end+1,:,:) = ETi_1;
        H(end+1,:,:) = HTi_1;
        Power(end+1,:,:) = 1/2.*real(ETi_1.*conj(HTi_1));
    end

    InputPower = Pins./Pins;
    TransmittedPower = Power(end,:,:)./Pins;
    ReflectedPower = (Pins - Pinc)./Pins;
    ReflectPower2 = abs(gammaT1).^2;

    % for s = 2:numlayers
    %     AbsPower(end+1,:,:) = Power(s-1,:,:)-Power(s,:,:);
    % end
    AbsPower = Power./Pins;
    TotAbsorbedPower = InputPower-TransmittedPower-ReflectedPower;


    %% Transmission Line Generalized

    V = [];
    I = [];
```

```
    Vs = 10;

    PowerTLin = [];
    AbsPowerTLin = [];

    Va = Vs.*(1+gammaTotal);
    Ia = (Vs./etaTAir).*(1-gammaTotal);
    V = Va;
    I = Ia;

    Pinc = 1/2.*real(Va.*conj(Ia)); %1-|gammaT1|^2
    Pins = 1/2.*real(abs(Vs).^2./etaTAir); %1
    PowerTLin = Pinc;

    for i = 1:numlayers %Calculate ET2 and ET3
        smallgammai = smallgamma(i,:,:).*l(i,:,:)./(1i);
        etaTi = etaT(i,:,:);
        Ii = I(i,:,:);
        Vi = V(i,:,:);
        Vi_1 = cos(smallgammai).*Vi-1i.*etaTi.*sin(smallgammai).*Ii;
        Ii_1 =
            -1i.*(1./etaTi).*sin(smallgammai).*Vi+cos(smallgammai).*Ii;
        V(end+1,:,:) = Vi_1;
        I(end+1,:,:) = Ii_1;
        PowerTLin(end+1,:,:) = 1/2.*real(Vi_1.*conj(Ii_1));
    end

    % for l = 2:numlayers
    %     AbsPowerTLin(end+1,:,:) = Pins-PowerTLin(l,:,:);
    % end

    AbsPowerTLin = PowerTLin./Pins;
    InputPowerTLin = Pins./Pins;
    TransmittedPowerTLin = PowerTLin(end,:,:)./Pins;
    ReflectedPowerTLin = (Pins - Pinc)./Pins;
    TotAbsorbedPowerTLin = InputPowerTLin-TransmittedPowerTLin...
        -ReflectedPowerTLin;

    for f = 1:length(freq)
        disp("Frequency: ")
        disp(freq(f,:))


        disp("Rutgers - Impedance and Reflection")
        disp("Incident Angle, Reflection Coefficient , Input
            Impedance")
        table = [rad2deg(thetaAir(:,:,f))',gammaT1(:,:,f)'...
             ,etaT_end(:,:,f)']

        disp("Transmission Line - Impedance and Reflection")
        disp("Incident Angle , Reflection Coefficient , Input
            Impedance")
        table = [rad2deg(thetaAir(:,:,f))',gammaTotal(:,:,f)'...
```

```
            ,ZinEnd(:,:,f)']

        disp("Rutgers - Normalized")
        disp("Angle,Incident Power,Ref. Power,Transm. Pow, Absorbed")
        table = [rad2deg(thetaAir(:,:,f))',InputPower(:,:,f)'...
            ,ReflectedPower(:,:,f)',TransmittedPower(:,:,f)'...
            ,TotAbsorbedPower(:,:,f)']

        disp("Transmission Line Technique - Generalized")
        disp("Angle,Incident Power,Ref. Power,Transm. Pow, Absorbed")
        table = [rad2deg(thetaAir(:,:,f))',(InputPowerTLin(:,:,f))'...
            ,(ReflectedPowerTLin(:,:,f))',(TransmittedPowerTLin(:,:,f))'...
            , (TotAbsorbedPowerTLin(:,:,f))']

    end

    TPower = real(10.*log10(reshape(TransmittedPower,1,...
        length(TransmittedPower))));
    TPowerTlin = real(10.*log10(reshape(TransmittedPowerTLin,1,...
        length(TransmittedPowerTLin))));
    RPower = real(10.*log10(reshape(ReflectedPower,1,...
        length(ReflectedPower))));
    RPowerTlin = real(10.*log10(reshape(ReflectedPowerTLin,1,...
        length(ReflectedPowerTLin))));
    AbsolutePowerIntermed = real(10.*log10(reshape(AbsPower,...
        size(AbsPower,1),size(AbsPower,3))));
    AbsolutePower = AbsolutePowerIntermed(2:end,:);

    n = 1;
    figure(n)
    plot(freq,(TPower))
    xlabel("Frequencies")
    ylabel("Transmitted Power (dB)")

    n=n+1;
    figure(n)
    plot(freq,(TPowerTlin))
    xlabel("Frequencies")
    ylabel("Transmitted Power (dB)")

    Layer = linspace(1,numlayers,numlayers);
    labels = ["Frequencies","TPower","TPowerTLin","RPower","RPowerTLin"];
    dataWindowModel = [freq,TPower',TPowerTlin',RPower',RPowerTlin'];
    togo = [labels;dataWindowModel];

    frequencylabel = string(freq);

    labels2 = [frequencylabel',"Layer"];
```

```
    dataWindowModel2 = [(AbsolutePower),Layer'];
    togo2 = [labels2;dataWindowModel2];

    switch windowtype
        case 0
            config = "TripleAir";
        case 1
            config = "DoubleAir";
        case 2
            config = "Single";
        case 3
            config = "TripleArgon";
        case 4
            config = "DoubleArgon";
    end

    writematrix(togo,"../../Accoustics/Figures/"+config...
        +typeInterpolation(a)+"Pane3mmGlass"+string(lspacing*1000)...
        +"mmSpace.csv");
    writematrix(togo2,"../../Accoustics/Figures/"+config...
        +typeInterpolation(a)+"PaneAbs3mmGlass"+string(lspacing*1000)...
        +"mmSpace.csv");

end
end

%% Necessary Functions for James Wait Approach

function [Tperp,Rperp,Y] = Coefficient(N,u,l,numLayer)
    Y = ImpedanceCalculatorJW(N,u,l,numLayer);
    tsubcoeff = tCoeffs(N,numLayer);
    d = dval(N,Y,u,l,numLayer);
    expPart = exponential(u,l);

    Tperp = tsubcoeff.*d.*expPart;
    Rperp = (N(end,:,:)-Y(end,:,:))./(N(end,:,:)+Y(end,:,:));
end

function d = dval(N,Y,u,l,numLayer)
    %Note N = [NM,NM_m1,....Nm,...,N0]; N = [N2,N1,N0];
    %Note Y = [YM,....,Y1]; Y = [Y2,Y1];
    d = ones(1,size(N,2));
    for currentlayer = 2:numLayer-1 %Starts at M-1 and ends at m = 1
        Nm_m1 = N(currentlayer+1,:,:);%m-1 is one lower than m
        Nm = N(currentlayer,:,:);
        Ym_1 = Y(currentlayer-1,:,:);%Actually is Ym+1
        u_m = u(currentlayer,:,:);
        l_m = l(currentlayer,:,:);


        dm = ((1-((Nm_m1-Nm)./(Nm_m1+Nm)).*((Ym_1-Nm)./(Ym_1+Nm))...
            .*exp(-2.*u_m.*l_m)));
        d = dm.*d;
```

```
    end
    d = 1./d;
end
%Y = [Y_M_theta1,Y_M_theta2,Y_M_theta3,Y_M_theta4]
%        [Y_m+1_theta1,Y_m+1_theta2,Y_m+1_theta3,Y_m+1_theta4]

function tsubcoeff = tCoeffs(N,numLayer)
    tsubcoeff = ones(1,size(N,2));
    for currentlayer =1:numLayer-1 %Starts at M
        Nm_m1 = N(currentlayer+1,:,:); %m-1 is one lower than m
        Nm = N(currentlayer,:,:);
        t = (2.*Nm_m1)./(Nm+Nm_m1);
        tsubcoeff = tsubcoeff.*t;
    end
end
%Y = [Y_M_theta1,Y_M_theta2,Y_M_theta3,Y_M_theta4]
%        [Y_m+1_theta1,Y_m+1_theta2,Y_m+1_theta3,Y_m+1_theta4]

function expPart = exponential(u,l)
    um_m1 = u(2:end,:,:);
    lm_m1 = l(2:end,:,:);
    expPart = exp(-sum(um_m1.*lm_m1));
end

function Y = ImpedanceCalculatorJW(N,u,l,numLayer)
    Y = [];
    N_M = N(1,:,:);
    Y_M = N_M.*ones(1,size(u,2),size(u,3));
    Y = Y_M;
    for currentlayer = 2:numLayer-1
        u_m = u(currentlayer,:,:);
        l_m = l(currentlayer,:,:);
        N_m = N(currentlayer,:,:); %organized so top is last slab
        Y_m = ImpedanceJW(Y(end,:,:),N_m,u_m,l_m);
        Y(end+1,:,:) = Y_m;
    end

end
%Y = [Y_M_theta1,Y_M_theta2,Y_M_theta3,Y_M_theta4]
%        [Y_m+1_theta1,Y_m+1_theta2,Y_m+1_theta3,Y_m+1_theta4]

function Y_m = ImpedanceJW(Y_m_1,N_m,u_m,l_m)
    Y_m =
        N_m.*(Y_m_1+N_m.*tanh(u_m.*l_m))./(N_m+Y_m_1.*tanh(u_m.*l_m));
end

%% Transmission Line
function Z = ImpedanceCalculatorTLin(Zval,gamma,l,numLayer)
    Z = [];
    Zval_M = Zval(1,:,:);
    Z_M = Zval_M.*ones(1,size(gamma,2),size(gamma,3));
    Z = Z_M;
    for currentlayer = 2:numLayer-1
```

```
        gamma_m = gamma(currentlayer,:,:);
        l_m = l(currentlayer,:,:);
        Zval_m = Zval(currentlayer,:,:); %organized so top is last slab
        Z_m = ImpedanceJW(Z(end,:,:),Zval_m,gamma_m,l_m);
        Z(end+1,:,:) = Z_m;
    end

end


function Z_in = ImpedanceTLin(Z_m_1,Z_m,gamma_m,l_m)
    Z_in = Z_m.*(Z_m_1+Z_m.*tanh(gamma_m.*l_m))./(Z_m+Z_m_1...
        .*tanh(gamma_m.*l_m));
end


%% Rutgers Impedance
function etaT_in = ImpedanceCalculatorRut(etaTval,del,numLayer)
    etaT_in = [];
    etaTval_M = etaTval(1,:,:);
    etaT_M = etaTval_M.*ones(1,size(del,2),size(del,3));
    etaT_in = etaT_M;
    for currentlayer = 2:numLayer-1
        del_m = del(currentlayer,:,:);
        etaTval_m = etaTval(currentlayer,:,:); %organized so top is last slab
        etaT_m = ImpedanceRut(etaT_in(end,:,:),etaTval_m,del_m);
        etaT_in(end+1,:,:) = etaT_m;
    end

end
%Y = [Y_M_theta1,Y_M_theta2,Y_M_theta3,Y_M_theta4]
%       [Y_m+1_theta1,Y_m+1_theta2,Y_m+1_theta3,Y_m+1_theta4]

function etaT = ImpedanceRut(etaT_m_1,etaT_m,del_m)
    etaT = etaT_m.*(etaT_m_1+etaT_m.*tanh(del_m.*1i))...
        ./(etaT_m+etaT_m_1.*tanh(del_m.*1i));
end

%% Declaring Constants

function [freq,w,thetaf,etaTf,nTf,Zf,lf,smallgammaf,smallgamma2f...
    ,delf,uf,Nf] = InitializeVariables(numlayers, numangles, ...
    numfrequencypoints,ZGlasses,gammaGlasses,lspacing,windowtype)
    %% Declaring Constants
    % All variables with an f have multiple frequencies
    thetaf = zeros(numlayers,numangles,numfrequencypoints);
    etaTf = zeros(numlayers,numangles,numfrequencypoints);
    nTf = zeros(numlayers,numangles,numfrequencypoints);
    Zf = zeros(numlayers,numangles,numfrequencypoints);
    lf = zeros(numlayers,1,numfrequencypoints);
    smallgammaf = zeros(numlayers,numangles,numfrequencypoints);
```

```
    smallgamma2f = zeros(numlayers,1,numfrequencypoints);
    delf = zeros(numlayers,numangles,numfrequencypoints);
    uf = zeros(numlayers,numangles,numfrequencypoints);
    Nf = zeros(numlayers,numangles,numfrequencypoints);

    w = zeros(numfrequencypoints,1);
    freq = zeros(numfrequencypoints,1);

    frequencies=linspace(125,4000,numfrequencypoints);

    i = 1;
    for f = 1:length(frequencies)

        w(i,:) = 2.*pi.*frequencies(i);

        c = 343; %In Air m/s
        cglass = 4540;
        cargon = 319; %In Argon at 20c
        rho0 = 1.293;
        rhoArgon = 1.603; %Engineering Toolbox

        lambdaAir = c./frequencies(i);
        lambdaGlass = cglass./frequencies(i);

        %% Transmission Line Calculation
        ZAir = rho0.*c;
        ZGlass = ZGlasses(i);
        ZAir2 = rho0.*c; %rho0.*c;
        ZArgon = rhoArgon.*cargon;

        %k = Beta-1i*alpha
        %ik = gamma = alpha+iBeta
        gammaAir = 1i.*w(i,:)./c;
        gammaGlass = gammaGlasses(i);
        gammaAir2 = 1i.*w(i,:)./c;
        gammaArgon = 1i.*w(i,:)./cargon;

        %% Width of the glass pane
        lglass = 0.003;
%         lglass = 0.09;

        %Length of tranmsission line
        la = 0;
        l1 = lglass;
        lb = lspacing;
        l2 = lglass;
        lc = 0;


        %Propagation Constant
        smallgammaGlass = gammaGlass;
        smallgammaAir = gammaAir;
        smallgammaArgon = gammaArgon;
```

```
        %Phase difference
        delAir = (gammaAir./1i).*lc;
        delGlass = (gammaGlass./1i).*l2;
        delAir2 = (gammaAir./1i).*lb;
        delArgon = (gammaArgon./1i).*lb;
        delGlass2 = (gammaGlass./1i).*l1;
        delAir3 = (gammaAir./1i).*la;

        switch windowtype
            case 0
                etaT = [ZAir;ZGlass;ZAir;ZGlass;ZAir;ZGlass;ZAir];
                Z = etaT;
                l = [lc;l2;lb;l1;lb;l1;la];
                smallgamma = [smallgammaAir;smallgammaGlass;smallgammaAir...
                    ;smallgammaGlass;smallgammaAir;smallgammaGlass...
                    ;smallgammaAir];
                del = [delAir;delGlass;delAir2;delGlass2;delAir2;delGlass2;delAir3];
            case 1
                etaT = [ZAir;ZGlass;ZAir;ZGlass;ZAir]; %Double Pane Air Gap
                Z = etaT;
                l = [lc;l2;lb;l1;la]; %Double Pane Air Gap
                smallgamma = [smallgammaAir;smallgammaGlass;smallgammaAir...
                    ;smallgammaGlass;smallgammaAir]; %Double Pane Air Gap
                del = [delAir;delGlass;delAir2;delGlass2;delAir3];
            case 2
                etaT = [ZAir;ZGlass;ZAir]; %Single Pane
                Z = etaT;
                l = [lc;l2;lb]; %Single Pane
                smallgamma = [smallgammaAir;smallgammaGlass...
                    ;smallgammaAir]; %Single Pane
                del = [delAir;delGlass;delAir2];
            case 3
                etaT = [ZAir;ZGlass;ZArgon;ZGlass;ZArgon;ZGlass...
                    ;ZAir]; %Triple Pane Argon
                Z = etaT;
                l = [lc;l2;lb;l1;lb;l1;la]; %Triple Pane Argon
                smallgamma = [smallgammaAir;smallgammaGlass...
                    ;smallgammaArgon;smallgammaGlass;smallgammaArgon...
                    ;smallgammaGlass;smallgammaAir]; %Triple Pane Argon
                del = [delAir;delGlass;delArgon;delGlass2...
                    ;delArgon;delGlass2;delAir3];
            case 4
                etaT = [ZAir;ZGlass;ZArgon;ZGlass;ZAir]; %Double Pane Argon
                Z = etaT;
                l = [lc;l2;lb;l1;la]; %Double Pane Argon
```

```
                  smallgamma = [smallgammaAir;smallgammaGlass...
                      ;smallgammaArgon;smallgammaGlass;smallgammaAir];
                  del = [delAir;delGlass;delArgon;delGlass2;delAir3];
         end

         etaTf(:,:,i) = etaT;
         Zf(:,:,i) = Z;
         lf(:,:,i) = l;
         smallgammaf(:,:,i) = smallgamma;
         delf(:,:,i) = del;

         freq(i,:) = frequencies(i);
         i = i+1;

     end
end
```