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CHARACTERIZATION OF HARBOR ENVIRONMENTS USING PASSIVE ACOUSTIC MEANS

by

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The use of active sonar to map shallow water environments is a common practice; however, it is not always practical or possible to use. Active sonar is not covert, and it exposes marine life to high intensity sound. The use of passive sonar to characterize subsurface harbor environments allows for increased maritime domain awareness with a smaller acoustic signature, favorable for environmentally sensitive and restricted environments. Previously, passive sonar has been successfully used to gain information about the subsurface environment. Successful studies determining bottom composition and sediment layering have been conducted, providing a quantifiable metric of the similarities between post-processed passive and active sonar data, demonstrating the utility of collecting and processing ambient noise within the water column. This study explores the feasibility of expanding the use of passive sonar methods to determine geometric information in harbor environments, characterized by multiple vertical boundaries. Using a three-dimensional ray acoustic model coupled with field work in Santa Cruz Harbor, the paths available for acoustic arrays were explored to determine the amount of information that can be gathered passively in this type of environment.

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CHARACTERIZATION OF HARBOR ENVIRONMENTS USING PASSIVE ACOUSTIC MEANS

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TABLE OF CONTENTS

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LIST OF FIGURES

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I. INTRODUCTION

Acoustic sensing technology has been used for decades across a wide variety of applications (Urick 1983). From military operational uses to commercial fishing applications, the utilization of the properties of sound propagation underwater has helped mankind characterize and understand what lays beneath the surface of the world's oceans (Urick 1983). The field of underwater acoustics is divided into two main branches, active and passive acoustics (Urick 1983). Active sonar systems are commonly used for hydrographic surveys, and bathymetric side scan sonar and multibeam sonar are common system for this application. They are currently used on autonomous underwater vehicles (AUVs), or can be hull-mounted on vessels. Using active techniques involves emitting sound signals into the water column and measuring the strength of the echo, or return of the signal from a target or the environment (Halmai 2020). Sensing techniques using active sonar have advantages over passive, including the ability to provide high fidelity imaging of the subsurface environment (via time-of-flight information) and the ability to provide a large degree of control over the measurement through emitting and directing the source signal, rather than simply using signals of opportunity (Kamal 2021). These advantages are also met with downfalls. Current survey methods for littoral environments typically require a large footprint of personnel, as well as equipment (Halmai 2020). The acoustic footprint of the source can result in a lack of stealth and potential harmful environmental impacts to organisms within the water column (Kamal 2021). Considerations regarding gaining approval from local leaders and environmental authorities to place active, sound emitting, sensors in territorial waters must also be considered.

The ability to characterize the subsurface environment of shallow water, complex environments, such as a harbor, is an important tool for both military and civil applications. Shallow water environments are highly dynamic. They are affected by human influences, such as vessel traffic, the construction of seawalls and jetties, as well as natural environmental influences (extreme weather, river runoff, changing water levels due to drought or heavy rainfall) (Halmai 2020). The shallow water environment changes on a time scale that is much faster than open ocean deep water environments. Tidal fluctuations happen multiple times a day in most regions, changing water depth drastically over a period of hours. Shallow water temperature also changes much more rapidly than open ocean water columns, solar heating is more effective on shallow bodies of water, due to the smaller thermal mass (Talley et al. 2011). These environments are also are subject to higher and more rapid salinity variations due to freshwater influx in estuarine environments or evaporation due to dry and or hot atmospheric conditions. Each of these environmental parameters affect acoustic measurements, both by complicating propagation dynamics and raising noise levels.

According to a report written by the U.S. Navy's amphibious capabilities working group on the 21st Century strategic amphibious mission and vision, shallow water environments are also tactically relevant for maritime and amphibious military forces because the coastline serves as the bridge of Naval power projection from ship to shore. The combination of the dynamic nature of the environment coupled with the operational need to understand what is happening within results in a need for a method of collecting subsea environmental information that is quicker, easier, and with less footprint than current surveying methods.

The ability to passively sense geometric information about a subsurface environment, including the location of vertical boundaries, would greatly reduce the acoustic footprint of a littoral survey team. Passive sensing could also reduce risk to environmentally sensitive organisms and provide a cost-effective tool to verify information about a littoral environment that cannot be gained by remote-sensing means.

The ultimate goals of this thesis were to construct a realistic propagation model and conduct real world measurements of signals of interest by a vector sensor in a harbor environment to characterize the behavior of acoustic propagation in harbor environments, with a focus on the multipath properties. These are the necessary first steps to lay the foundation for further research in order to eventually remotely sense geometric information about a harbor via passive acoustic means. To accomplish these goals, three main lines of effort were conducted. First, a three-dimensional model of Santa Cruz Harbor was generated. This model was ingested into Bellhop-3D, an acoustic propagation model written in FORTRAN, to simulate different frequencies of interest and their potential propagation paths within a local, harbor.

The next line of effort was fieldwork was conducted within Santa Cruz Harbor using passive sensors in different frequency ranges to analyze and understand real world data and support future model refinement and verification. High and low frequencies were used in order to discern what information could be gained from each. The low frequency receiver used was a vector sensor. Vector sensors are passive, directional, and can sense signal strength and the direction (angle) from which it came. The source for low frequency was the inboard motor of a sailboat. The high frequency passive receiver was an autonomously recording hydrophone manufactured by Ocean Sonics with the high frequency source being an autonomous battery powered source manufactured by Ocean Sonics, but was ultimately not used due to problems with the source.

This thesis is organized as follows. Chapter II contains background information on foundational research associated with the goals in this thesis. In Chapter III, an overview of acoustic modeling and results s discussed. In Chapter IV, an explanation of fieldwork and post processing of the data collected is discussed. In Chapter V, the results from all data analysis are discussed.

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II. BACKGROUND

Passive acoustic sensing has been used scientifically since the invention of the first hydrophones in the early 1900s (Muir 2015). The initial primary use of passive acoustic sensing was focused on marine mammal researching, using passive hydrophones to sense and track dolphin and whale species (Muir 2015). The use of passive acoustics for military applications drastically increased during World War II, where it played a critical role in naval operations, allowing submarines to locate and track enemy ships by using the sound of adversary's propulsion systems (Kamal 2021).

A. VECTOR SENSORS

Vector sensors differ from traditional hydrophones by measuring particle motion in addition to pressure changes associated from a sound wave (Scowcroft et al. 2021). Vector sensors contain an omnidirectional hydrophone coupled with sensors that measure quantities that are related to particle velocity. A common implementation is the use of three uni-axial accelerometers mounted orthogonally, which allow for particle motion to be sensed in addition to the pressure wave from a source (Shipps and Abraham 2004). Being able to sense acoustic particle intensity allows the direction of acoustic particle velocity to be determined in addition to the pressure.

To illustrate this ability, consider a plane wave travelling in the direction $\hat{k}$ and angular frequency ω. The acoustic pressure as a function of time and space is given by the formula

$$p = p_0 e^{i(\hat{k}\cdot\vec{r}-\omega t)}, \tag{1}$$

where $p_0$is the pressure amplitude, $\vec{r}$ is the position vector is the angular velocity, and t is time. The acoustic particle velocity of this wave can be calculated using the linearized Euler equation (Kinsler et al. 1982) and results in

$$\vec{u} = \hat{k}\frac{p_0}{p_0 c} e^{i(\vec{k}\cdot\vec{r}-\omega t)}. \tag{2}$$

In the above equations, c is the speed of sound propagation, given by the formula

$$c = 1402.7 + 488T_1 - 482T_1^2 + 135{T_1}^3 + (15.9 + 2.8T_1 + 2.4{T_1}^2)(\frac{\mathcal{P}_G}{100}) \qquad (3)$$

where $\mathcal{P}_G$ is the gauge (hydrostatic) pressure in bar, and T_1 is given by the formula

$$T_1 = \frac{T}{100}, \qquad (4)$$

where T is temperature in degrees Celsius. The average vector intensity of this wave is given by the integral

$$\vec{\bar{I}} = \frac{1}{T}\int_0^T p\vec{u}\,dt, \qquad (5)$$

where $\vec{I}$ is the average vector intensity, T is the period of the wave, p is acoustic pressure, and $\vec{u}$ is the velocity of the wave. Note that this is the average vector intensity, and the averaging time is greater than the period of the wave. The integration of equation (2) yields

$$\vec{\bar{I}} = \hat{k}d\,\frac{{p_0}^2}{p_0 c}, \qquad (6)$$

qhere $\vec{\bar{I}}$ is the average vector intensity, $\hat{k}$ is the directional component, $p_0$is the pressure amplitude, and c is the speed of sound propagation. This relationship lets the vector sensor measure direction using the $\hat{k}$ component, as well as the magnitude of sound waves. The bearing angle, θ, of this vector is calculated by the inverse tangent of the ratio of the x and y components of intensity, as seen in equation (4).

$$\theta = tan^{-1}\left(\frac{\bar{I}_y}{\bar{I}_x}\right) \qquad (7)$$

The velocity sensors within the vector sensor used in this research have a dipole response, and thus have a 180 degree ambiguity themselves. The phase relationship between pressure a velocity resolves this ambiguity in the calculation of intensity. These relationships will be used later in Chapter IV of this thesis.

Previous vector sensor research on source localization has to date focused on long range, low frequency applications. Vector sensors have been used to successfully track ships (Sheeler 2020) in deep water environments. Sheeler's thesis explains the advantages of vector sensor use over arrays of omnidirectional hydrophones. A single vector sensor can accomplish what a spatially extended array of multiple hydrophones can accomplish with the similar accuracy (Sheeler 2020).

The ability to detect directionality of incoming waves via measuring the intensity is a critical capability in acoustic monitoring. A study conducted by Smith and others explains how vector sensors provided critical information regarding the change in the Monterey Bay underwater soundscape before and during COVID-19 (Smith et al. 2022). This study showed that shipping noise levels in the water column did not decrease as much as anticipated in the wake of COVID-19 shutdowns. Rather than the hypothesized decrease in manmade noise within the soundscape, there was no significant decrease in sound, however there was a change in location of sound sources: rather than shipping noise from transiting ships, there was noise from ships idling off the coast waiting for clearance into port (Smith et al. 2022).

The use of vector sensors to fulfill the critical capability of detecting directionality has been proven and well-studied in open ocean and minimally constrained environments, however there is a lack of data and analysis on the effectiveness and utility of theses sensors in shallow, vertically constrained environments. If vector sensors are proven capable of determining directionality in shallow water harbor environments, it will greatly advance the ability to understand and characterize littoral environments via passive acoustic means. The ability to use a directional sensor to validate propagation paths in a novel environment can provide acoustic model enhancement and increase our overall understanding of shallow water acoustic propagation.

B. ACOUSTIC MODELING

In the latter half of the twentieth century, advances in technology and computing power allowing digital signal processing and the utilization of computer algorithms, revolutionized the field of passive acoustic sensing. These technological tools allowed scientists and researchers to process and analyze large amounts of acoustic data, leading to new insights into the underwater environment and the behavior of marine mammals. A study in 1995 by Davis and Pitre capitalized on advanced computational resources for processing underwater acoustic data. They conducted model simulations attempting to localize an acoustic source at low frequency in a shallow water environment (Davis 1995). This study was partially successful. Even under low signal to noise ratio conditions, they were not able to accurately determine a source location, however they were able to extract enough information from initial model simulations to provide useful input for subsequent iterations (Davis 1995). This study was also useful in determining the benefit of multiple dispersed hydrophone placement for sensor localization, reducing the need for explicit beamforming and frequency combinations in sensor localization attempts (Davis 1995).

In 2006, Tiemann and others successfully demonstrated the ability to track sperm whales using real data from one or two hydrophones off of Southeast Alaska (Tiemann et. al 2006). By taking advantage of multipath propagation and diverse bottom composition and bathymetry, researchers were able to generate three verifiable sperm whale tracks from stationary hydrophones. To accomplish this, comparisons between received acoustic arrival patterns and modeled arrival pattern were made.

One of the dominant methods for processing acoustic data where source and receiver are in close proximity and accuracy in processing is critical, such as a shallow water environment, is matched filtering (Bucker 1976). Matched filtering is a method of data processing that involves correlation between data received by a sensor and a generated replica of the original signal (Baggeroer 1993). There are various methods to apply matched filters, including conventional matched field processing (Baggeroer 1993; Jensen, 2011) and frequency-difference matched field processing (Worthmann, 2015). MFP takes advantage of acoustic field complexities and allows for exploitation of complicated ocean environments that is not possible using traditional plane-wave based algorithms (Baggeroer 1993). A study in 2006 by Thode and others successfully used time differences between various arrival paths of acoustic signal to multiple subarrays on a towed four element hydrophone to fix the location of an impulsive sound. The location of a source was able to be determined when the time differences were compared with predicted time difference tables generated by using numerical modeling.

A significantly studied and used technique in recent years for passive acoustic sensing is passive acoustic tomography (PAT). PAT is a technique to reconstruct the spatial distribution of acoustic sources in an underwater environment. It is a branch of the field of acoustic tomography in which active sources at known locations are used to estimate the salinity and temperature of the ocean by analyzing the time delay between source and receiver (Woolfe 2015). In contrast, PAT involves measuring sound fields with a distributed array of acoustic receivers at known locations in order to estimate position and characteristics of sound sources within the water column (Godin 2012). The method of gathering this information from received signals is completed by solving an inverse problem and reverse engineering source locations. A recent paper by Kubicko in 2016 provides an overview of the mathematic and computational methods using in PAT while discussing some of the challenges involved.

Applications of PAT vary from localization of marine animals (Gervaise 2007) to monitoring underwater noise aiding in the ability to detect the presence of submarines in shallow waters (Li 2019). PAT has many potential applications but has significant challenges involved in its utility as well. PAT relies on ambient noise within the water column, if operating in a high noise environment, such as a shallow water region in the vicinity of high winds and waves, the broadband spectrum of noise within the water column can drown out signals of interest (Li 2019). There are also computational challenges due to the complexity of data processing, limiting scalability of this technique (Kubicko 2016).

There are many passive acoustic techniques used to characterize the physical environment. They usually rely on some sort of acoustic modeling to compare measurements with, and obtain location information from the source, usually using the multipath structure of the various sound channels of the ocean. However, passive techniques are most well studied and understood in open ocean environments. Constrained environments with many vertical boundaries are incredibly challenging to model and predict, the goal of this thesis is to lay foundational work to improve shallow water passive acoustic sensing.

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III. ACOUSTIC MODELING

A. MODEL DEVELOPMENT

In an attempt to understand the behavior of acoustic propagation as a source transited within a shallow water environment, a model was developed to simulate this concept. The model was developed after Santa Cruz harbor in order to foster the eventual comparison of real-world data vs. model acoustic propagation data. In order to create as accurate of a model of the harbor as possible, polygons were created using Google Earth, representing the shape of the harbor. Figure 1 shows the polygon generated for the model overlayed on the google earth output of Santa Cruz harbor. The coastline was extended approximately 1000m from either side of the mouth of the harbor. Of note, the docks within Santa Cruz harbor were not included in the model environment because they are floating docks, not solid vertical boundaries in the water column.

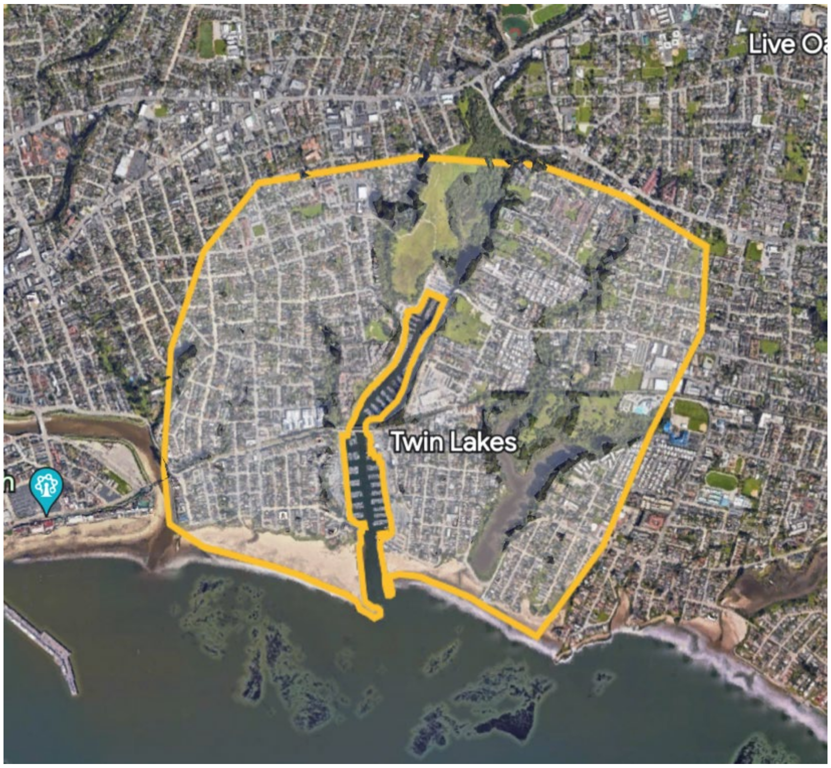

Figure 1. Google Earth depiction of polygon created for Santa Cruz Harbor acoustic modeling

Once this polygon was created, it was the vertices loaded into MATLAB where a grid was generated and overlayed on top of the polygon. Every point on the grid was given a value based on whether it was inside of the polygon generated or outside. The interior of the polygon represented land and was given a depth of -1m, every other point lying outside of the polygon was initially given a depth of 10m (in the model, negative depth values correlate to above sea level, indicating land). Figure 2 shows the initial environment generated for modeling purposes, the yellow areas indicated 10m water depth, and the purple area indicating land. The labels on the x and y axes are northings and eastings in meters from the center of the polygon used to create this environment.

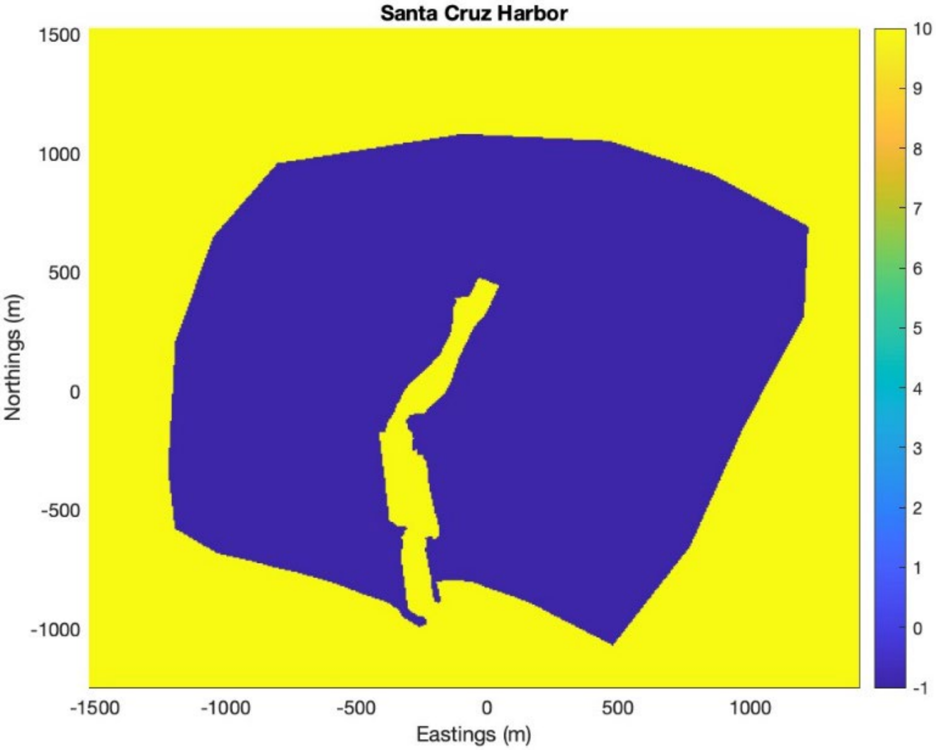

Figure 2. Initial model environment generated of Santa Cruz Harbor

Although this initial model of Santa Cruz harbor had correct placement of vertical boundaries, there was an unrealistic sharp change in bathymetry. All vertical boundaries had no slope between the harbor floor and the sides of the harbor, resulting in unrealistic boundary reflections at 90 degree corners. In an effort to make the environment more similar to real-world conditions, a gradient was implemented in the bathymetry grid at the vertical boundaries, effectively making the vertical boundaries rounded rather than sharp corners. Figure 3 shows an image of the upper harbor with the sloped bathymetry at vertical boundaries within the harbor.

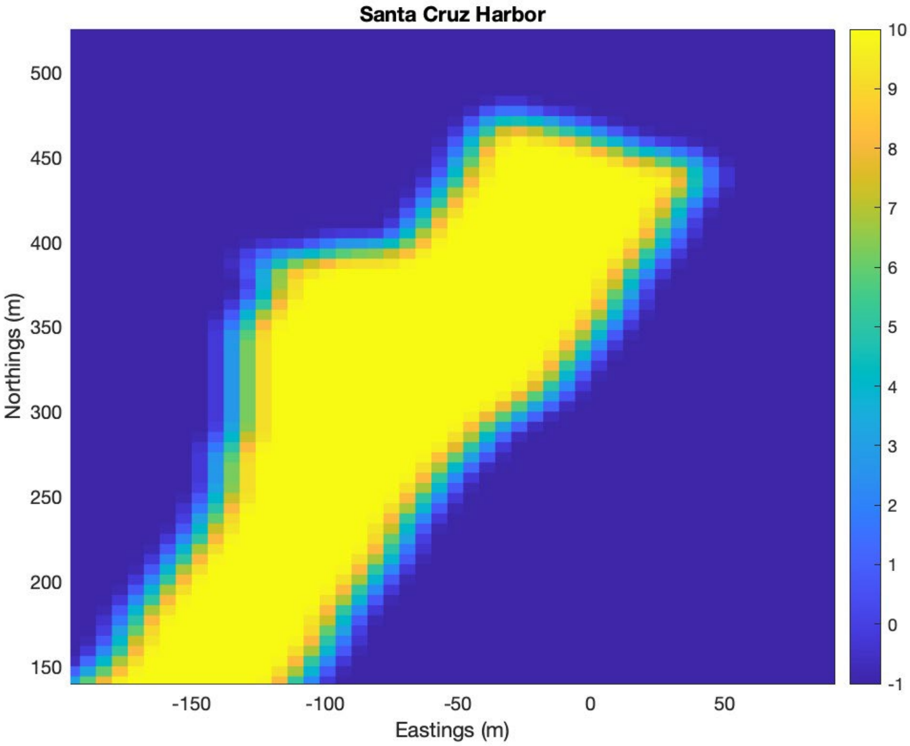

Figure 3. Upper Santa Cruz Harbor with sloping vertical boundaries

To determine what information can be gained from a source of opportunity in a harbor, a simulated ship track was generated and overlayed on the model of Santa Cruz harbor. This track was placed in the center of the northern portion of the harbor, simulating a channel transit, with the boat traveling from North to South. A planar array of 65 simulated hydrophones was also placed in the harbor environment to determine what a passive sensor can exploit from signals of interest generated from a source. The array was placed within upper Santa Cruz harbor. Figure 4 shows the location of the ship track and sensor array. The ship track is the red line, the sensor array is the cluster of stars. The ship track generated is 515m long. For tracking and analysis purposes, 200 source position indices equally spaced along the ship track, 2.57m apart, were used to mark ship positions of interest.

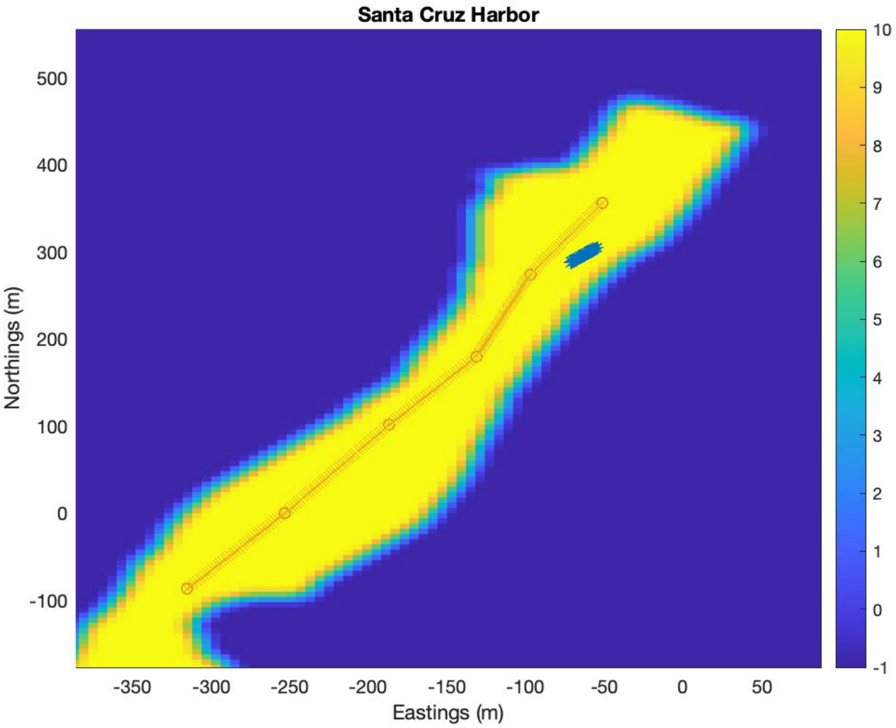

Figure 4. Ship track and planar array location in modeled Santa Cruz Harbor

B. MODEL ANALYSIS AND RESULTS

The simulated ship transit was conducted with a source frequency of 10 kHz,and was assumed to be perfectly coherent. This assumption was not completely realistic, but provided the best possible conditions for observing multipath. Acoustic signals received by the array were beamformed to estimate a bearing of source noise from the receiver. Beamforming was completed by defining angles spanning +/- 90 degrees with 1 degree of spacing. The phases of a plane wave traveling in each direction between each element were then computed. Then, a complex exponential using the computed phases was multiplied with the complex pressure from each element within the array. After this, the weighted hydrophone elements were summed and then squared to produce a value that was proportional to the received intensity in that particular direction. Outputs of beamformed data are shown in Figure 5. Notably there is a peak intensity with a discernable bearing of +15 degrees at source position indices 18–40. There are areas of intensity within the first 60 source position indices that are less strong and less organized, with little to no intensity beyond source position 60.

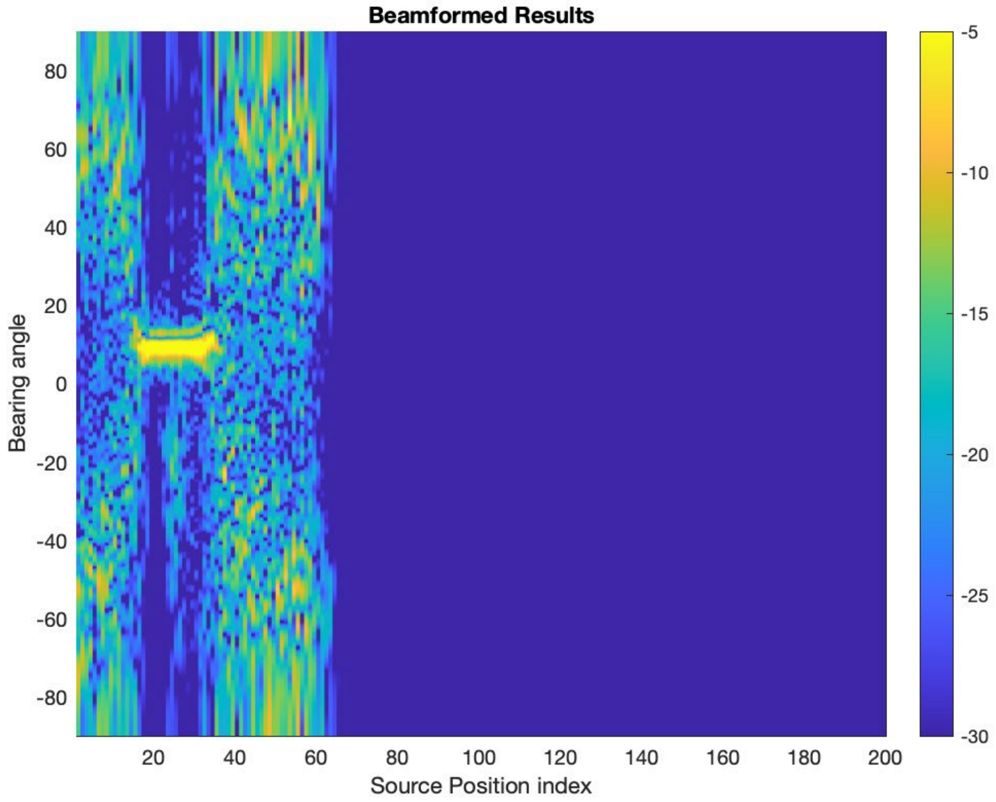

Figure 5. Beamformed results show intensity from ship track simulation in Santa Cruz Harbor

The beamformed data was then normalized in an attempt to see any additional information outside the point of closest approach. This data is visible in Figure 6. The same range of source position indices show peak intensity at a bearing angle of +15 degrees.

There is also intensity data visible beyond source position 60, however it is chaotic, with the maximum intensity exhibiting wild fluctuations as a function of source position.

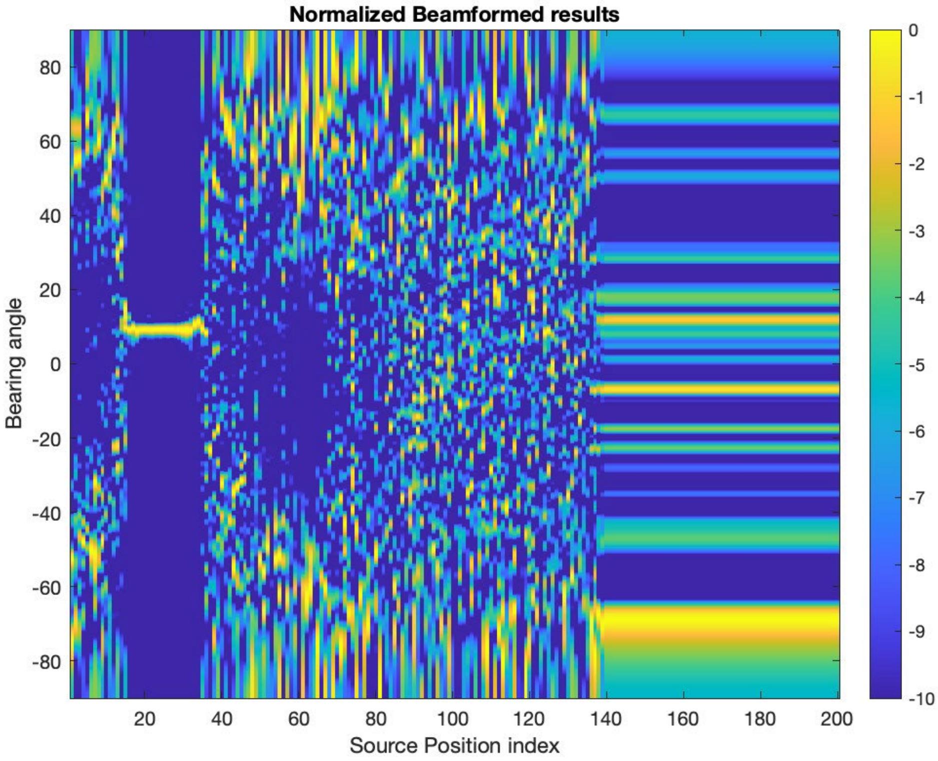

Figure 6. Beamformed results show intensity from ship track simulation in Santa Cruz Harbor

When comparing the identifiable peak intensity source position indices with the ship track, it is evident that source positions 18–40 are the positions where the source is closest to the receiver. Due to the proximity between source and receiver, it can be inferred that when in the vicinity of direct path propagation, source bearing can be resolved. Figure 7 shows a graph depicting source position indices and range from source to receiver at each point on the simulated track. As previously stated, positions 18–40 lie in the vicinity of source closest point of approach to the receivers. Figure 8 provides an overview with source position indices that correlate with peak intensity highlighted along the ship track.

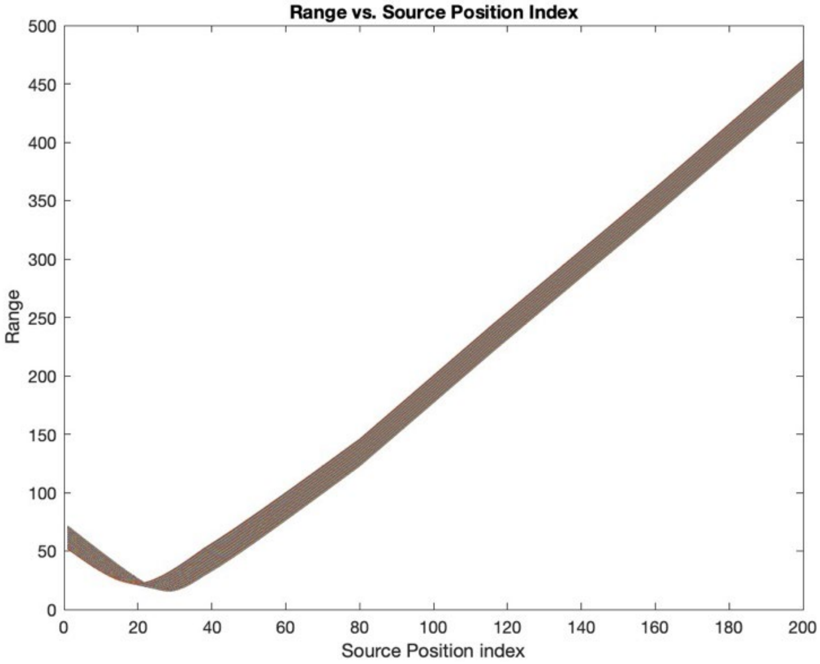

Figure 7. Range in meters from source to receiver along simulated transit

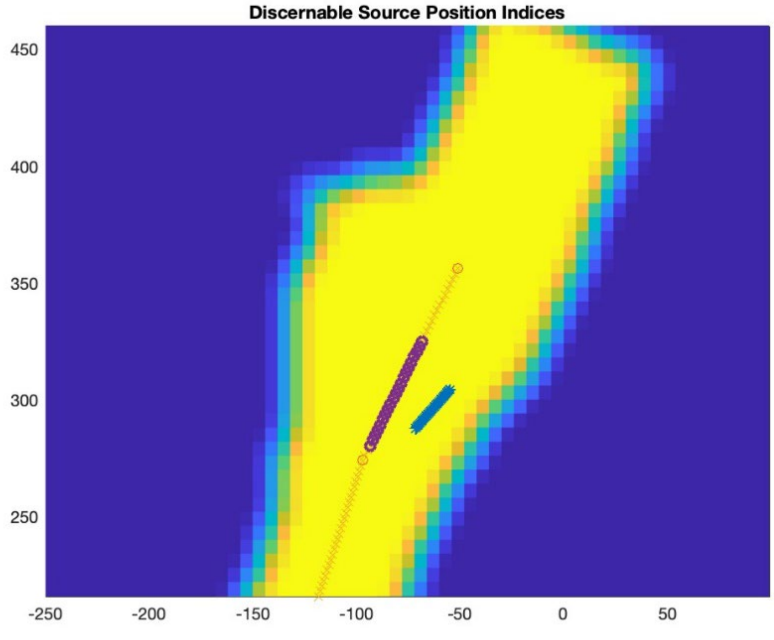

Figure 8. Source position indices that showed a peak intensity at a resolvable bearing

The ability to resolve a bearing of the source is possible within the vicinity of direct path propagation. As range from source to receiver increased, the shallow, boundary filled environment of the harbor most likely causes propagation to quickly shift from direct path to multipath. Evident in source position indices 1–18 and 40–200, multipath propagation appears to be dominant in this environment, making tracking a source very difficult due to the multiple local maxima that appear. To estimate geometrical information about the environment, a dominant direct path signal, with lower amplitude multipath arrivals is ideal. With no discernable maximum, disambiguating the direct path with multipath arrivals is quite difficult.

IV. SANTA CRUZ HARBOR FIELDWORK

A. FIELDWORK DESIGN

Field work was conducted in Santa Cruz Harbor. Attempts were made to use conduct simultaneous high frequency (10-20kHz) and low frequency (100-1000Hz) field work, however equipment issues arose, which resulted in utilizing solely low frequency sensors. The source used was the propulsion noise of a sailboat under power (this thesis focused on frequencies between 500 and 600Hz for data processing), and the receiver used was a M612-100 particle motion sensor bottom mounted system, manufactured by GeoSpectrum Technologies Incorporated (GTI). This vector sensor is composed of multiple subsystems mounted on the same frame, including the M20-105 particle motion sensor, a datalogger, a battery case, and a one-way acoustic link. Figure 9 shows the vector sensor instrument.

Figure 9. M612-100 particle motion sensor bottom mounted system used as low frequency receiver

The frequency range of the M612-100 is 10Hz-3kHz, with a maximum operating depth of 600 meters. The data storage capacity is 256GB with 12 days of continuous recording capability. The M20-105 can be seen hanging from the top of the system frame by a braided rope, which ensures the sensor is freely compliant with the fluid medium. This particle motion sensor utilizes three orthogonal directional channels of accelerometer dipole sensors coupled with an omni-directional acoustic pressure sensor (Sheeler 2020). This sensor measures acoustic pressure and particle acceleration directly.

Figure 10 depicts an overview of the scheme of maneuver conducted for this research. The blue star indicates the location where the vector sensor was placed, and the red arrows show the path of the boat during the experiment. After the vector sensor was placed on the harbor floor, the sailboat left the dock and conducted multiple transits up and down the harbor, resulting in multiple passes to the North and South of the vector sensor. Specific times of interest were logged, such as underway time, turnaround points and closest point of approach to the receiver, as well as any additional vessel traffic transiting the harbor.

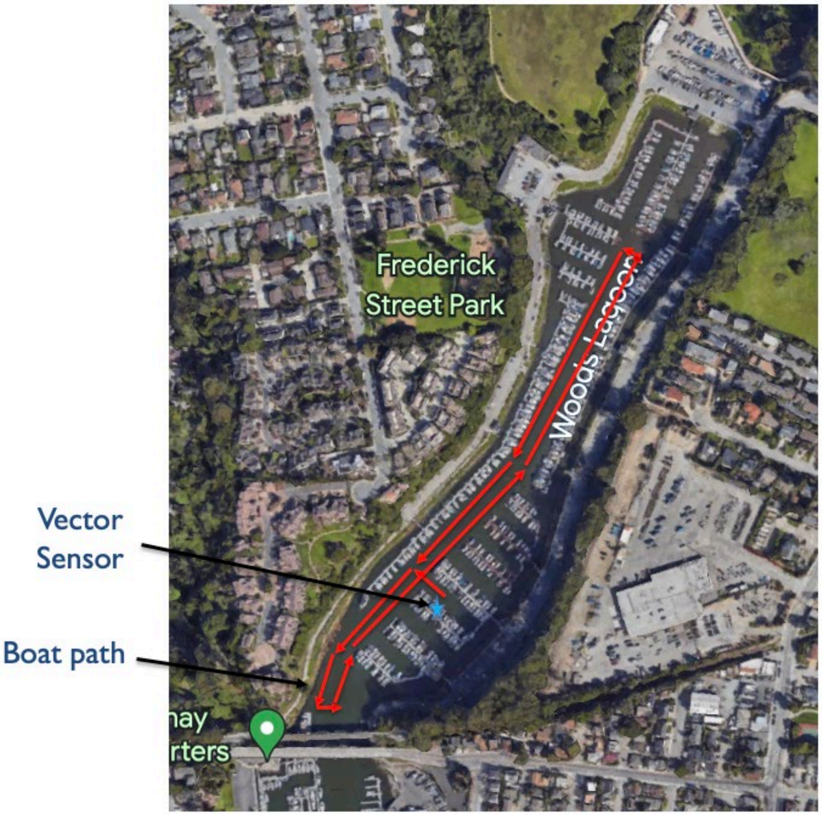

Figure 10. Scheme of maneuver for fieldwork in Santa Cruz Harbor

B. FIELDWORK DATA ANALYSIS AND RESULTS

Once data was offloaded from the vector sensor, it was post processed. To do this, the previously mentioned method of calculating the instantaneous intensity was completed, resulting in the real part of the acoustic pressure being determined and from that, the direction of arrival of a signal of interest. Figure 11 depicts the visual output from data processing. The top image is a spectrogram of pressure received by the vector sensor throughout the full two hours of field work. The bottom image is a bearing spectrogram, showing the bearing of the dominant frequency received for each time and frequency bin during the entire duration of the experiment. These bearings were calculated using equations (5), (6), and (7).

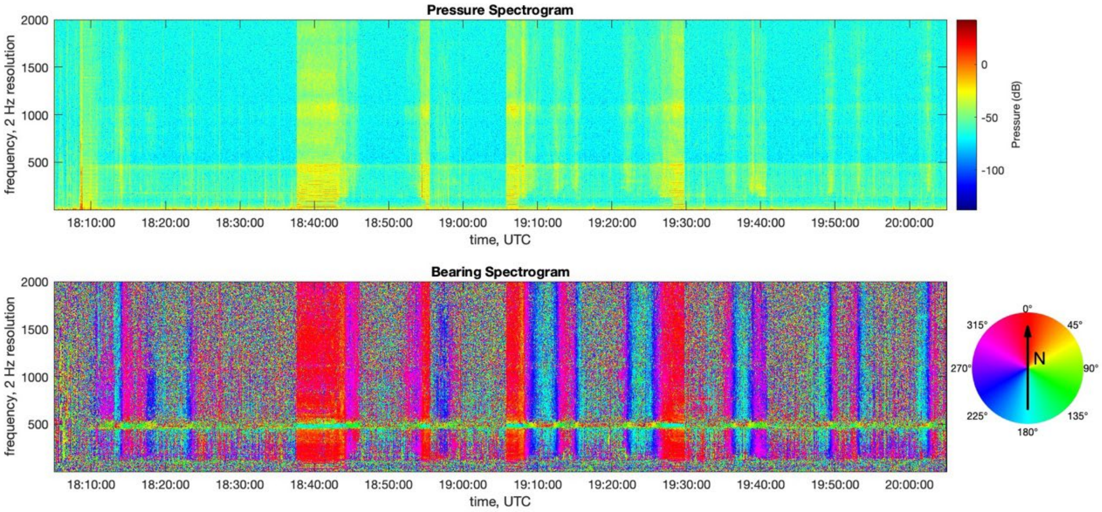

Figure 11. Pressure and bearing spectrograms generated from fieldwork data processing

Figure 12 shows the pressure and bearing spectrograms of this period of time, annotated with the known boat movements. When cross referenced with known boat movements during field work, trends in bearing and pressure changes that correlate with these movements are observable. Of note, the dominant bearing displayed in the bearing spectrogram spans a large bandwidth (100Hz-2kHz), rather than at a specific frequency.

There was a constant 500Hz tone from the same direction during the entire experiment, indicating a possible source of electrical noise from within the harbor.

For analysis purposes, a smaller time window within the experiment is shown in Figure 12. During this period of time, the boat engine started, the boat conducted a transit to the South, completed one full pass of the harbor going from the southernmost point to the furthest north and back, prior to returning back to the slip. As the boat got underway and transited from the dock to the channel, it was moving in a WSW direction before turning South. These direction changes are visible in the bearing spectrogram.

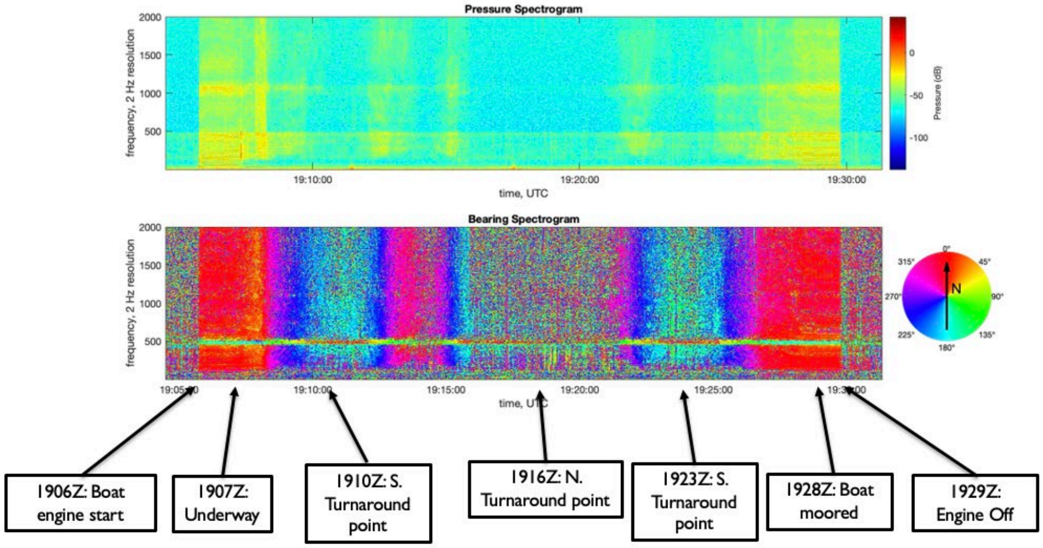

Figure 12. Annotated pressure and bearing spectrograms from transit during fieldwork

When analyzing the annotated spectrograms above, a resolvable bearing is visible at the southern turnaround point, but not at the northern turnaround point. When looking at the experiment overview, the southern point is closer to the location of the vector than the northern point is. The most likely cause for the bearing ambiguity in the northern portion of the transit is due to the loss of direct path propagation and increased reliance on multipath propagation to hear the source.

Figure 13 shows an alternative view of the received intensity bearing during the same time window subset of fieldwork. This image is a graph of bearing of the horizontal acoustic intensity magnitude over a time period of 30 minutes. For data comparison purposes with past research, data in a 100Hz bandwidth from 600–700Hz is depicted. This frequency range provide a relatively high signal to noise ratio and provided consistent bearings throughout the data collection period. In this image, bearing changes as the boat transits north and south are visible, however there is large spread of bearing angles. This spread fluctuates in intensity and location. From this it can be seen that the source bearing is changing, however further data analysis may have to be done to determine exact direction with enough fidelity for navigation or mapping purposes. This is also most likely due to the complex propagation properties of a harbor environment, where even when source and receiver are in close proximity, multipath cannot be ignored.

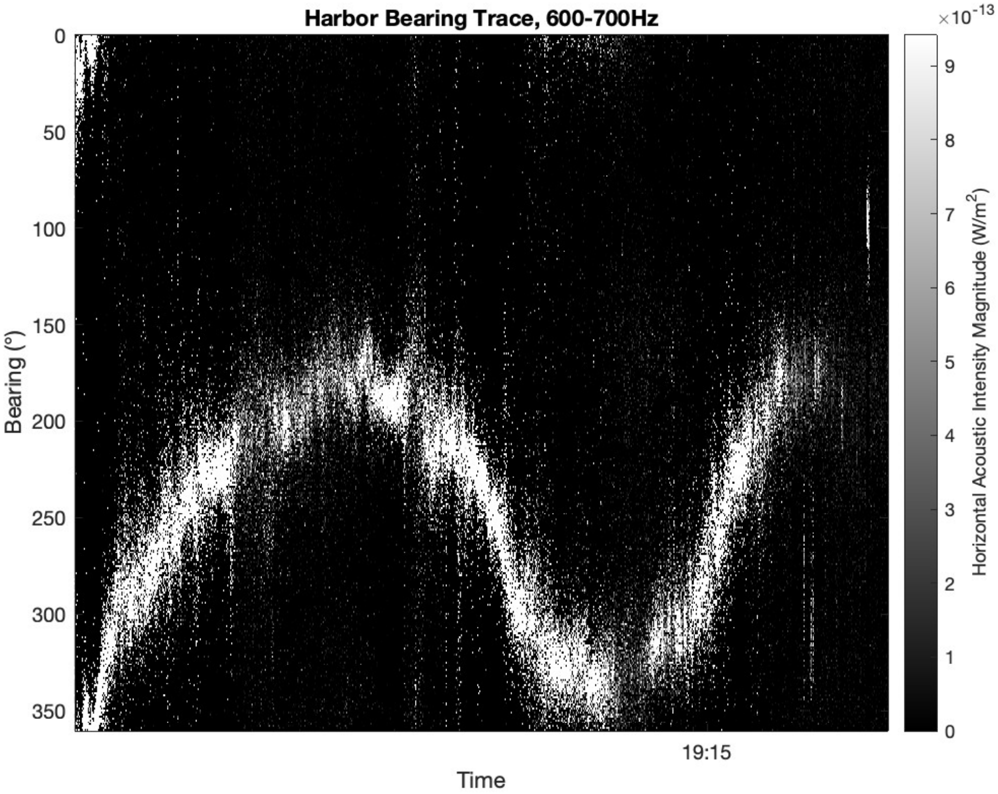

Figure 13. Intensity in each bearing bin for each snapshot in time during the boat transit

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V. DISCUSSION AND CONCLUSION

A. MODELING

Developing a model of a harbor environment to study acoustic behavior is an extremely useful tool. The ability to provide a visual summary of what is happening within the environment helps to conceptualize the complexity of the acoustic soundscape. Harbor environments are incredibly complicated, and creating a realistic model that is accurate is imperative to properly model what is happening acoustically within the water column. The importance of vertical boundaries cannot be ignored, as well as the varying depth and often obscure shapes of basins. Figure 14 shows a visual example of a three- dimensional ray trace simulation within the Santa Cruz harbor done in Bellhop-3D. This image shows only 8 radial directions of sound propagation and shows the complexity of the propagation paths. From this output, the importance of understanding multipath propagation is highlighted – ray paths are complex and travel at many different directions throughout the harbor. The amount of reflections occurring in an enclosed basin indicate that regardless of source or receiver position, the ability to understand multipath propagation is necessary to exploit information about the environment via passive means.

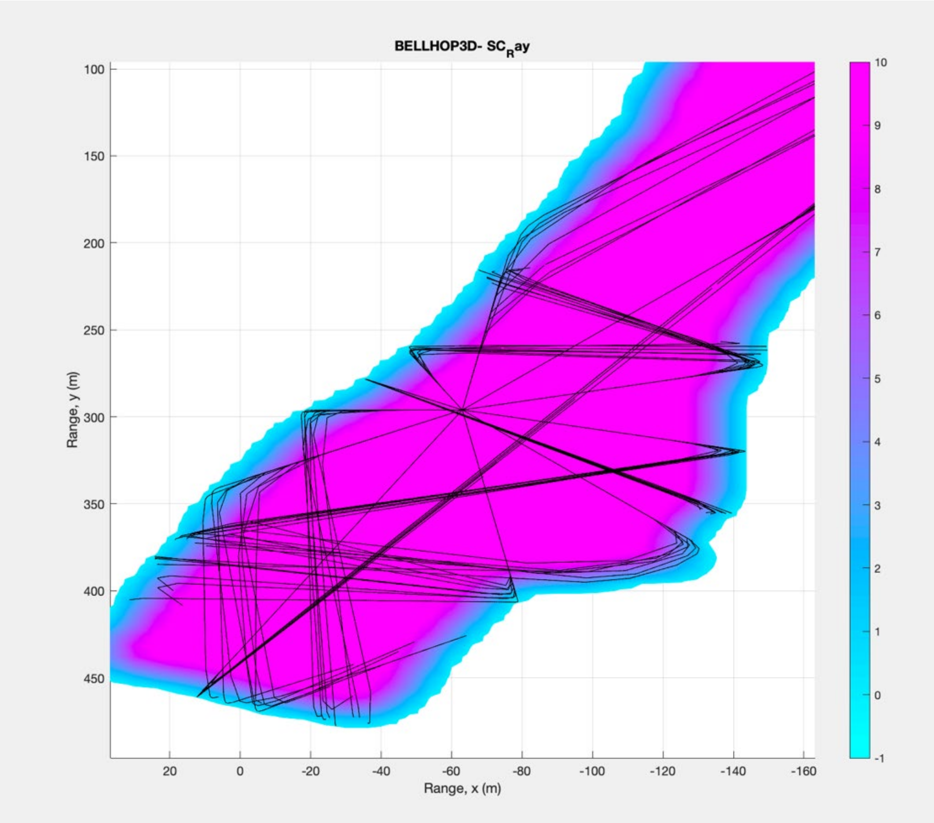

Figure 14. Modeled acoustic propagation paths in Santa Cruz Harbor

Figure 15 shows the same model simulation within Bellhop-3D from a different viewing angle. This vantage point shows that even with only eight radials of acoustic propagation traced, the amount of multipath propagation is complicated and the soundscape appears very complex. Acoustic waves propagating in this environment appear to have multiple vertical and horizontal boundary interactions.

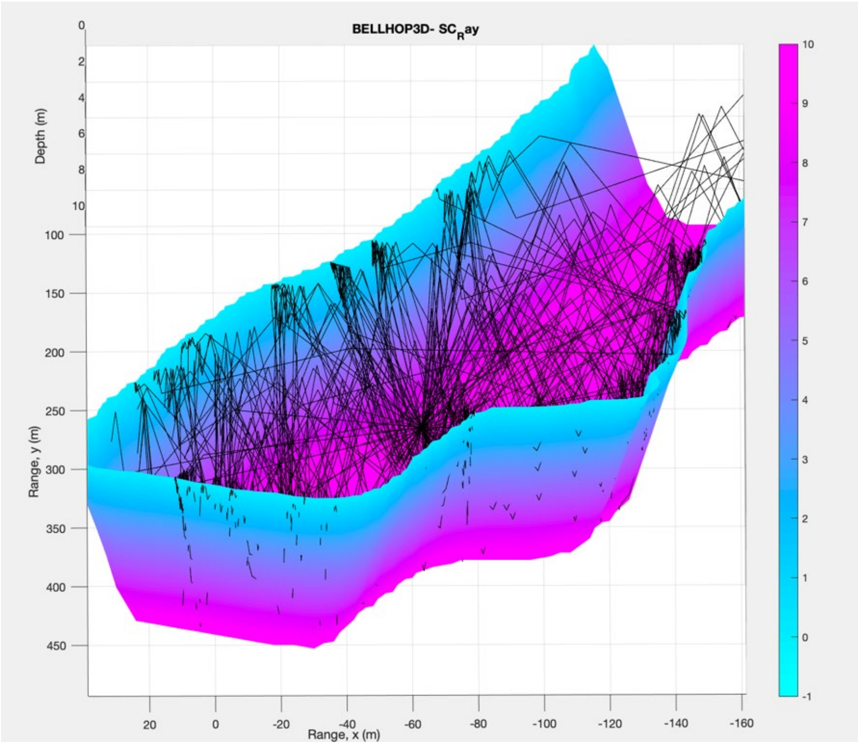

Figure 15. Bellhop-3D simulation within Santa Cruz Harbor

These model simulations were completed in a simplified model of Santa Cruz harbor. Support structures for docks, and ship hulls were not included in the model, and bathymetry was assumed to be constant. Although simplified, this model does provide a characterization of the harbor soundscape, and helps to draw the conclusion that direct path propagation exists in a harbor environment, however multipath sound propagation is dominant and the ability to understand it is critical for characterizing the acoustic soundscape of harbor environments.

B. FIELD WORK

Previous work with vector sensor data has involved long range low frequency ship tracking in an open ocean environment (Sheeler, 2020). In contrast, this thesis attempted to use the vector sensor for tracking in a shallow water constrained basin.

To evaluate effectiveness of shallow water source localization using a vector sensor, comparison with deep water source tracking provides insight. Figure 16 shows the bearing intensity for a 100Hz window centered at 200Hz, collected during previous thesis research tracking a ship in open shelf conditions near Santa Cruz in ~70m water depth. Figure 17 shows the bearing intensity for a 100Hz window centered at 650Hz at one point in time within Santa Cruz harbor, taken from data in Figure 13.

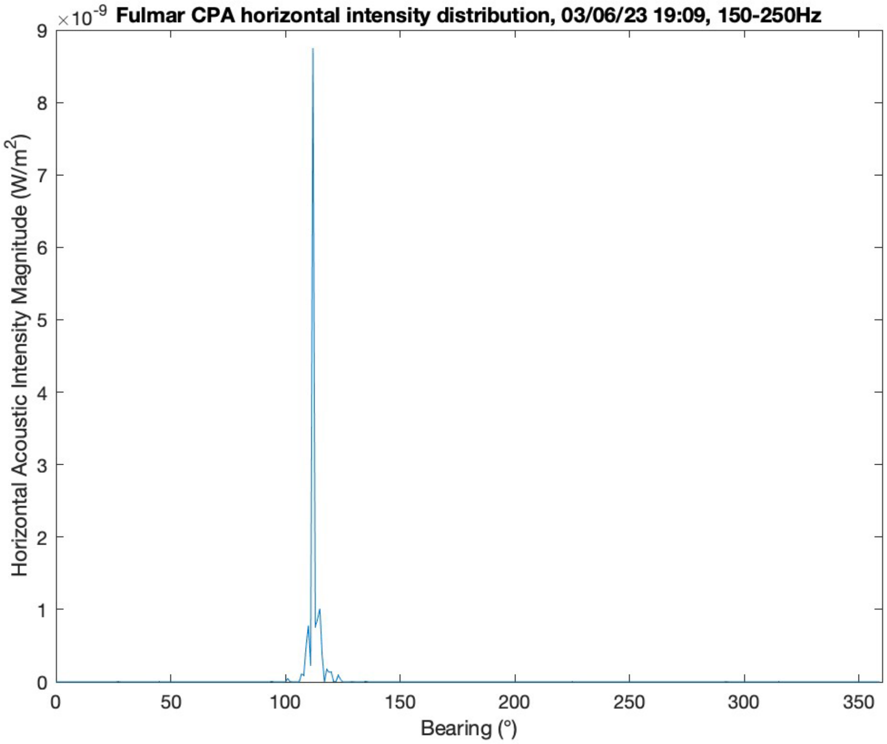

Figure 16. Horizontal intensity distribution for deep water ship tracking. Source: Sheeler (2020).

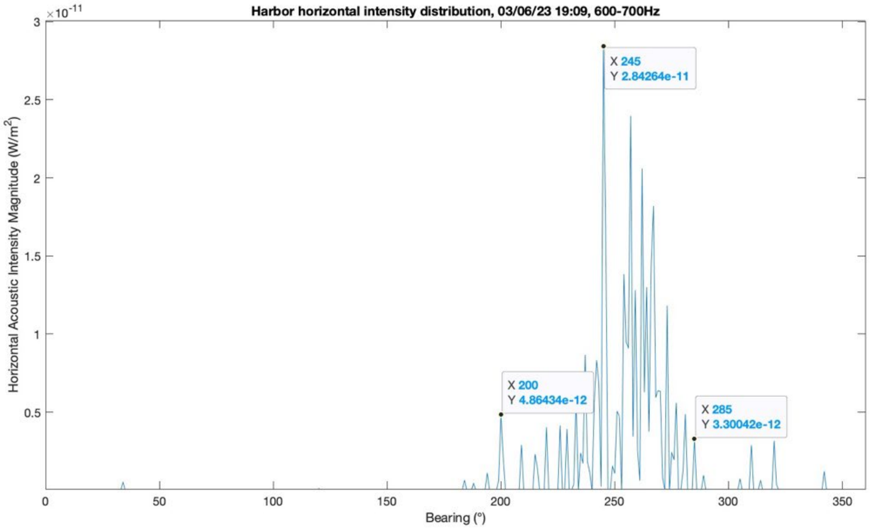

Figure 17. Horizontal intensity distribution for harbor environment

From these two figures, it is clear there are differences in horizontal intensity distribution as a function of bearing angle between the two environments. The horizontal intensity distribution for open ocean ship tracking shows a large peak of 8.75×10^{-9} W/m^2 at 112 degrees with much smaller peaks on either side (at 115 degrees, intensity magnitude is 1.01×10^{-9} W/m^2, and at 110 degrees, the intensity magnitude is 7.79×10^{-10} W/m^2. This conservative estimate gives the bearing ambiguity in open ocean a range of 5 degrees, with a very prominent main intensity spike. If using the half power of the maximum intensity to determine the ambiguity width, the value is only 1 degree in bearing. In the harbor environment, a peak is visible, however there is a very large intensity spread over a large range of bearings. The intensity spread ranges from 200 to 285 degrees with a peak at 245, indicating an almost 90 degree window of source bearings. If using the half power of the maximum intensity to determine bearing ambiguity in the harbor data, the bearing spread is 35 degrees, much lower than the entire intensity range, however still not small enough for accurate source localization without further data processing.

In harbor environments, accurate source localization is imperative due to the small and constrained nature of the environment. Future applications of this research involve supporting maritime operations in harbor and littoral environments, where high fidelity environmental information is imperative for successful mission planning and execution. The ability to remotely sense vertical boundaries is a critical skill that will increase environmental sensing effectiveness in shallow water areas. This initial analysis demonstrates the importance of modeling and understanding the multipath propagation in order to remotely sense vertical boundary locations. Future research opportunities exist in developing hypothetical environments and using model data to match with vector sensor data. The data collected in this thesis research indicates that a harbor environment is rich in acoustic information that may be useful for many applications, not solely tracking sources of interest. In addition, future research opportunities exist in exploring high frequency field work and determining what data can be parsed from the littoral soundscape across both low and high frequencies.

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