Portland State University

PDXScholar

Dissertations and Theses

Dissertations and Theses

Spring 1-1-2012

Passive Acoustic Vessel Localization

Pasang Sherpa Suwal

Portland State University

Follow this and additional works at: https://pdxscholar.library.pdx.edu/open_access_etds

Part of the [Electrical and Computer Engineering Commons](#)

Let us know how access to this document benefits you.

Recommended Citation

Suwal, Pasang Sherpa, "Passive Acoustic Vessel Localization" (2012). *Dissertations and Theses*. Paper 757.

<https://doi.org/10.15760/etd.757>

This Thesis is brought to you for free and open access. It has been accepted for inclusion in Dissertations and Theses by an authorized administrator of PDXScholar. Please contact us if we can make this document more accessible: pdxscholar@pdx.edu.

Passive Acoustic Vessel Localization

by

Pasang Sherpa Suwal

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

Master of Science
in
Electrical and Computer Engineering

Thesis Committee:
Lisa M. Zurk, Chair
Martin Siderius
Mark D. Sytsma

Portland State University
2012

Abstract

This thesis investigates the development of a low-cost passive acoustic system for localizing moving vessels to monitor areas where human activities such as fishing, snorkeling and poaching are restricted. The system uses several off-the-shelf sensors with unsynchronized clocks where the Time Difference of Arrival (TDOA) or time delay is extracted by cross-correlation of the signal between paired sensors. The cross-correlation function uses phase correlation or Phase Transform (PHAT) which whitens the cross-spectrum in order to de-emphasize dominant frequency components. Using the locations of pairs of sensors as foci, hyperbolic equations can be defined using the time delay between them. With three or more sensors, multiple hyperbolic functions can be calculated which intersect at a unique point: the boat's location. It is also found that increasing separation distances between sensors decreased the correlation between the signals. However larger separation distances have better localization capability than with small distances. Experimental results from the Columbia and Willamette Rivers are presented to demonstrate performance.

Acknowledgments

I would like to thank my advisor Dr. Lisa M. Zurk for her guidance and support during this research. I am also grateful to all my fellow students at the Northwest Electromagnetics and Acoustics Research Laboratory (NEAR-Lab) at Portland State University for their help and support. In addition, I would like to thank The Nature Conservancy for presenting this project to the NEAR-Lab and funding this work. I am also grateful to Dr. Martin Siderius and Dr. Mark Sytsma for serving on my committee. Finally I would like to thank my husband and parents for their patience and support during this research.

Contents

Abstract	i
Acknowledgments	ii
List of Tables	v
List of Figures	vi
1 Introduction	1
1.1 Executive Summary	1
1.2 Contributions of This Work	5
1.3 Passive Sonar	7
1.4 Problem Description	9
1.4.1 The Propagation Model Assumptions	9
1.4.2 The Localization Problem	11
1.4.3 Transmission Loss	12
1.5 Outline of Thesis	14
2 Correlation Processing	15

2.1	Data Collection and Pre-processing	15
2.2	Window Size for Time Delay Estimation	21
2.3	Time-varying Time Delay Estimation from Data Cross-correlation	26
2.4	Hyperbolic Position Estimation Method	32
3	Results and Analysis	40
3.1	Results	40
3.2	Frequency Band for Cross-correlation	45
3.3	Accuracy of Localization Algorithm	48
4	Conclusions and Future Work	51
	References	54

List of Tables

2.1	Willamette River Sensor Separation Distances	18
2.2	Columbia River Sensor Separation Distances	18

List of Figures

1.1	Example of a Marine Protected Area indicated by the red line. Demonstrates a sensor setup for deployment, with an anchor at the bottom and a bouy at the top to keep the sensors vertical.	4
1.2	(Left) An example of active sonar which consists of a transmitter and a receiver. (Right) An example of passive sonar which uses a receiver to record sound generated by self-emitting sources.	7
1.3	Time delay associated with wavefronts emitted by an acoustic source.	10
2.1	Boat used for the deployment of sensors in the Willamette River. It was 17 ft long made of aluminum with a 30 horse power engine. . . .	19
2.2	Willamette River deployment sensor locations. Sensors in each pair S_1, S_2 and LH_3, LH_4 are on average 30 m apart from each other and two pairs are ~120 m apart.	20
2.3	Columbia River deployment sensor locations where the sensors are on average 400 m apart from each other.	21

2.4	Spectrogram of a boat moving in circle track (clockwise direction) recorded by sensor S_1 in the Willamette River. Two vertical dark patches around 20-30 and 50-60 sec on the time axis resulted when the boat engine stopped temporarily. The CPA is seen at 155 sec on the time axis.	22
2.5	Acoustic pulses in time domain recorded by sensor S_1 before the deployment in the Willamette River. These pulses are used to align the time bases of the data recorded by different sensors.	23
2.6	A data of snapshot length $T=0.2$ sec of a circular track recorded by sensors S_1 and S_2 in the Willamette River deployment, corresponds to 70-70.2 sec on the time axis in Figure 2.4.	25
2.7	Phase correlation of two signals shown in Figure 2.6.	25
2.8	The DFT of the 0.2 sec long signals shown in Figure 2.6 using (2.3). The data are from a circular track collected in the Willamette River by sensors S_1 and S_2 and corresponds to 70-70.2 sec on time axis of Figure 2.4.	28
2.9	Phase correlation of two signals shown in Figure 2.6 of a circular track in the Willamette River using (2.8) with $\tau_{max}=0.011$ sec. The amplitude is normalized so that a perfect correlation gives value 1. . .	30

2.10	Standard correlation of two signals shown in Figure 2.6 of a circular track in the Willamette River with $\tau_{max}=0.011$ sec. The amplitude is normalized so that a perfect correlation gives value 1.	30
2.11	Time delay vs. time using sensors S_1, S_2 and LH_3, LH_4 of a circular track in the Willamette River using (2.9). Total snapshots $K=825$ and snapshot length $T=0.2$ sec is used for cross-correlation. The red points are uncorrected data and the corrected time delay shown in blue color.	31
2.12	Hyperbolic functions in local coordinates.	34
2.13	Sensors setting in the Columbia River deployment. The intersection of the pair of hyperbola gives the estimated boat position using real data. The black hyperbola corresponds to sensors S_1 and S_2 and the red hyperbola to sensors S_2 and S_3	35
2.14	Sensors setting in the Willamette River deployment. The intersection of the pair of hyperbola gives the estimated boat position using real data. The red hyperbola corresponds to sensors S_1 and S_2 and the black hyperbola to sensors LH_3 and LH_4	36

2.15	A fixed error/noise of 1 ms is introduced in time delay which defines an uncertainty area shown in the red shaded region. If there were no errors, then there would be just one hyperbola on which the source must lie. For close sensors, the area of uncertainty is much larger with the fixed error than for far sensors.	39
2.16	A fixed error/noise of 1 ms is introduced in time delay which defines an uncertainty area shown in the red shaded region. Same as Figure 2.15 except S_2 is shifted to right by 10 m. Small increase in the sensor separation decreased the area of uncertainty where the source must lie.	39
3.1	TDOA obtained from cross-correlation between sensors S_1 and S_2 for a circular track using (3.1) with $T=0.2$ sec in the Willamette River. Refer to the geometry in Figure 2.2 for sensor locations. Secondary peaks are visible alongside the main peak due to multiple reflected signals in shallow water.	41
3.2	TDOA obtained from cross-correlation between sensors LH_3 and LH_4 of a circular track using (3.1) with $T=0.2$ sec in the Willamette River. Refer to the geometry in Figure 2.2 for sensor locations. Secondary peaks are visible alongside the main peak due to multiple reflected signals in shallow water.	42

3.3	The GPS track and the estimated boat track from the corrected time delay of a boat moving in a circular track (clockwise) in the Willamette River. The position at $t=155$ sec corresponds to CPA in Figure 2.4. The entire frequency band of 1 Hz- to 22 KHz is used for cross-correlation with snapshot size $T=0.2$ sec	43
3.4	The GPS track and the estimated boat track from the corrected time delay of a boat moving in a sinusoidal track (north to south) in the Willamette River. The entire frequency band of 1 Hz- to 22 KHz is used for cross-correlation with snapshot size $T=0.2$ sec.	44
3.5	TDOA obtained from cross-correlation between sensors S_1 and S_2 of $T=0.6$ sec in the Columbia River. Refer to the geometry in Figure 2.3 for sensor locations. The two sensors are around 400 m apart. Frequency band of 1 Hz- to 1 KHz used.	46
3.6	Estimated boat track in the Columbia River. No GPS data available ; visual observation only. The frequency band of only 1 Hz- to 1 KHz was used for cross-correlation with snapshot size of $T=0.6$ sec.	47
3.7	Error in range between the GPS position and the estimated position for a circular track shown in Figure 3.3.	49

3.8	Error in range between the GPS position and the estimated position for a sinusoidal track shown in Figure 3.4.	49
3.9	Estimated and GPS speed of the boat on a circular track. The re- duction of speed around 20-30 sec and 50-60 sec on time axis resulted in the two vertical dark patches in the boat spectrogram shown in Figure 2.4.	50

Chapter 1

Introduction

1.1 Executive Summary

Localization and tracking small vessels are essential for improving security in Marine Reserve Areas (MRA) where hunting, fishing, collecting fish or marine organisms are strictly prohibited. Monitoring these areas is a challenge because of the lack of physical boundaries to demarcate them. The need for similar systems arises in the monitoring of harbor traffic and port security.

There are many different methods that can be used for such applications. Examples include radar [1], optical systems such as electro-optic (EO) and infrared cameras (IR) [2], and both active and passive sonar. However these technologies are not without drawbacks. Radars may be limited by line of sight and optical systems are susceptible to environmental influence such as rain, fog and may require light. Active sonar require the installation of a powerful and expensive transmitter that emit signals which can affect marine life, limiting its utility. For this work, passive sonar was chosen because it records sounds from moving boats, which are self-emitting sources. Noise spectra produced by boats include broadband noise as well as tonals due to the harmonics of the engine speed and shaft/propeller rotation [3]. Ogden and Zurk [4] have used

these harmonic tones to generate a harmonic signature of the boat.

Passive sonar recording devices used in this research are low-cost off-the-shelf sensors, very simple to deploy, and do not adversely affect the surrounding environment. For spatially separated sensors, the boat noise recorded by two sensors are delayed versions of the same signal. The time delay associated with the paired sensors is a fundamental parameter for localization and is calculated using cross-correlation operation. Cross-correlation is a measure of similarity between the two signals as a function of time delay. In this method, a frequency domain phase correlation is performed to obtain time delay because it enhances the spectral areas with low signal-to-noise ratio (SNR) [5] and it reduces strong tonals in the Fourier transform. The estimated time delay gives rise to one hyperbolic function. With three or more sensors, multiple hyperbolic functions can be calculated which intersect at a unique point: the boat's location.

Other passive methods have been developed for source localization. Array signal processing techniques are generally used for precise localization using beamforming. They increase the signal gain by maximizing the output SNR and have increased detection range. This technique is useful but the sensor arrays are expensive and cumbersome to deploy [6], [7], [8].

An estimate of boat locations or tracking can also be found using an Extended Kalman Filter (EKF) [9], [10] or other smoothing techniques but since

the method is robust the sophistication of a tracking solution is not needed.

The Stevens Institute of Technology has done vessel detection, classification and tracking using noise generated by vessels [11]. Their passive acoustic system consists of four sensors in cross configuration with a common clock, and requires both a land-based computer for data processing and an in-water system for pre-processing of data. The two systems are connected via an underwater cable. With real-time data link, this method looks promising, but the need for multiple systems and connectivity between them can make it very complex, expensive and labor intensive.

Conservation Technology Initiative (CTI), a Northwest Electromagnetics and Acoustics Research Laboratory's (NEAR-Lab) project supported by The Nature Conservancy (TNC) was initiated to harvest cutting-edge technology for use in conservation applications. The main objective of the project is to provide a surveillance network to monitor intrusion/poaching activities in the MRA's, and to better protect the endangered marine species native to these regions. The use of the system should not require special skills so deployment and placement of the sensors needs to be easy, and the algorithm for interpreting the data (such as in this thesis) must be readily available. Ou et.al describes one such software interface application [12].

The method presented in this thesis makes use of low-cost sensors with clocks

that are not synchronous. These sensors are deployed in areas of interest for short periods of time (~weeks). After they are retrieved, the data is downloaded and processed. The deployment process does not require professional skills and can be done by anyone after some basic training. An example of a deployment of sensors is shown in Figure 1.1. While this system does not perform real time boat localization, it provides historical statistics of vessel intrusions from which traffic volumes and violations can be determined, making it possible for marine reserve patrols to operate effectively. Future extensions may include a real-time data link, but with increased cost and complexity.

Figure 1.1: Example of a Marine Protected Area indicated by the red line. Demonstrates a sensor setup for deployment, with an anchor at the bottom and a buoy at the top to keep the sensors vertical.

1.2 Contributions of This Work

The following contributions are made by the work presented in this thesis.

- * A localization method to trace an approximate vessel/boat track using time delay measurements computed from signals received by at least three spatially separated fixed sensors. For this method, low-cost off-the-shelf sensors without any time synchronization can be used.
- * Results from deployments in the Willamette and the Columbia Rivers are shown to be good agreement when compared to the GPS location data.
- * An algorithm is designed and implemented in MATLAB to do the following:
 - 1) Pre-process raw data from unsynchronized sensors to align the time bases and correct the clock drift of the sensors.
 - 2) Generate hyperbolas based on time-delay data to pin-point boat locations.
- * Showed experimental results with different types of cross-correlation functions on a real time domain signals to estimate time delay and developed MATLAB code to compute phase cross-correlation.
- * Analyzed the effects of different “snapshot size” and frequency band used

for time delay estimation using the data collected by NEAR-Lab members in the Willamette and the Columbia Rivers.

1.3 Passive Sonar

SONAR (SOund Navigation And Ranging) is a technique that uses acoustic signals for navigation, detection and communication [3]. There are two main methods of sonar, active and passive. In an active sonar system, a short pulse signal is transmitted through a medium towards a target and its echo received by a hydrophone/sensor is used to determine the range of a target. Passive sonar on the other hand, uses a sensor to record sound generated by self-emitting sources in the environment. Figure 1.2 shows examples of active and passive sonar mechanisms.

Figure 1.2: (Left) An example of active sonar which consists of a transmitter and a receiver. (Right) An example of passive sonar which uses a receiver to record sound generated by self-emitting sources.

Radiated noises of boats and underwater targets can be divided into two different types. One type is broadband noise having a continuous spectrum and the other is tonal noise having a discrete spectrum. The hydrodynamic noises

such as flow on the hull, air bubbles and cavitations are continuous whereas the spectral representation of mechanical noises such as engine, propellers, vibrations, etc occurs at discrete frequencies [3]. Passive sonar has been chosen for this research because the sensors record the sound from moving boats, which are self-emitting sources. Passive sonar recording devices can also be relatively cheap to construct, very simple to deploy, and do not adversely affect the surrounding environment.

1.4 Problem Description

When processing real data, there are factors that affect the capability of localization of sources. A few of these factors are described briefly in this section.

1.4.1 The Propagation Model Assumptions

The speed of sound in water, c is considered constant (1500 m/s) and is not affected by the medium, considered homogeneous and shallow. The time it takes the signal from the source to reach the spatially separated sensors depends on the distance between the source and the sensor. The time delay difference between the arrival times of the signal at multiple sensors is called the Time Difference of Arrival (TDOA).

A two dimensional problem illustration of a passive acoustic monitoring system is shown in Figure 1.3. Here, a source radiates acoustic energy by means of propagating wavefronts that reach the first receiving sensor and then the second sensor. The distance between the two wavefronts is the speed of sound in water times the time delay. When the source is on the broad side of the sensors, the wavefronts will reach both the sensors around the same time, but if the source is on the endfire (the source is on the same axis as the sensors), the wavefronts will reach one sensor before the other with maximum time delay. Thus, the maximum time delay related to the distance between the sensors

provides a physical constraint to the time delay. This time delay is used to define the time window for cross-correlating signals from the two sensors. Boats generally move slow enough that their position does not change significantly during this time window.

Figure 1.3: Time delay associated with wavefronts emitted by an acoustic source.

Time delay is a fundamental parameter for passive localization and can be estimated through the use of cross-correlation techniques, in which the received signal at one sensor is correlated with the received signal at another sensor. The peak of the cross-correlation output gives the time delay. Phase correlation for time delay estimation is used because it whitens the cross-spectrum and de-emphasizes dominant frequency components. If a cross-spectrum has a

dominant frequency component such as the 60-Hz component, then the cross-correlation function is heavily dominated in the time domain by this 60-Hz sine wave. The cross-correlation function becomes broad with multiple peaks which makes it difficult to pick the correct time delay.

So, phase correlation helps to reduce the effects caused by tones due to the harmonics of engine speed and shaft/propeller rotation. This results in a sharper peak in the correlation series and a better time delay estimation, which increases the accuracy of the localization of source.

1.4.2 The Localization Problem

A particular value of the time delay estimate defines a hyperbola between the two sensors along which the source may exist, assuming that the source and the sensors are coplanar. If this procedure is repeated with another sensor in combination with any of the previously used sensors, another hyperbola is defined and the intersection of the two hyperbolas results in the position estimate of the source. This method is referred to as the hyperbolic position estimation method. In practice, there might be some measurement noise in time delay estimation due to inaccuracies in the sensors or the correlation of data. The noise added to the time delay estimate defines a hyperbola area rather than a single hyperbola.

1.4.3 Transmission Loss

When sound signals propagate underwater, they get distorted, and attenuated. Transmission loss expresses the magnitude of one of the many phenomena associated with sound propagation underwater [3]. It may be considered to be the sum of losses due to spreading and attenuation. Spreading loss is due to the expansion of transmitted energy over a larger surface area as the signal spreads outward from the source. Attenuation loss includes the effects of absorption and scattering. Absorption involves a process of conversion of acoustic energy into heat as it propagates in the medium. The surface and the bottom of the river are both reflector and a scatterer of sound. However, bottom surface reflection are more complicated because of its multilayered composition. These reflections cause the signals to decay at every bounce as it propagate, and also multipath arrivals at the receiver causing an interference pattern.

At relatively short ranges, the increasing surface area can be represented as the surface of a sphere so signal energy decay due to spreading loss is at a rate of R^{-2} where R is the range from the source. However, any body of water like a river is bounded from above by the surface and below by the river bottom. Thus, at some range from the source, the acoustic signal no longer spreads vertically and the nature of spreading changes from spherical to cylindrical. This transition typically occurs at ranges much greater than the water depth

[13]. In cylindrical spreading, signal energy decays at a rate of R^{-1} . A second mechanism of signal loss results from the conversion of energy into heat and is called the absorption loss. Under water, the absorption loss of an acoustic signals is dependent on its frequency and increases with increasing frequency [14]. Signal energy decay due to absorbtion loss is proportional to $\exp^{-\beta(f)R}$ where $\beta(f)$ is an increasing function of frequency and is in dB/km. Transmission loss due to cylindrical spreading and absorption may be expressed as

$$TL = 10 \log R + \beta(f)R \times 10^{-3} \quad (1.1)$$

where the first term represents cylindrical spreading and the second term absorption.

As the signal propagates for longer ranges it gets weakened and distorted due to different loss mechanism as described earlier. Larger range will have higher transmission loss so, the correlation between signals from far sensors will be low. Hence, the distance between sensors cannot be too large that it results in low correlation between the signals and increases measurement noise in time delay estimation. Also, the frequency dependence of absorption loss limits the frequency band that can be used for a certain range, and vise versa.

1.5 Outline of Thesis

The remainder of this thesis is organized as follows.

Chapter 2 provides a detailed discussion of the TDOA estimation technique and methods used in hyperbolic position estimation. Phase correlation technique in TDOA estimation is reviewed. The hyperbolic position estimation method commonly used to provide solutions to the localization problems is described. Methods used to synchronize the time bases of the data recorded by sensors are also discussed.

Chapter 3 presents the experimental results from the Willamette and the Columbia Rivers. The estimated boat track is compared to the GPS boat track. It is seen that increasing separation distance between the sensors decreases the signal correlation.

Chapter 4 concludes this thesis by summarizing the results and discusses future work.

Chapter 2

Correlation Processing

This chapter provides details of the correlation processing used to estimate time delay and the hyperbola position estimation technique used for source localization. It also describes different deployment set ups and their locations for data collection.

2.1 Data Collection and Pre-processing

In this section, details on the data collection in the Willamette and the Columbia Rivers are presented. Different sensor arrangements were chosen for the two deployments with the goal of using the hyperbola position estimation method in different settings. This section also describes pre-processing done on the data collected to align time bases since the sensors do not have common clock.

There were two different sensors used in the Willamette deployment; Soren (S) sensors built in the NEAR-Lab [15] and the commercially available Loggerhead (LH) sensors with sampling frequencies f_s of 44.1 KHz and 80 KHz respectively. Both the sensors are completely autonomous passive recording devices. The data samples recorded by LH sensors were downsampled to obtain the same f_s as Soren sensors.

The GPS (Global Positioning System) used during the deployment was Garmin eTrex 20 which recorded the position every 2 sec. The GPS recorded the coordinate in easting and northing as well as latitude and longitude. A point near the deployment was chosen as a reference. The reference point (in easting and northing coordinates) is subtracted from the easting and northing coordinates of the GPS data. This way the reference point will be the origin of the new coordinates for boat localization. With this new coordinate system, with x and y axes in meters, it is easier to visualize distance.

Consider $r_i(t)$ to be the data recorded by the i th sensor where $i = \{1, \dots, M\}$, is the sensor index and $r_i(t)$ is of finite length T_r . S_i and LH_i denote the i th Soren and Loggerhead sensors respectively where the index of LH follows that of S . For the Willamette River deployment, the sensors are indexed as (S_1, S_2, LH_3, LH_4) . The signal is sampled at frequency f_s , sampling period $\Delta t = 1/f_s$, and can be written as $r_i(p \Delta t)$ where $p = \{0, 1, \dots, N_r - 1\}$ and $N_r = T_r / \Delta t$. Then the signal is partitioned into K non-overlapping snapshots, where each snapshot is of length T seconds, or N_s samples where $N_s = T / \Delta t$. Time delays for all snapshots are estimated using correlation analysis to obtain time-varying time delay.

The notation $r_{i_k}(n) \equiv r_i(kT + n \Delta t)$ is used to represent the n th sample of the k th snapshot recorded by the i th sensor where $n = \{0, 1, \dots, N_s - 1\}$ and

$$k = \{1, 2, \dots K\}.$$

Four sensors were deployed for a 3 hour period on November 7, 2011 near $45^{\circ}31'32''\text{N}$, $122^{\circ}39'59''\text{W}$ in the Willamette River forming two pairs of sensors. The pairs were approximately 120 meters apart and sensors in each pair were on average 30 meters away from one another. Refer to Figure 2.2. A control boat with on-board GPS device was deployed at approximately uniform speed in a circular and a sinusoidal path to the west of the sensors. The boat was 17 ft long made of aluminium with a 30 horsepower engine. See Figure 2.1.

Three sensors were deployed on March 29, 2011 in the Columbia River for a week near $45^{\circ}37'16''\text{N}$, $122^{\circ}40'34''\text{W}$ forming a triangle and were on average 400 meters away from one another. Locations of this deployments is illustrated in Figures 2.3. At both deployment site, the sensors were tethered to the river bottom using 3-meter ropes with 70- to 80-lb anchors and were tied to a buoy on top to make the sensors stand vertically in the water column. The water depth averaged 13 meteres in both cases. The drifting of the sensors due to water current is not taken into account; a discrepancy of several meters is possible.

The sensor separation distances between sensors for the two deployments are shown in Table 2.1 and 2.2.

A typical boat noise is shown in spectrogram format in Figure 2.4 with data collected by sensor S_1 during deployment in the Willamette River. A

Table 2.1: Willamette River Sensor Separation Distances

Sensor Pair	Distance Between Them (m)
S_1 and S_2	~30
LH_3 and LH_4	~30
S_1 and LH_4	~120

Table 2.2: Columbia River Sensor Separation Distances

Sensor Pair	Distance Between Them (m)
S_1 and S_2	~380
S_2 and S_3	~466
S_1 and S_3	~610

spectrogram is a time-varying representation which shows the spectral density of a signal varies with time. The data is from a boat moving in a circular track with a radius of approximately 100 meters. It consists of a series of harmonically related tones as well as broadband noise, which is a result of cavitations caused by the boat propeller contacting the water. Around 20-30 and 50-60 sec on the time axis, the boat engine stopped temporarily causing the vertical dark patches in the spectrogram. A classical bathtub pattern (with Closest Point of Approach (CPA) at 155 sec on the time axis) is caused due to the different multi-path arrivals of the noise adding up, in and out of phase.

Since each sensor contains its own clock for timing and these clocks are not synchronous, the first step in processing the acoustic data is to align the time bases. The bases are aligned by playing a sequence of high SNR acoustic pulses close to the sensors before deployment. Since the sensors are very close to one

Figure 2.1: Boat used for the deployment of sensors in the Willamette River. It was 17 ft long made of aluminum with a 30 horse power engine.

another, it is assumed that the time taken by these pulses to reach the sensors are the same. The pulses are played from an acoustic release transmitter mainly used for the recovery of underwater equipment [16] and are easily detectable in the recorded data. The time (HH:MM:SS) at which these pulses are played are noted. Figure 2.5 shows time domain acoustic pulses signal recorded by sensor S_1 before deployment in the Willamette River. The first pulse from the sequence of pulses, corresponds to the time noted earlier. Then the rest of the data after the first pulse is saved with the time information. This process is required for sensors like Soren that are very basic and do not have any time stamp on the data. If the sensors already have time information, this step can be skipped.

Figure 2.2: Willamette River deployment sensor locations. Sensors in each pair S_1, S_2 and LH_3, LH_4 are on average 30 m apart from each other and two pairs are ~ 120 m apart.

There is a finer correction done during the cross-correlation calculation. Besides the time synchronization between the sensors, clock drift also needs to be taken into account. Clock drift occurs in a sensor, when the clock crystal frequency deviates over time. These crystals undergo a gradual change in frequency over time, known as aging, causing the clock to drift. The sensors were tested with multiple acoustic pulses for a 24-hr period to estimate the relative clock drift. The drift between S_1, S_2 and LH_3, LH_4 is on average 0.3 ms/s and is corrected during the time delay estimation by adding this drift amount to the estimated time delay every second.

Figure 2.3: Columbia River deployment sensor locations where the sensors are on average 400 m apart from each other.

2.2 Window Size for Time Delay Estimation

The time dependent signal delay time for 2 sensors is calculated using short intervals (creating a “snapshot” or “window”) of data for cross-correlation. The time series signals are partitioned into K snapshots, where each snapshot is of length T seconds with no overlaps. For each snapshot available, it is assumed that the signal is stationary over T . The length of T , is an important consideration. For example, in computing frequency spectra, high resolution in frequency requires a long coherent integration period, T (frequency resolution is inversely proportional to snapshot length). However, if the snapshot is too long, the assumption of a stationarity signal is no longer valid and the Doppler effect may

Figure 2.4: Spectrogram of a boat moving in circle track (clockwise direction) recorded by sensor S_1 in the Willamette River. Two vertical dark patches around 20-30 and 50-60 sec on the time axis resulted when the boat engine stopped temporarily. The CPA is seen at 155 sec on the time axis.

become prominent [17] because signal is subjected to additional distortions due to the motion of source. Doppler effect can also be considered as the constant change in phase of the signal, resulting in the frequency shift. Correlating these distorted signals can result in undetectable peaks in correlation series. Hence, for fast maneuvering boats, the value of T should not be too large. The broadband noise generated by boats does not remain stationary for a long time interval but it may be assumed to be stationary for a short time interval making our approximation of a stationarity signal over the snapshot valid.

The choice of the snapshot length must be set based on experimental analysis. The minimum snapshot length T is set by the distance between the two

Figure 2.5: Acoustic pulses in time domain recorded by sensor S_1 before the deployment in the Willamette River. These pulses are used to align the time bases of the data recorded by different sensors.

sensors. If the source is at the endfire, the acoustic wavefront will reach one sensor before the other, with the maximum time delay. T should be large enough to contain the maximum time delay between the sensors and improve the cross-correlation estimate. Two time series data of length $T=0.2$ sec of a circular track in the Willamette River recorded by sensors S_1 and S_2 , shown in Figure 2.6 corresponds to 70 sec on the time axis of Figure 2.4. The separation between the two sensors were approximately 30 m. The maximum time delay for these two sensors is 0.02 sec which is just the distance between the sensors divided by the speed of sound in water. But T is chosen to be 10 times larger than the maximum time delay to improve time delay estimation. It can be noticed in this figure is that, the two signals appear to be random. However, when the correlation technique is applied, a clear correlation is seen between

the two, as shown in Figure 2.7.

$$T \gg \frac{D}{c}, \tag{2.1}$$

where D is the distance between two sensors.

Figure 2.6: A data of snapshot length $T=0.2$ sec of a circular track recorded by sensors S_1 and S_2 in the Willamette River deployment, corresponds to 70-70.2 sec on the time axis in Figure 2.4.

Figure 2.7: Phase correlation of two signals shown in Figure 2.6.

2.3 Time-varying Time Delay Estimation from Data Cross-correlation

This section illustrates the phase correlation method applied to each snapshot of data to estimate time delay. Time delay is estimated for all K snapshots to obtain time-varying time delay.

The cross-correlation function of the k th snapshot between two digitized series of data $r_1(n)$ and $r_2(n)$ (the subscript k from $r_{i_k}(n)$ is suppressed for simplicity where $k = 1, 2, \dots, K$) can be denoted by

$$c_{r_1, r_2}(m) = \begin{cases} \sum_{n=0}^{N_s-m-1} r_1(n+m)r_2(n) & m \geq 0 \\ c_{r_2, r_1}(-m) & m < 0. \end{cases} \quad (2.2)$$

The index m is the (time) shift (or lag) parameter and the subscripts r_1, r_2 on the cross-correlation sequence $c_{r_1, r_2}(m)$ indicate the sequence being correlated.

By means of the correlation theorem, correlation can be determined equivalently in the transform domain. When computing spectra, it is not possible to carry out the integrals involved in the continuous-time Fourier Transform. Instead a related transform called the Discrete Fourier Transform (DFT) is used. The relation in (2.3) is a formula for transforming a sequence $r_i(n)$ of length N_s into a sequence of frequency samples $R_i(l)$ of length N_s

$$R_i(l) = \sum_{n=0}^{N_s-1} r_i(n) e^{-j2\pi l \frac{n}{N_s}} \quad l = 0, 1, 2, \dots, N_s - 1, \quad (2.3)$$

where l is the frequency index.

In turn, the relation in (2.4) that allows the recovery of the sequence $r_i(n)$ from its frequency samples is called the Inverse DFT (IDFT)

$$r_i(n) = \frac{1}{N_s} \sum_{l=0}^{N_s-1} R_i(l) e^{j2\pi l \frac{n}{N_s}} \quad n = 0, 1, 2, \dots, N_s - 1, \quad (2.4)$$

where j is called the imaginary unit and $j^2 = -1$.

The DFT of (2.2) given by (2.5) may be called the “cross-power spectrum”, or simply the “cross-spectrum” [19], [20]

$$C_{r_1, r_2}(l) = R_1(l) R_2^*(l). \quad (2.5)$$

The shift in the time-domain is indicated by a phase change in the spectrum domain. The calculation of this phase change is called “phase correlation”. Next, the normalized cross-spectrum is obtained by dividing it by its magnitude,

$$C_{r_1, r_2}(l) = \frac{R_1(l) R_2^*(l)}{|R_1(l) R_2^*(l)|} \quad (2.6)$$

$$C_{r_1, r_2}(l) = e^{j\phi_{r_1, r_2}}, \quad (2.7)$$

where $R_1(l)$ and $R_2(l)$ are the DFT of $r_1(n)$ and $r_2(n)$ and $*$ denotes the

complex conjugate. The IDFT of (2.7) gives us the desired cross-correlation series shown by (2.8).

$$c_{r_1, r_2}(m) = \mathcal{F}^{-1}\{e^{j\phi_{r_1, r_2}}\}, \quad (2.8)$$

where $\mathcal{F}^{-1}$ represents the IDFT in eqn.(2.4). The cross-correlation function peaks at the value τ_{max} corresponding to the desired time delay

$$\tau_{max} = \arg \max[c_{r_1, r_2}(m)]. \quad (2.9)$$

Figure 2.8: The DFT of the 0.2 sec long signals shown in Figure 2.6 using (2.3). The data are from a circular track collected in the Willamette River by sensors S_1 and S_2 and corresponds to 70-70.2 sec on time axis of Figure 2.4.

Phase correlation is used because it whitens the cross-spectrum and de-emphasizes dominant frequency components caused to due to propellers of boat. It uses the DFT and its inverse which is much faster to compute and is also easier to chose the desired frequency band for correlation processing. The DFT of the two time series in Figure 2.6 is shown in Figure 2.8. Phase correlation of this data is calcuated using (2.8) and is shown in Figure 2.9 with the estimated (x-axis) time delay $\tau_{max}=0.011$ sec. For comparison, a standard cross-correlation series of the same dataset is shown in Figure 2.10. It can be seen that the peak is much clearer and sharper using phase correlation while both result in the same time delay.

The data for the circular track was 165 secs long resulting in $K=825$ snapshots with $T=0.2$ sec. The time delay is estimated for all K snapshots as described above and the estimated delay between the two pairs of sensors are shown in Figure 2.11. Even though a clear track of the time delay is visible, there are noisy measurements that occur during the period when the boat is temporarily stopped. The cross-correlation series for this period of time, when no broadband noise is present, contains random peaks due to low SNR, from which the time delay cannot be estimated.

These outliers are isolated from the data and the remaining time-varying time delays are interpolated to get smoothed or corrected time delay. This

Figure 2.9: Phase correlation of two signals shown in Figure 2.6 of a circular track in the Willamette River using (2.8) with $\tau_{max}=0.011$ sec. The amplitude is normalized so that a perfect correlation gives value 1.

Figure 2.10: Standard correlation of two signals shown in Figure 2.6 of a circular track in the Willamette River with $\tau_{max}=0.011$ sec. The amplitude is normalized so that a perfect correlation gives value 1.

correction provides a clean estimate of time-varying time delay between the pair of sensors. The corrected time delay for all snapshots for the circular track is illustrated in blue in Figure 2.11. A similar approach was taken for the other data sets to get corrected time delay.

Figure 2.11: Time delay vs. time using sensors S_1, S_2 and LH_3, LH_4 of a circular track in the Willamette River using (2.9). Total snapshots $K=825$ and snapshot length $T=0.2$ sec is used for cross-correlation. The red points are uncorrected data and the corrected time delay shown in blue color.

2.4 Hyperbolic Position Estimation Method

Hyperbolic position estimation technique estimates the location of the source by the intersection of hyperboloids that describe range difference measurements between three or more sensors. The range difference between two sensors is determined by estimating the time delay of signal between them.

Consider the signals $r_1(t)$ and $r_2(t)$ received by two sensors. Both the signals originate from a common source transmitting the waveform $s(t)$. The received signals are expressed as

$$r_1(t) = s(t) + w_1(t) \quad (2.10)$$

$$r_2(t) = s(t - \tau_{max}) + w_2(t) \quad (2.11)$$

where $w_1(t)$ and $w_2(t)$ are the contaminating noise at the sensor locations. The noise sources are assumed to be mutually independent, as well as independent of the source signal, and τ_{max} is the unknown time delay between the received signals [21], [22]. This model does not consider multipath or Doppler effects and can be employed in slowly varying environment where the characteristics of the signal and noise remain stationary for a finite window size T . Let the i th sensor be located at $(x_i(t), y_i(t))$ and the transmitter or boat be at position $(x(t), y(t))$ at any time t , which is unknown. The range difference between the two sensors is calculated by finding the time delay between sensors. The

relationship between the range difference and time delay is given by

$$\Delta d_{1,2} = c \tau_{max} = c (\tau_2 - \tau_1). \quad (2.12)$$

where $\Delta d_{1,2}$ is the range difference, τ_1 and τ_2 are the propagation times for the signal to travel from the transmitter to the receivers S_1 and S_2 respectively and c is the speed of sound in water.

For the two fixed sensors, S_1 and S_2 , a hyperbola is a set of points such that the range difference from position $(x(t), y(t))$ to S_1 and S_2 is constant. So, each $\Delta d_{1,2}$ corresponds to position $(x(t), y(t))$ along the hyperbola where the source can lie. The location ambiguity can be resolved by calculating another hyperbola between different pair of sensors and finding their point of intersection; the boat location. With M number of sensors, J number of hyperbolas are produced which ideally intersect at one unique point, but only two hyperbolas are sufficient to get a correct boat location.

$$J = \binom{M}{2} = \frac{M!}{2!(M-2)!} \quad (2.13)$$

where $M \geq 2$.

The equation of a hyperbola has the form [23]:

$$\frac{x^2}{a^2} - \frac{y^2}{b^2} = 1, \quad (2.14)$$

where $h^2 = a^2 + b^2$, h = distance of the focus (sensor location) from the center of hyperbola and $2a = \Delta d_{1,2}$.

Figure 2.12 illustrates how two receivers can calculate the range difference from the time delay, and how this range difference corresponds to a hyperbolic function.

Figure 2.12: Hyperbolic functions in local coordinates.

Two hyperbolas are shown in Figure 2.13, produced from data collected by sensors deployed in the Columbia River; the intersection (green circle) indicates the estimated boat position, the black hyperbola corresponds to sensors S_1 and S_2 and the red hyperbola to sensors S_2 and S_3 . Figure 2.14 illustrates estimated

boat position for the Willamette River arrangement. In this setting, two hyperbolas are produced from two close sensors. The red hyperbola corresponds to sensors S_1 and S_2 and the black hyperbola to sensors LH_3 and LH_4 and the green circle indicates the estimated boat position.

Figure 2.13: Sensors setting in the Columbia River deployment. The intersection of the pair of hyperbola gives the estimated boat position using real data. The black hyperbola corresponds to sensors S_1 and S_2 and the red hyperbola to sensors S_2 and S_3 .

For a general sensor position, the hyperbolic function in (2.14) is translated from local coordinates (x,y) to global coordinates (X,Y) . The hyperbolic function in global coordinates is thus given by [24],

Figure 2.14: Sensors setting in the Willamette River deployment. The intersection of the pair of hyperbola gives the estimated boat position using real data. The red hyperbola corresponds to sensors S_1 and S_2 and the black hyperbola to sensors LH_3 and LH_4 .

$$\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} \cos(\alpha) & \sin(\alpha) \\ -\sin(\alpha) & \cos(\alpha) \end{pmatrix} + \begin{pmatrix} X - X_o \\ Y - Y_o \end{pmatrix} \quad (2.15)$$

$$D = \sqrt{(Y_i - Y_j)^2 + (X_i - X_j)^2} \quad (2.16a)$$

$$\alpha = \arctan\left(\frac{Y_i - Y_j}{X_i - X_j}\right) \quad (2.16b)$$

where $X_o = (X_i + X_j)/2$, $Y_o = (Y_i + Y_j)/2$ locates the center point of the receiver

pair located at (X_i, Y_i) and (X_j, Y_j) .

The following steps were taken to generate the hyperbola points $(x(t), y(t))$ at any time t with an estimated time delay:

- * Estimate time delay τ_{max} using the correlation analysis. This time delay is abscissa value at which the correlation function peaks.
- * Convert time delay into range difference (distance) by multiplying by c (speed of sound). Obtain a for the hyperbola equations. $\Delta d_{1,2} = c \tau_{max} = 2a$.
- * Calculate b using $h^2 = a^2 + b^2$ (a is known from previous step and h is the sensor locations).
- * Choose a range of y values and obtain their x values for the hyperbola using (2.14).
- * Finally translate the local hyperbola points to global points using (2.15).

For a fixed error/noise Δe in time delay, the accuracy of the localization improves as the distance between the receivers grows [5], [24]. The noiseless time delay defines a hyperbola on which the emitter must lie. The error added to the time delay defines an uncertainty area about this hyperbola. Figure 2.15 and 2.16 illustrates an uncertain hyperbolic area when there is an error introduced in time delay estimation. It is noticed that the larger uncertainty in position is

seen for close sensors with the same fixed error of 1 ms. In the Figure 2.16 the sensor distance is increased by 10 m horizontally by moving S_2 and error range shrinks considerably.

But there is a limitation on the separation distance between sensors even though the accuracy of localization increases. This is because of the propagation loss of sound energy as it travels from one sensor to another. For sensors that are far apart, the signal received by one sensor might be weaker and more distorted than that received by the other, and there might be more noise introduced during correlation analysis.

Figure 2.15: A fixed error/noise of 1 ms is introduced in time delay which defines an uncertainty area shown in the red shaded region. If there were no errors, then there would be just one hyperbola on which the source must lie. For close sensors, the area of uncertainty is much larger with the fixed error than for far sensors.

Figure 2.16: A fixed error/noise of 1 ms is introduced in time delay which defines an uncertainty area shown in the red shaded region. Same as Figure 2.15 except S_2 is shifted to right by 10 m. Small increase in the sensor separation decreased the area of uncertainty where the source must lie.

Chapter 3

Results and Analysis

In this chapter results of time-varying time delay estimation and its use in position estimation using the sensor configurations in the Columbia and the Willamette Rivers are shown.

3.1 Results

First, two data sets from the Willamette River are shown where all 4 sensors recorded the radiated noise produced by a supporting boat that travelled along a circular and a sinusoidal track. A total of six hyperbolas can be calculated with 4 sensors, but only two were calculated using time delay estimates from the pairs of close sensors (S_1, S_2) and (LH_3, LH_4) because of their high SNR and clear peaks in cross-correlation series.

A snapshot size of $T=0.2$ sec is used and for each kth snapshot the peak index is extracted using (2.9) resulting in the time delay over time shown as red dots in Figure 2.11. Results with varying time delay are also shown in Figures 3.1 and 3.2. The graph is made with two geometric dimensions: the horizontal axis represents time, the vertical axis represents time delay between two sensors. The grayscale indicates the amplitude of the cross-correlation

function and were created using the normalized cross-correlation from (3.1).

After calculating time delays for all snapshots, the matrix $(c_{r_1,r_2}(m)_K)$ of size $[(2N_s - 1) \times K]$ is normalized so that the maximum value in the graph is 0 dB.

The normalization is done as:

$$c_{norm}(m)_K = 10 \log_{10} \frac{|(c_{r_1,r_2}(m)_K)|}{|(\max(c_{r_1,r_2}(m)_K))|} \quad (3.1)$$

where $c_{r_1,r_2}(m)_K$ denotes the matrix of the cross-correlation series for all snapshots K between sensors 1 and 2.

Figure 3.1: TDOA obtained from cross-correlation between sensors S_1 and S_2 for a circular track using (3.1) with $T=0.2$ sec in the Willamette River. Refer to the geometry in Figure 2.2 for sensor locations. Secondary peaks are visible alongside the main peak due to multiple reflected signals in shallow water.

Because of the cluttered and shallow environment of the river, there are

Figure 3.2: TDOA obtained from cross-correlation between sensors LH_3 and LH_4 of a circular track using (3.1) with $T=0.2$ sec in the Willamette River. Refer to the geometry in Figure 2.2 for sensor locations. Secondary peaks are visible alongside the main peak due to multiple reflected signals in shallow water.

multiple reflections of the signals generated from the boat [25] which cause secondary peaks seen in Figures 3.1 and 3.2. The reflections modulate the spectral power density, destroy the coherence in certain frequency areas and create secondary peaks in the cross-correlation functions [5]. The sidepeaks are ignored because the time delay is estimated by selecting the abscissa value of the main peak only. But sometimes these secondary peaks can be stronger and can be selected as the estimated time delay.

Using the corrected time-varying time delay described in previous sections, the estimated boat positions are plotted for two data sets along with the GPS boat positions in Figures 3.3 and 3.4. The estimated positions are acceptable

compared to the GPS positions because of factors such as approximated sensor locations, out-of-sync sensor clocks, and the use of two different kinds of sensors.

Figure 3.3: The GPS track and the estimated boat track from the corrected time delay of a boat moving in a circular track (clockwise) in the Willamette River. The position at $t=155$ sec corresponds to CPA in Figure 2.4. The entire frequency band of 1 Hz- to 22 KHz is used for cross-correlation with snapshot size $T=0.2$ sec

Figure 3.4: The GPS track and the estimated boat track from the corrected time delay of a boat moving in a sinusoidal track (north to south) in the Willamette River. The entire frequency band of 1 Hz- to 22 KHz is used for cross-correlation with snapshot size $T=0.2$ sec.

3.2 Frequency Band for Cross-correlation

In passive localization, the correlation of the received signal at two receiving sensors influences the outcome. Higher the correlation, better the time delay estimation and position estimation. It is shown in [26] that the correlation between the signals decreased with the increased distance between the sensors. The acoustic attenuation for higher frequencies is much greater than for lower frequencies. This puts a limitation on the separation distance between the sensors. Furthermore, for far apart sensors, the inclusion of the full band during cross-correlation adds noise. Therefore, the frequency band was decreased as the distance between the sensors increased. For a close pair of sensors (~ 30 m) in the Willamette River deployment, the entire frequency band of 1 Hz- to 22 KHz is used (see Figure 2.8) and a sharp peak was seen in the cross-correlation series. But when the sensors are far apart (~ 400 m) as in the Columbia River deployment, using the entire frequency band did not produce similar results. So, a narrower frequency band (1 Hz- to 1 KHz) was used to get a better estimation. Figure 3.5 shows the TDOA obtained by correlating the data between S_1 and S_2 . Frequency band of 1Hz-to 1KHz is used with window size of 0.6 sec. A clear peak is seen, which corresponds to the time-varying time delay for this dataset.

The sensors in the Columbia River recorded the broadband noise of random

Figure 3.5: TDOA obtained from cross-correlation between sensors S_1 and S_2 of $T=0.6$ sec in the Columbia River. Refer to the geometry in Figure 2.3 for sensor locations. The two sensors are around 400 m apart. Frequency band of 1 Hz- to 1 KHz used.

boats that passed by during the deployment. Using corrected time delay between (S_1, S_2) and (S_2, S_3) , a boat track is generated which is shown in Figure 3.6. The third hyperbola from (S_1, S_3) was not used in the estimation because of the low SNR caused by large distance (~ 600 m) between them. There were no GPS coordinates available for the boat for comparison, but the estimated track looks very reasonable.

Figure 3.6: Estimated boat track in the Columbia River. No GPS data available ; visual observation only. The frequency band of only 1 Hz- to 1 KHz was used for cross-correlation with snapshot size of $T=0.6$ sec.

3.3 Accuracy of Localization Algorithm

For a fixed error in the time delays, the accuracy of the localization is better as the distance between the sensors is increased [20], [27]. But the sensors cannot be so far apart that one sensor has much higher SNR than the others. When the source is closer to the one sensor and far from the other sensor, the signals in the far sensor will have decorrelated and attenuated due to different loss mechanisms. Cross-correlating this data would not result in a clear peak and would cause error in the time delay estimation. Other variables that play important role in the accuracy of the algorithm are the accuracy of the sensor locations, sensor-clock synchronization and clock drift. Due to water current in the rivers and oceans; a discrepancy of several meters is possible in sensor locations, contributing to the error in localization.

Considering the uncertainties, the track of the boat is estimated with a reasonable error margin. The average difference in distance between the GPS position and the estimated position for the circular and sinusoidal tracks is less than 10 meters. See Figure 3.7 and 3.8.

The speed of the boat is also calculated using the boat locations to determine the distance covered during a time interval. For the circular track shown in Figure 3.9, the estimated speed looks very reasonable compared to the speed recorded by the GPS receiver. Around 163-165 sec on the time axis, according

to the GPS data, the boat started slowing down but the estimation shows the boat speeding up. This discrepancy is due to the larger error in localization for this time interval, which results in a sharply increased speed estimation.

Figure 3.7: Error in range between the GPS position and the estimated position for a circular track shown in Figure 3.3.

Figure 3.8: Error in range between the GPS position and the estimated position for a sinusoidal track shown in Figure 3.4.

Figure 3.9: Estimated and GPS speed of the boat on a circular track. The reduction of speed around 20-30 sec and 50-60 sec on time axis resulted in the two vertical dark patches in the boat spectrogram shown in Figure 2.4.

Chapter 4

Conclusions and Future Work

A simple and cost efficient method to trace an approximate track of vessels using three or more spatially separated passive sensors is shown. Off-the-shelf sensors that do not have time-stamp capability can be used for this method. Different types of sensors can be used and the sensors can be deployed in a relatively short amount of time without the need for any special skills. All these factors make this method ideal for low-cost, low-technology and time-constrained deployments.

The passive acoustic vessel localization method is summarized in the following steps:

- * Data collection and preprocessing : The unsynchronized data from the sensors are aligned in time bases by using high SNR acoustic sync pulses played before deployment.
- * Correlation processing: The time base aligned data are partitioned into K non-overlapping snapshots of length T sec and time delay is estimated for each snapshot using correlation analysis. Phase correlation method is applied as it reduces the effects from strong tonals produced by harmonics of the engine speed and propeller rotation which results in sharper peak

in correlation series. Depending on the separation of the sensors, different snapshot size T and frequency bands were used for correlation. T is chosen such that it is larger than the maximum time delay, which is determined by the distance between sensors. Frequency band used must be reduced as the sensors separation distance increases because acoustic attenuation for higher frequencies is much greater than for lower frequencies.

For the data collected in the Willamette river, $T=0.02$ second and frequency band of 1 Hz- 22 KHz were used because of smaller sensor separation (~ 30 m). But for the data collected in the Columbia River, $T=0.02$ sec and frequency band of 1 Hz- 1 KHz were used because of larger sensor separation (~ 400 m).

- * Hyperbola position estimation: The intersection point of hyperbolas, generated using the time delays, is the estimated source location.

Given the uncertainties (clock synchronization, discrepancy in sensor location), an acceptable boat track is obtained, and this was true using either of two different types of sensors (showing robustness of the approach). The estimated track is compared to a reference track based on GPS data and results showed good agreement with less than 10 m error in range. Sensor distance should be around 200 m apart and form a triangular like shape such as the Columbia River deployment for good correlation between data and localization accuracy.

Frequency band of 1 Hz- 1KHz should be used for the phase correlation of such sensor distances.

Future work can include tracking algorithms such as Extended Kalman Filter, in combination with methods of optimum sensor arrangements. A real-time data linkage could also be done but it would increase cost and complexity.

This algorithm could be further developed to obtain tracks of multiple vessels. Another aspect is the possibility of localization with only relatively low frequencies for large sensor separation. Using only low frequencies would have lower sampling frequency and therefore require less computation or processing power.

References

- [1] M. McDonald and S. Lycett. Fast versus slow scan radar operation for coherent small target detection in sea clutter. *IEEE Proceedings: Radar, Sonar and Navigation*, 152(6):429-435, 2005.
- [2] S. P. Van Den Broek, H. Bouma, and M. A. C. Degache. Discriminating small extended targets at sea from clutter and other classes of boats in infrared and visual light imagery. Vol. 6969, Orlando, FL, United States, 2008. SPIE.
- [3] R. J. Urick. *Principles of Underwater Sound*. 3rd ed., McGraw-Hill, New York, 1983.
- [4] G. Ogden, L. Zurk, M. Jones, M. Peterson. Extraction of small boat harmonic signatures from passive sonar, *J. Acoust. Soc. Am*, vol. 126, pp.3768-3776 (2011)
- [5] B. Xerri, J. Cavasilas, B. Borloz. Passive Tracking in Underwater Acoustic Signal Processing 82 (2002) 1067-1085

- [6] G. C. Chen, W. S. Hodgkiss. VLF Source Localization with a Freely Drifting Acoustic Sensor Array, *IEEE J. Oceanic Eng.* 18 (3) (1993) 209-223
- [7] T. Peli. Evaluation of a wideband direction estimation algorithm for acoustic arrays, in *International Conference on Acoustics, Speech and Signal Processing*, 1987 ,p.52.4.
- [8] C. Feuillade, D. R. Del Balzo, M. M. Rowe. Environmental mismatch in shallow-water matched-field processing: Geoacoustic parameter variability, *J.Acoust.Soc.Am.*, vol. 85, June 1989.
- [9] F. Fletcher, B. Ristic, D. Musicki. Recursive Estimation of Wmitter Location using TDOA Measurements from Two UAVs. *Information Fusion*, July 2007.
- [10] B. Friedlander. A Passive Localization Algorithm and Its Accuracy Analysis, *IEEE J. Oceanic Eng.* vol.OE-12, January 1987.
- [11] K. W. Chung, A. Sutin, A. Sedunov, M. Bruno. DEMON Acoustic Ship Signature Measurements in an Urban Harbor Vol. 2011 Article ID 952798
- [12] H. Ou, L. Zurk, A. Lutwak. Acoustic Monitoring of Marine Conservation Areas. submitted for *IEEE Journal of Oceanic Engineering Society* for publication.

- [13] F. B. Jensen, W. A. Kuperman, M. B. Porter, H. Schmidt. *Computational Ocean Acoustics*. AIP series in modern acoustics and signal processing, Springer-Verlag, New York, pp. 279-281, 1993.
- [14] C. S. Clay, H. Medwin. *Acoustical Oceanography: Principles and Applications*. John Wiley and Sons, New York, NY, 1977, pp.88 and 98-99.
- [15] E. Sorensen, H. Ou, L. Zurk, and M. Siderius. Passive Acoustic Sensing for Detection of Small Vessels. Oceans (September 20-23, 2010) pp. 1-8.
- [16] Subsea Sonics. “Underwater Acoustic Release System”.
<http://www.dosits.org/technology/basictechnology/acousticrelease/>
- [17] S. J. Orfanidis. *Optimum Signal Processing: An Introduction*. Macmillan, New York, 1985. .
- [18] G. Clifford Carter, E. Richard Robinson Ocean Effects on Time Delay Estimation Requiring Adaptation, IEEE J. Oceanic Eng. vol.18, October 1993.
- [19] J. O. Smith. *Mathematics of the Discrete Fourier Transform (DFT)*. W3K Publusing., 2003.

- [20] C. Knapp, C. Carter. The generalized correlation method for estimation of time delay, IEEE Trans. Acoust.Speech Signal Process.33, 1114-1122, October 1985.
- [21] M. Azaria, D. Hertz Time Delay Estimation by Genertalized Cross Correlation Methods. IEEE Trans. Acoust.Speech Signal Process.vol. 32. no. 2, pp.280-285, 1984.
- [22] M. Wikstrom, U. Ahnstrom, J. Falk ,P. Handel. Implementation of an Acoustic location-finding system for TDOA measurements Department of Electronic Warface Systems
- [23] G. A. Korn. *Theresa M. Mathematical Handbook for Scientists and Engineers: Definitions, Theorems, and Formulas for Reference and Review.* 2nd ed.,Dover Publ., 2000:p.40
- [24] F. Gustafsson, F. Gunnarsson. Positioning Using Time-Difference of Arrival Measurements, in Proc. IEEE Conf. Acoustics, vol.6.pp.553-556
- [25] N. Kottege. Cross-correlation tracking for Maximum Length Sequence based acoustic localisation, In Proceesing of the Australasian Conference on Robotics and Automation (ACRA 2008), Canberra, ACT, Australia.
- [26] V. Zetterberg, M. I. Pettersson, I. Claesson. Comparision between whitened generalized cross correlation and adaptive filter for time delay estimation

with scattered arrays for passive positioning of moving targets in Baltic Sea shallow waters, Proceedings of Oceans 2005 MTS/IEEE Conference “One Ocean”., USA. CD-ROM 2005 .

- [27] C. Carter. Time delay estimation for passive sonar signal processing, IEEE Trans. Acoust.Speech Signal Process.29(3), June 1982.