DEVELOPMENT OF AN ACOUSTIC TRACKING SYSTEM
FOR HARBOR PORPOISES (*PHOCOENA PHOCOENA*)
IN THE VICINITY OF GILL NETS

BY
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ABSTRACT

The Marine Mammal Protection Act of 1972 mandates the reduction of the incidental bycatch of marine mammals by the commercial fishing industry. Catch statistics for the harbor porpoise (Phocoena phocoena) indicate that the subpopulation of these animals in the Gulf of Maine and Bay of Fundy is in danger of depletion as a result of gill net fishery operations. Efforts undertaken to reduce the likelihood of net entanglement have had mixed results. One problem is a lack of general information about the mechanism of bycatch of these animals.

This thesis describes the development of an acoustic tracking system to provide information about the behavior of individual submerged animals. The system passively localizes a porpoise using the animal's own ultrasonic sonar clicks. The system consists of two tetrahedral arrays of four hydrophones apiece. Measurement of the time differences of arrival (TDOA) of the click signals between the hydrophones determines a bearing to the animal from each array. The intersection of the lines of position (LOP) from the two arrays indicates the position of the animal. This system was tested in Penobscot Bay, Maine during August 1997. Position estimates relative to the arrays are presented for a sample encounter. Recommendations for improvements to the system are discussed.
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1. **Introduction.**

In section 1.1 immediately following, the problem of incidental bycatch of marine mammals resulting from commercial fishing is introduced, beginning with the specific issue that motivated Congress to establish the Marine Mammal Protection Act of 1972. Some of the goals of the MMPA are discussed along with specific terminology. The particular problem of bycatch of harbor porpoise in the Gulf of Maine/Bay of Fundy gill net fishery is then discussed, including bycatch statistics collected during the early- and mid-1990s. Finally, some of the bycatch mitigation strategies that have been implemented are mentioned briefly.

Section 1.2 contains the specific goals set forth for the acoustic tracking system described in the remainder of this thesis, namely its use as a tool for studying mitigation effectiveness and gathering behavioral information.

Section 1.3 gives a brief discussion of particulars of the system design, i.e., the overall operational concept, deployment strategies, and data processing and display issues.

1.1. **Overview of the Bycatch Problem.**

The mortality of various marine mammal species arising from human activity has become a major issue. Besides direct targeting of the species by commercial whaling and subsistence hunting, the incidental killing of marine mammals by commercial fishing industry practices has been a matter of great public concern that came to prominence in the late 1960s. The term "bycatch" has been applied to this
situation, used to describe any species not targeted by the fishery that is inadvertently taken in the fishing gear. Outcry over the bycatch of Pacific dolphins due to ensnarement in tuna fishing nets led to Congress passing the Marine Mammal Protection Act of 1972. The primary management goal set forth by the MMPA is the reduction of mortality and serious injury levels for certain types of marine mammals that are threatened with depletion by human interaction.

In the act's Findings and Declaration of Policy (Section 2.), Congress found that:

“(1) certain species and population stocks of marine mammals are, or may be, in danger of extinction or depletion as a result of man's activities;

(2) such species and population stocks should not be permitted to diminish beyond the point at which they cease to be a significant functioning element in the ecosystem of which they are a part, and, consistent with this major objective, they should not be permitted to diminish below their optimum sustainable population.”

From the Definitions (Section 3),

“(9) The term “optimum sustainable population” means, with respect to any population stock, the number of animals which will result in the maximum productivity of the population or the species, keeping in mind the carrying capacity of the habitat and the health of the ecosystem of which they form a constituent element.” (Marine Mammal Commission, 1995).
In recent years, one issue has dominated discussions of human/marine mammal interactions in the northeastern U.S. Off the New England coast, in the Gulf of Maine and Bay of Fundy, the population of harbor porpoise (*Phocoena phocoena*) has been determined to be in danger of depletion as a result of commercial bottom-set gill net fishing practices. A petition to list the species as threatened is currently being considered under the U.S. Endangered Species Act of 1973. The following table depicts the annual estimated bycatch of harbor porpoises in the Gulf of Maine during the years 1990–1995.

<table>
<thead>
<tr>
<th>Year</th>
<th>Number of Takes</th>
<th>Coefficient of Variation</th>
<th>95% Confidence Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990</td>
<td>2900</td>
<td>0.32</td>
<td>1500 - 5500</td>
</tr>
<tr>
<td>1991</td>
<td>2000</td>
<td>0.35</td>
<td>1000 - 3800</td>
</tr>
<tr>
<td>1992</td>
<td>1200</td>
<td>0.21</td>
<td>800 - 1700</td>
</tr>
<tr>
<td>1993</td>
<td>1400</td>
<td>0.18</td>
<td>1000 - 2000</td>
</tr>
<tr>
<td>1994</td>
<td>2100</td>
<td>0.18</td>
<td>1400 - 2900</td>
</tr>
<tr>
<td>1995</td>
<td>1400</td>
<td>0.27</td>
<td>900 - 2500</td>
</tr>
</tbody>
</table>

Table 1.1: Estimated Bycatch of Harbor Porpoise in the Gulf of Maine, 1990–1995

(Potter *et. al.*, 1997)

In 1994, the MMPA was amended to introduce a mortality limit figure known as the “potential biological removal level” or PBR:
"(20) The term "potential biological removal level" means the maximum
number of animals, not including natural mortalities, that may be removed from
a marine mammal stock while allowing that stock to reach or maintain its
optimum sustainable population..." (Marine Mammal Commission, 1995).

The PBR is calculated as follows (Marine Mammal Commission, 1995):

\[ \text{PBR} = N_{\text{MIN}} \times \frac{1}{2} R_{\text{MAX}} F_R, \]  

(1-1)

where

\[ N_{\text{MIN}} = \text{the minimum population estimate of the stock}. \]

\[ \frac{1}{2} R_{\text{MAX}} = \text{one-half of the maximum theoretical or estimated net productivity} \]

\[ \text{rate of the stock at a small population size}. \]

\[ F_R = \text{a recovery factor between 0.1 and 1.0}. \]

The weighted average of 1991 and 1992 abundance estimates is 47,200 animals (CV = 19\%, 95\% CI 39,500 - 70,600) (Smith, et. al., 1993). The 20th percentile of the
abundance estimate (40,297 animals) is used as \( N_{\text{MIN}} \). For cetaceans a default value of
0.4 is selected for \( R_{\text{MAX}} \) and \( F_R \) is set to 0.5. The result is a PBR of 403 animals
(Wade, 1998). As indicated in the table, annual bycatch exceeded the PBR by a factor
of three to five during every year that bycatch surveys were conducted. For the harbor
porpoise, this level of mortality is unsustainable.

In an effort to mitigate the bycatch levels, several different steps have been
taken. In addition to time-area closures restricting the activity of fishing vessels, there
have been attempts to modify the nets to make them more detectable to the animals. Much of this work has involved acoustic modifications. In some cases, objects are attached to the net or the net filaments are modified to increase acoustic reflectivity. In other cases, active alarms ("pingers") are used to deter the animals from the nets. The use of acoustic modifications to gill nets is discussed in more detail in section 2.3.

1.2. Goals for the System.

The concept of a system designed to track an animal through passive localization of its acoustic signals is not a new one; some examples of past efforts in this area are briefly reviewed in section 2.4.

This project arose from a conversation in December 1995 between Professor James H. Miller of the URI Ocean Engineering Department, and David C. Potter of the Northeast Fisheries Science Center (NEFSC) of the National Marine Fisheries Service (NMFS) in Woods Hole, MA. Potter, of the Protected Species Branch, had conceived of a system designed for deployment in the vicinity of a gill net section that would provide 3-D position tracks of a submerged harbor porpoise. NMFS researchers had previously been able to track large-scale movements of individuals using transmitter tags that communicated with a satellite, but the tags only operated during the times the animals were at the surface. Miller and Potter concluded that a system could be designed to track a harbor porpoise passively using the animal’s own ultrasonic echolocation signals. This system has been proposed as a tool to accomplish the following:

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(1) Study the effectiveness of various types of net modifications designed to mitigate bycatch. Assessing the effectiveness of deterrents has been (by necessity) a statistical problem. Having a means of observing activity near the nets provides new insight into the mechanism of entanglement.

(2) Correlate submerged behaviors with observed surface behaviors. With visual observation at the surface the only current means for gaining information about the behavior of wild porpoises, the system could provide details about underwater movements as well as synchronization between those movements and any vocalizations.

(3) Provide information about the animals when visual sightings are not practical, i.e. at night or in high sea state conditions.

As referenced in the last section, much of the NMFS experimental effort in the 1990s has been devoted to surveys of “strategic stocks” such as the Gulf of Maine harbor porpoise, i.e. population groups in which the bycatch level exceeds the PBR. Shipboard and land-based visual surveys have been used to provide abundance estimates. Data on bycatch incidents come from reports from fishermen or observers placed on fishing vessels. To date, the effectiveness of any bycatch reduction strategy has been assessed only through changes in the numbers of fatalities. An observation tool that can be deployed near a net section can provide useful information about the mechanism of net entanglements and can be an important part of any experimental approach to deterring bycatch through modifications to fishing gear.

All information about the animals' behavior is either from studies of captive animals in controlled experimental conditions or from observed behaviors of wild
animals at the surface. The porpoise spends a disproportionately small amount of time at the surface, typically characterized by a flash of dorsal fin and a small puff as the animal exhales through the blowhole on top of its head. Some information can be inferred from the numbers of animals present, frequency of sightings, distances between individual surfacings, etc. Given the turbidity of the water in the Gulf of Maine, however, visual surveillance of the animals underwater is virtually impossible. In this regard, an acoustic tracking system might provide valuable insight into submerged behaviors as well as correlation between submerged and surface behaviors.

The harbor porpoise is a relatively small animal that can be increasingly difficult to observe under varying environmental conditions. When abundance surveys are conducted by NMFS researchers, estimates of population density vary widely depending on sea state conditions (Palka, 1996). The animals are dark in coloration, and thus difficult to see in low-light situations. Though this system is not being considered as an alternative to the statistically sound surveying methods currently being used, it may serve well to provide informal information about the animals given poor observation conditions, i.e. high Beaufort sea state or at night.

1.3. Basic Conceptual Design of the System.

This project was conceived in a number of steps, progressing up to eventual deployment in the fishery itself. The desired final system would be placed near an actual gill net in the Gulf of Maine, an autonomous instrument that could be deployed from a boat and remain on the bottom in approximately 100 meters of water. The
instrument would detect the presence of the acoustic signals of an echolocating harbor porpoise, perform the data and signal processing tasks necessary to localize and track the animals, record the localization data and transmit it to a remote personal computer for logging and display.

As a preliminary step in the process, a prototype system was tested in Penobscot Bay, Maine during August 1997. In this system, two spatial arrays of four hydrophones apiece are deployed in 20–30 meters of water. The echolocation signals arrive at different times at the various hydrophones, depending on the direction of arrival of the incoming signals. The signals are sent along a cable to a shore station, where they are detected audibly with envelope detection circuitry, annotated, and recorded on a multichannel tape recorder for post-processing. Later, the analog recordings are digitized with a computer data acquisition system. Once digitized the signals are processed using Matlab. Time delay estimates are computed and used to determine the directional arrival angles of the signals. Triangulation of the bearing angles from each array provides estimates of location, which are in turn displayed graphically. The particulars of the analysis methodology, system construction and the experiment will be described in further detail in subsequent chapters.
2. Background.

In this section, various topics that form part of the background of this project are discussed in more detail. In section 2.1, some pertinent aspects of harbor porpoise biology are reviewed, followed by a more-in-depth look at the acoustic properties of the animal in section 2.2. This is followed by section 2.3, which investigates some particulars of the fishery operations, the mechanism of bycatch and mitigation efforts. Section 2.4 briefly introduces the subject of passive localization of animals, including some of the notable past efforts that have been undertaken. Lastly, section 2.5 reviews the mathematical basis for acoustic ray theory as a precursor to the methodology used for this acoustic tracking system.

2.1 Physical Characteristics of the Harbor Porpoise.

The harbor porpoise (*Phocoena phocoena*) is one of the smallest members of the marine mammal order Cetacea. It belongs to the suborder known as odontocetes or toothed whales, distinguished from the larger mysticetes or baleen whales.

The animal has nondescript coloration, usually ranging from gray to black on the back with a white belly and a small triangular dorsal fin. It has a small rounded head and lacks a distinct beak like some of the more commonly encountered dolphin species. It has earned the nickname “puffing pig” from the small puff of exhalation from its blowhole upon surfacing. An adult harbor porpoise ranges from 140–190 centimeters in length, with a mass from 55–65 kilograms. The life span is typically from 12–15 years. Harbor porpoise subsist primarily on groundfish such as herring
and mackerel, supplemented occasionally with mollusks or crustaceans. The species reaches sexual maturity at about 4–5 years, females typically giving birth to one calf per year. At birth, the animals are approximately 65–85 centimeters in length, with a mass of 5 kilograms.

![Harbor Porpoise](image)

*Figure 2.1: Harbor Porpoise (Phocoena phocoena)*

The animals inhabit coastal regions in the temperate and subarctic waters of the Northern Hemisphere. They typically move alone or in small groups. There are several apparently distinct population groupings in the North Atlantic. One of these populations is concentrated in the Gulf of Maine and Bay of Fundy region during the summer, and leaves during the winter. The winter destination isn't well known, but animals have been spotted along the entire eastern seaboard from New England to Cape Hatteras.

### 2.2 Acoustical Characteristics of the Harbor Porpoise.

Like most cetaceans, harbor porpoises use echolocation sonar to locate objects underwater. The exact mechanism for acoustic signal production is not yet fully understood. However, it is generally agreed upon that cetacean vocalizations are
produced in the animal's upper nasal passages and focused through a fatty region known as the melon, located in the forehead. One set of researchers compared the anatomical structure of a *Phocoena* head with that of a Commerson's dolphin (*Cephalorhynchus commersoni*). Despite the similarity in acoustic wave pattern and spectrum, there were major differences in the anatomical structure between the two species (Amundin et. al., 1988) that still leave questions open about the sound production apparatus.

Another anatomical study demonstrated that skull asymmetry in *Phocoena* (considered to play an important role in sound production) varies with individuals, yet is independent of size and age. This implies (1) that the animals can distinguish their own vocalizations from those of others and (2) that the anatomical components for echolocation are fully formed in juveniles, a very useful adaptation in areas of high turbidity like the Gulf of Maine (Yurick and Gaskin, 1988).

A number of researchers have studied the different types of vocalizations produced by the harbor porpoise. Some of the noteworthy experiments over the past 30 years are reviewed here.

During the mid-1960s the ability of a blindfolded porpoise to avoid thin wires was demonstrated, with the accompanying assumption that the animal was using echolocation (Busnel, Dziedzic, and Andersen, 1965; Busnel and Dziedzic, 1967; both referenced in Möhl and Andersen, 1973).

After the work of Busnel *et. al.* in France, Schevill, Watkins and Ray of the U.S. obtained recordings of *Phocoena* vocalizations. They reported short-duration
pulses of very narrow bandwidth, at 2000 Hz, with source levels of approximately 100 dB re 1μPa at 1 meter. Sometimes the clicks appeared singly, at other times repetition rates reached nearly 1000 per second (Schellwiek et al., 1969). They noted the lack of any apparent frequency-modulated “whistle” signal, characteristic of most delphinid species.

In 1970, Andersen performed experiments on the sensitivity and directionality of the hearing in a captive harbor porpoise. While his results were incomplete for the directionality test, his audiogram is the first completed for this species (Andersen, 1970). Andersen was unaware at the time of the experiments that the porpoise emitted any signals other than the 2 kHz clicks. He found, though, that the range of best sensitivity falls between 4 and 40 kHz. Hearing acuity is still sensitive at much higher frequencies, yet drops off sharply above 140 kHz.

Figure 2.2: Audiogram of the Harbor Porpoise (Andersen, 1970).
By 1970, it had been established that harbor porpoises echolocate, and that they generate tones in a band centered at 2 kHz. Higher frequency signals had been established for the bottlenose dolphin (*Tursiops truncatus*), but none had yet been discovered for *Phocoena*. In the USSR, Dubrovskii, Krasnov, and Titov noted a disparity. The harbor porpoise and a species of bat (*Myotis lucifugus*) had comparable abilities in discriminating thin metal wires (approximately 0.3 mm). The bat’s vocalizations at 55 kHz had a ratio of wavelength to filament thickness \( \lambda/d \) of about 20, whereas the porpoise vocalizations at 3 kHz (wavelength 0.5 meter) gave a \( \lambda/d \) nearly two orders of magnitude larger. Given further evidence of size discrimination experiments with *Tursiops*, they came to the conclusion (and later confirmed experimentally) that *Phocoena* emits an ultrasonic echolocation signal of at least 100 kHz, often in concert with a component in the 25-30 kHz region. They also expressed the important hypothesis that, given the differences in object size resolution and signal directionality, the animals would possibly use a high frequency signal for detection and discrimination of targets, and a lower frequency signal for acoustic orientation in a body of water (Dubrovskii *et. al.*, 1971).

The experiment that set the basis for current knowledge of the high-frequency echolocation was reported by Møhl and Andersen in 1973. They took Andersen’s audiogram work to refute the idea of echolocation using the 2 kHz clicks. The signals (at source levels estimated by Schevill *et. al.* at only 100 dB re 1\(\mu\)Pa) would have return echoes from a 0.5 mm wire at a distance of 0.5 meter of approximately 0 dB re 1\(\mu\)Pa, nearly 65 dB lower than the animal’s auditory threshold at that frequency. They
set out to detect higher frequency signals with a sophisticated array of analysis equipment. Three hydrophones were positioned in a triangle 1 meter on a side, 0.4 meters below the surface in a tank measuring 9 x 5 x 1 meters. They detected a high frequency signal in the form of a gated sine wave of duration on the order of 100 $\mu$sec. The computed source level was on average 140 dB re 1 $\mu$Pa at 1 meter. Their analysis of the spectral content of the signal indicated that the bulk of the energy was concentrated between 100 and 160 kHz, centered at 130 kHz, near the upper limit of the auditory sensitivity of the animal. An example of this high frequency signal appears in Figure 2.3.

![Echolocation Signal](image)

**Figure 2.3: Echolocation Signal of the Harbor Porpoise (Møhl and Andersen, 1973)**

Regardless of the limited dynamic range of their equipment and the directionality of the high-frequency signals, when the porpoise was facing a hydrophone and within 1 meter, the high frequency signal was consistently emitted
during the first cycle of an accompanying low frequency component. They estimated
the directionality at 27 dB of attenuation measured 90° from straight ahead of the
animal, and used this information to explain the observation that they had not been able
to track the porpoise by triangulation (Møhl and Andersen, 1973).

In 1981, Kamminga and Wiersma in the Netherlands experimented with a
captive juvenile and obtained clicks with a dominant frequency of 140 kHz.

![Echolocation Signal and Spectrum of the Harbor Porpoise](image)

**Figure 2.4: Echolocation Signal and Spectrum of the Harbor Porpoise**

(Kamminga, 1988)

However, a new animal arrived at the aquarium, and recordings were made
shortly after her arrival. They indicated a bimodal click, with spectral peaks at both
120 and 20 kHz. Both components are tightly locked in time over the course of a train
of clicks. To quote, “The different propagation and resolution properties of the two
dominant frequencies are assumed to be responsible for short range and long range
echolocation.” (Kamminga, 1988).
A very different type of experiment to study the porpoise's auditory perception was conducted in the USSR (Popov et. al., 1986). The researchers measured the evoked potentials (electrical response to neural stimuli) in the auditory cortex of a test animal over a range of frequencies. The lowest evoked potential thresholds were observed between 120 and 130 kHz, with another sensitivity peak between 20 and 30 kHz. The minimum threshold levels eliciting an evoked potential response were on the order of 60 dB re 1μPa. It appears logical that these peaks in sensitivity cover the same frequency bands as the vocalizations.

New data on the source levels of harbor porpoise echolocation signals appeared in 1992. In an experiment to determine the rate of occurrences of click trains, Akamatsu et. al. developed an instrument known as a click light. Due to the problems of directionality and echoes off the surface, echolocations could be counted more accurately by observing light pulses activated by the vocalizations. The circuitry was set to trigger the click light for signals between 28 and 180 kHz at strengths greater than 150 dB re 1μPa, detected with a hydrophone attached to the melon. Another
hydrophone in the pool was used to make the recordings. With the animal oriented towards this hydrophone at known distances, source level could be calibrated. As shown in figure 2.6, many of the clicks had source levels 20–30 dB higher than the previously recorded values of 140 dB re 1 µPa at 1 meter (Akamatsu et. al., 1994). It is worth noting that these signal levels are still orders of magnitude weaker than the echolocation signals of *Tursiops*, with maximum source levels near 229 dB re 1 µPa at 1 meter (Au, 1993).

![Figure 2.6: Source Levels vs. Frequency (Akamatsu et. al., 1992)](image)
In 1993, several juvenile harbor porpoises were rescued after strandings and brought to the Harderwijk Marine Mammal Park in the Netherlands. Numerous experiments were performed by different sets of participants using these animals, each with the goal of gaining insight into the entanglement issue. Goodson et. al. (1995) conducted an experiment to study the characteristics of the echolocation signals of these animals. Their results showed an average source level of 149.5 dB re 1 µPa at 1 meter for both of the two animals tested. A distinction to note is that these data were obtained in a pool, whereas the experiments of Akamatsu et. al. were conducted in an outdoor net enclosure. A reduced source level for the highly reverberant environment of the pool seems intuitively reasonable. The peak frequency was approximately 145 kHZ for both animals. This high frequency seems consistent with the intuitive notion that the dominant frequency of the click would be high for juveniles, and would drop with increasing body size.

Another experiment at Harderwijk (Verboom and Kastelein, 1995) studied the characteristics of echolocations of the animals as they swam freely in the pool. They noted a number of differing “phrase” types. These ranged from single clicks of approximately 100 µsec duration, to “click bursts,” short series of clicks of longer duration and high pulse repetition frequency (PRF). Beyond this were the “click series” lasting multiple seconds. A conclusion was that the single clicks and low PRF click trains were emitted for navigation and general survey, and that the high PRF click bursts, blocked bursts and click series were used for detailed investigation of objects. They noted the effects of high PRF on analysis, with harmonics of the PRF
superimposed on the low frequency click spectrum. Currently, there seems to be no conclusive purpose for the low frequency (2 kHz) component of the signal, whether it is used for communication or is just a by-product of the high-frequency signal generation. They also noted a broadband (13–100 kHz) click of very short duration, hypothesized to be for long-range observations, and the existence of variable frequency continuous tone whistles were also demonstrated, not previously mentioned in any of the literature. The whistles were of low frequency, varying between 47 and 600 Hz, with the 2 kHz component superimposed.

Another facet of the phocoenid sonar that has not been extensively studied is its directionality. While most researchers studying the sound production apparatus agree that signal generation occurs in the dorsal bursae, Aroyan et. al. (1992, referenced in Goodson and Sturtivant, 1996) concluded that the melon and air sacs within the head determine the directivity. The melon is filled with a fatty substance that allows for impedance matching with the water, and the cross-sectional dimensions form the aperture for estimating the beamwidth in azimuth and elevation (Goodson and Klinowska, 1990, referenced in Goodson and Sturtivant, 1996). Studying post mortem tissue samples, Goodson and Sturtivant found maximum melon dimensions of 62 mm in the horizontal and 37 mm in the vertical. This translates to -3 dB beam widths of approximately 9 and 15 degrees, respectively. For details, beam width calculations for both line arrays and circular plane arrays are covered in section 3.9 of Urick (1983).
2.3 Gill Net Fishing, B ycatch and Bycatch Reduction Strategies.

Many commercial fishermen frequently make use of gill nets in order to catch fish. The following information describing these nets and their use comes from DeAlteris and Castro (1990). The nets are composed of a wall of nylon monofilament mesh webbing of variable size. The mesh openings are designed specifically for a given target species so that a fish swimming into it will become stuck when its body circumference is larger than the mesh opening; typically fish get caught behind the gills. Various methods of deployment of these nets are used, i.e. they can be bottom-set, free drifting, or dragged. The nets are usually placed in areas of high current, set across the path of fish migration.

In the Gulf of Maine, the bulk of gill net fishing is with bottom-set nets for catching groundfish species such as cod and pollock. For bottom deployment, each section of net is weighted along the bottom edge and has floats along the top to keep the nets open and upright. A section of net is typically 300 feet long, and 12–15 feet high; “strings” of nets are formed by attaching multiple nets end-to-end. The net strings are placed on the bottom for at least 24 hours before retrieval.

![Gill Net Section](image)

Figure 2.7: Gill Net Section (DeAlteris and Castro, 1990)
The mechanism of bycatch of harbor porpoises and other cetaceans in gill nets is poorly understood. Gaining insight into that mechanism is one of the principal motivations for this project. While time-area closures restricting fishing operations are effective in reducing bycatch, the hopes of finding an effective deterrent that will not have a negative impact on the industry motivate continued research into gear modifications. Given the lack of knowledge about the entanglement process, a simplification of the issues leads to two basic questions: (1) can the animals detect the nets, and (2) if they are detected, do the animals perceive the nets as a danger?

In order to answer the first question, experiments to determine the acoustic properties of the nets themselves have been conducted (e.g. Au and Jones, 1991). Given their calculations of the target strength of nets with various filaments, Au and Jones concluded that an echolocating dolphin or porpoise should be able to detect the nets at distances large enough to avoid entanglement. Hatakeyama and Soeda (1990) reported detection ranges of 2 meters for the net mesh and 9 meters for the float line, which runs along the top of the net. They also recalled a 1983 experiment in open water where a Dall's Porpoise (*Phocoenoides Dalli*) successfully navigated through a 1.5 x 1 meter hole in a gill net without reducing its swimming speed.

In tank tests, harbor porpoises detected the float line of the net and swam more cautiously. As they became accustomed to the surroundings, they became careless and became entangled (Hatakeyama and Soeda, 1990). In another experiment, juvenile harbor porpoises became entangled immediately, but swam more cautiously, only getting caught when approaching the nets from oblique angles (Kastelein, *et. al.*, )
Given that the possibility of net detection exists, dolphins and porpoises are still being caught. In most cases of mortality, the animals’ stomach contents indicate recent feeding. Assuming that the animals are caught while foraging for food, the question of why they become entangled in the nets arises. Au and Jones (1991) and Au (1994) suggested the following theories:

(1) Cetaceans may not always be echolocating. Wood and Evans (1980, cited in Dawson, 1991) showed that dolphins could repeatedly catch fish without echolocating, presumably listening to the sounds generated by the fish as it swam.

(2) Detecting an object is not the same as perceiving that object as an obstacle (the concept of a barrier is likely an alien one to a wild animal).

(3) The animals are feeding on prey in the same general location as the fishing operation and are too distracted to notice the nets,

(4) The sonar returns from the fish are much stronger than the nets (20 dB or more increase in target strength over the nets at echolocation frequencies) so the dolphin or porpoise fails to perceive it.

(5) Disturbances caused by entangled fish actually attract the attention of the animals and draw them to the net.

Goodson and Sturtivant (1996) theorized that the vertical beamwidth of the animal may determine whether the height of the float line can affect the bycatch. In slack water, the risk for entanglement would be greatest, as the float line would be highest and the noise generated by the motion of the net would be minimal. An explanation offered for the inability to distinguish the net while echolocating on a target
is that the porpoise echolocates at a range-dependent pulse repetition rate. When
locked on a target, echoes that fall outside the expected time window may be ignored.

The use of acoustic modifications to the gill nets is a matter of vigorous debate.
Passive devices designed to increase the reflectivity have had a marginal impact (if any)
on bycatch (e.g. Hembree and Harwood, 1987, cited in Dawson, 1991). The use of air
filled reflectors—with "soft" echo characteristics—may be perceived of as "food-like"
by the animals (Goodson et. al., 1994a).

In order for a net modification scheme to be practical, (1) the modifications
should have reasonable longevity under commercial fishing conditions, (2) they must
be safe to handle, (3) they should be lightweight and inexpensive, and (4) they cannot
decrease the catch of target fish species below an economic level (Dawson, 1994).
Although the bycatch levels are high, the catch per unit effort is low. In order to
assess the effectiveness of a practical modification, the modifications have to be tested
on a large scale in order for the results to be judged statistically significant
(Dawson, 1991).

Active acoustic devices ("pingers") are even more hotly debated. The high cost
and complications of maintenance are prohibitive. For high frequency alarms,
attenuation is a consideration, so multiple emitters would be needed to successfully
sonify a long net string. In order for active acoustic alarms to work, one of the
following must be true (1) the sound generated must be aversive enough to frighten the
animals away from the net, (2) the alarm should attract the notice of the animal and
encourage it to investigate the net thoroughly, or (3) it should be effective as a warning
of danger associated with the nets. This last option requires learning; only an animal
that survives an entanglement learns to make that association (Dawson, 1994). If the
cetacean fails to make the association, it quickly becomes habituated to the signal
(Gaskin, 1984, cited in Dawson, 1994).

Despite the difficulties, a series of experiments were conducted in New England
waters from 1992–1994 to test the effectiveness of acoustic alarms on gillnet sections
(Lien, 1993; Kraus et. al., 1994). In the 1992 and 1993 experiments, the data sampled
weren’t considered extensive enough to provide a statistically significant result. The
1994 experiment (a larger, standardized effort with double blind experimental
procedures to minimize bias) concluded with the judgment that the pingers had reduced
the level of bycatch of harbor porpoise to the point of statistical significance. The
questions of why and how the pingers work, whether the porpoises will habituate to the
sounds, whether the results would apply to other species, etc. still remain. One theory
is that the animals avoided the area because their prey avoided the alarms. The
alarmed nets showed a large reduction in the incidental take of Atlantic herring, a
primary food fish for the harbor porpoise. The herring is known to have hearing
sensitivity at least high enough in frequency to be affected by the 10kHz pingers that
were used in the experiment.

In 1994, Kastelein et. al. (1995b) performed an experiment in a pool with two
juvenile harbor porpoises and two samples of the alarms used in Lien’s 1993
experiment. Both of the alarms had fundamental frequencies at 2.5 kHz, but one
generated a pure sine tone and the other had sizable harmonic distortion, particularly at
the 7th harmonic (17.5 kHz). The purely sinusoidal alarm prompted the animals to approach the alarm and echolocate on it. By contrast, the animals seemed frightened by the distorted alarm, would not echolocate, and schooled together, swimming in circles.

While acoustic bycatch deterrents have been the cause of much dispute, it would seem cost effective to be able to assess the effectiveness of an experimental solution on a small scale before recommending its implementation to a large proportion of the commercial fishing effort for evaluation.

2.4 Passive Acoustic Localization of Animals: Discussion of Past Efforts.

To make the distinction from active sonar (in which sound is generated, reflects from a target and is received), passive localization techniques provide the ability to estimate the location of a sound source, based on one-way acoustic transmission between the source and the localization system. The acoustic localization system operates in receiving mode only. This is a fundamental feature for submarine operations, where detecting an enemy without alerting him to your presence is highly desirable. In the case where the sound source is a vocalizing animal, position estimates can be determined by measuring the time-of-arrival differences of the signal between pairs of acoustic receivers separated in space. The time delay between arrivals at one pair of receivers constrains the position of the animal to some region of space. Another pair of sensors determines a different region. The intersections of these regions determine the location of the animal (Spiesberger and Fristrup, 1990).
A number of different experiments to localize animals have been constructed on the basis of time delay measurements. Watkins and Schevill (1972) used an array of four hydrophones in a tetrahedral configuration, suspended from a boat. They were able to localize (in bearing angle) various whale species from vocalizations as well as tail fluke slaps at the surface. Systems with different configurations of receiving elements have been used in air for localizing birds (e.g. Magyar, et. al., 1977). Others have been used in the water for other marine mammal species; some examples are Hawaiian spinner porpoises (Watkins and Schevill, 1974), Southern right whales (Clark, 1980), Atlantic bottlenose dolphins (Freitag and Tyack, 1993) and Atlantic Spotted dolphins (Au and Herzing, 1997). Spiesberger and Fristrup (1990) demonstrated the use of animal vocalizations for tomographic mapping of wind and sound speed fields. The fact that this localization can be performed is a consequence of acoustical ray theory. The next section contains a derivation of the ray equation and describes its use to determine the direction of the incoming wave.

2.5 Ray Acoustics.

In this section, the theory of ray acoustics is presented as the basis for the bearing angle estimation problem. It will be demonstrated that a solution to the wave equation exists in which the direction of acoustic energy propagation is normal to a surface of constant phase. The derivation that follows comes primarily from section 6.2 of Ziomek (1985) with some information from section 5.13 of Kinsler and Frey (1982). The solution begins with the linearized wave equation. In this case the
parameter varying in space and time is pressure \( p(r,t) \), but this can be replaced with velocity potential \( \Phi(r,t) \) without affecting the solutions.

\[
\nabla^2 p(r,t) = \frac{1}{c^2(r)} \frac{\partial}{\partial t} p(r,t)
\]

(2-1)

where \( r = (x,y,z) \) and \( c(r) \) is the spatially dependent speed of acoustic propagation through the medium. Assume that the signal has harmonic time dependence.

Substituting \( p(r,t) = p(r) \exp[j \omega t] \) in (2-1):

\[
\nabla^2 p(r) \exp[j \omega t] + \frac{\omega^2}{c^2(r)} p(r) \exp[j \omega t] = 0
\]

(2-2a)

dividing out the complex exponential, this can be reduced to

\[
\nabla^2 p(r) + k^2(r)p(r) = 0
\]

(2-2b)

where the wave number \( k(r) = \omega/c(r) \). This is the time-independent Helmholtz wave equation. We assume a solution of the form

\[
p(r) = a(r)\exp[j \Phi(r)] = a(r)\exp[-jk_0 W(r)]
\]

(2-3)

where \( a(r) \) is a real-valued amplitude function, and the reference wave number \( k_0 = \omega/c_0 \), where \( c_0 \) is the speed of sound at \( r = (x_0,y_0,z_0) \). \( W(r) \) has units of length. Values of \( r \) that cause \( W(r) \) to be equal to a constant define surfaces of constant phase.
or wavefronts. $\nabla W(r)$ is normal to the wavefront everywhere on the face of the wavefront, defining the ray path (the direction of energy propagation).

In order to apply the solution suggested in equation 2-3 we obtain the Laplacian of $p(r)$, by first taking the gradient of $p(r)$, then taking the divergence of the result:

$$\nabla p(r) = \left[\nabla a(r) - jk_0 a(r) \nabla W(r)\right] \times \exp[-jk_0 W(r)]$$

$$\nabla^2 p(r) = \nabla \cdot (\nabla p(r))$$

$$= \left[\nabla^2 a(r) - k_0^2 a(r) |\nabla W(r)|^2 - jk_0 [a(r) \nabla^2 W(r) + 2 \nabla a(r) \cdot \nabla W(r)]\right]$$

$$\times \exp[-jk_0 W(r)]$$

Substituting this value of $\nabla^2 p(r)$ into the Helmholtz equation (2-2b):

$$\nabla^2 a(r) + k_0^2 \left[n^2(r) - |\nabla W(r)|^2\right] a(r)$$

$$- jk_0 [a(r) \nabla^2 W(r) + 2 \nabla a(r) \cdot \nabla W(r)] = 0$$

(2-4)

where the index of refraction $n(r) = c_0/c(r) = k(r)/k_0$. Both the real and imaginary parts of equation (2-4) must be equal to zero. The imaginary part is known as the transport equation and is used in the calculation of $a(r)$. For this development, we will eventually assume a constant $a(r) = A$, which will satisfy the transport equation.

Taking the real part of (2-4) and dividing by $k_0^2 n^2(r) a(r)$,

$$1 + \frac{1}{k_0^2 n^2(r)} \left[\frac{\nabla^2 a(r)}{a(r)} - k_0^2 |\nabla W(r)|^2\right] = 0$$

(2-5)
If \(a(r)\) and \(c(r)\) do not vary appreciably over the distance of a wavelength, we can assume
\[
\frac{\nabla^2 a(r)}{a(r)} \ll k_0^2 |\nabla W(r)|^2
\]

The validity of this assumption increases with frequency. Then the \(\nabla^2 a(r)/a(r)\) term can be dropped and equation (2-5) reduces to
\[
|\nabla W(r)|^2 = n^2(r)
\]  \hspace{1cm} (2-6)

Equation (2-6) is called the **eikonal equation**, which gives the point-by-point trajectory of the ray path as it travels through the acoustic medium by relating the gradient of the wavefront to the local index of refraction. Assume that \(\nabla W(r)\) can be written as
\[
\nabla W(r) = n(r) \left( u(r) \hat{x} + v(r) \hat{y} + w(r) \hat{z} \right)
\]  \hspace{1cm} (2-7)

where \(u(r), v(r), w(r)\) are direction cosines that the ray path makes with the coordinate axes at a given point \(r\). They are defined by the relationship
\[
u^2(r) + v^2(r) + w^2(r) = 1,
\]  \hspace{1cm} (2-8)

which insures that the eikonal equation is satisfied. If the gradient of \(W(r)\) is written out,
\[ \nabla W(r) = \frac{\partial}{\partial x} W(r) \hat{x} + \frac{\partial}{\partial y} W(r) \hat{y} + \frac{\partial}{\partial z} W(r) \hat{z} \]  

(2-9)

then from (2-7) and (2-9)

\[ n(r)u(r) = \frac{\partial}{\partial x} W(r) \]  

(2-10)

\[ n(r)v(r) = \frac{\partial}{\partial y} W(r) \]  

(2-11)

\[ n(r)w(r) = \frac{\partial}{\partial z} W(r) \]  

(2-12)

Next we define an infinitesimal element along the ray path at position \( r \) of arc length \( ds \), where \( u = dx/ds, v = dy/ds, \) and \( w = dz/ds \). The directional derivative of \( W(r) \) is

\[ \frac{d}{ds} W(r) = \frac{\partial}{\partial x} W(r) \frac{dx}{ds} + \frac{\partial}{\partial y} W(r) \frac{dy}{ds} + \frac{\partial}{\partial z} W(r) \frac{dz}{ds} \]

\[ = n(r)u^2(r) + n(r)v^2(r) + n(r)w^2(r) \]

\[ = n(r) \]  

(2-13)

and the variation of \( \nabla W(r) \) along the ray path is determined from differentiating \( d(\nabla W(r))/ds \). Separating \( \nabla W(r) \) into components (x-direction used for example),

\[ \frac{d}{ds} \left( \frac{\partial W}{\partial x} \right) = \frac{\partial}{\partial x} \left( \frac{\partial W}{\partial x} \right) \frac{dx}{ds} + \frac{\partial}{\partial y} \left( \frac{\partial W}{\partial x} \right) \frac{dy}{ds} + \frac{\partial}{\partial z} \left( \frac{\partial W}{\partial x} \right) \frac{dz}{ds} \]

Rearranging the order of the partial differentiations,
\[
\frac{d}{ds} \left( \frac{\partial W}{\partial x} \right) = u \frac{\partial}{\partial x} \left( \frac{\partial W}{\partial x} \right) + v \frac{\partial}{\partial x} \left( \frac{\partial W}{\partial y} \right) + w \frac{\partial}{\partial x} \left( \frac{\partial W}{\partial z} \right)
\]

\[
= u \frac{\partial}{\partial x} (nu) + v \frac{\partial}{\partial x} (nv) + w \frac{\partial}{\partial x} (nw)
\]

\[
= u^2 \frac{\partial n}{\partial x} + v^2 \frac{\partial n}{\partial x} + w^2 \frac{\partial n}{\partial x}
\]

\[
= \frac{\partial n}{\partial x}.
\]

Similar results for the components in the \( y \) and \( z \) directions lead to the vector form of the ray equation (2-14).

\[
\frac{d}{ds} \nabla W(r) = \nabla n(r) \tag{2-14}
\]

To determine the scalar form of the ray equations, take the derivative with respect to \( s \) of the three equations (2-10) through (2-12). For the \( x \)-component,

\[
\frac{d}{ds} n(r)u(r) = \frac{d}{ds} \left( n(r) \frac{dx}{ds} \right) = \frac{d}{ds} \frac{\partial}{\partial x} W(r) = \frac{\partial}{\partial x} \frac{d}{ds} W(r)
\]

substituting in (2-13), the three scalar ray equations are

\[
\frac{d}{ds} \left( n(r) \frac{dx}{ds} \right) = \frac{\partial n(r)}{\partial x} \tag{2-15}
\]

\[
\frac{d}{ds} \left( n(r) \frac{dy}{ds} \right) = \frac{\partial n(r)}{\partial y} \tag{2-16}
\]

\[
\frac{d}{ds} \left( n(r) \frac{dz}{ds} \right) = \frac{\partial n(r)}{\partial z} \tag{2-17}
\]
Equations (2-15), (2-16) and (2-17) are a generalized form of Snell's Law, which describes refraction in a medium based on spatial variation of the speed of propagation.

For an example, assume a sound speed profile that varies only in depth, in other words, \( n(r) = n(z) = c_0 \cdot c(z) \), then \( \partial n/\partial x = \partial n/\partial y = 0 \) and the ray equations are:

\[
\frac{d}{ds} \left( n(z) \frac{dx}{ds} \right) = 0 \tag{2-18}
\]

\[
\frac{d}{ds} \left( n(z) \frac{dy}{ds} \right) = 0 \tag{2-19}
\]

\[
\frac{d}{ds} \left( n(z) \frac{dz}{ds} \right) = \frac{\partial n(z)}{\partial z} = \frac{dn(z)}{dz} \tag{2-20}
\]

Integrating (2-18) and (2-19) with respect to \( s \),

\[
n(z) \frac{dx}{ds} = \text{constant} \tag{2-21}
\]

\[
n(z) \frac{dy}{ds} = \text{constant} \tag{2-22}
\]

Dividing (2-21) by (2-22) gives the result \( u/v = \text{constant} \). The physical implication of the constant ratio of the two direction cosines is that the ray path is confined to a plane orthogonal to the XY plane, i.e. the projection of the ray path on the XY plane is a straight line.

Making use of the wave number \( k(z) = k_0 n(z) = \omega/c(z) \), we define the propagation vector \( \mathbf{k}(z) \).
\[ k(z) = k(z) \hat{n}(y) \]
\[ = k_o \left[ n(z) \frac{dx}{ds} \hat{x} + n(z) \frac{dy}{ds} \hat{y} + n(z) \frac{dz}{ds} \hat{z} \right] \]
\[ = k_x \hat{x} + k_y \hat{y} + k_z \hat{z}, \]
\[ (2-23) \]

where \( k_x \) and \( k_y \) are constants. The projection of \( k(z) \) onto the \( XY \) plane \( k_r \) is
\[ k_r = \sqrt{k_x^2 + k_y^2} \]
\[ (2-24) \]

It can be seen that the constant \( k_r = k(z) \sin \theta(z) \), and therefore,
\[ \frac{\sin \theta(z)}{c(z)} = \frac{\sin \theta(z_0)}{c(z_0)} \]
\[ (2-25) \]

which is the familiar form of Snell's Law.

For the case of a homogeneous medium with constant sound speed, all the components of the propagation vector are constants. The resulting ray path is a straight line, and the wavefront is a plane. A solution to the wave equation is given by

\[ p(r, t) = A \exp \left[ j \left( \omega t - k_o \hat{n} \cdot r \right) \right] \]
\[ = A \exp \left[ j \omega \left( t - \frac{\left( ux + vy + wz \right)}{c_o} \right) \right] \]
\[ (2-26) \]
The system that this thesis describes makes use of the plane wave solution to the wave equation, in which estimates of the time delays between spatially separated hydrophones are used to determine the direction cosines of the ray path of the incoming signal.
3. Methodology.

3.1 Passive Acoustic Localization.

As a consequence of ray theory, it is possible to localize a sound source underwater by measuring the time delays between acoustic signal arrivals at spatially separated receivers. As mentioned in chapter 2, researchers have used this approach to the localization of animals using their natural sounds. Typically, position is determined by defining curves of constant time difference of arrival (TDOA) between pairs of receivers, then finding the intersections of those curves. The constant TDOA curves are hyperboloids of rotation; in two dimensions they are reduced to hyperbolae. With a minimum of four hydrophones, three intersecting hyperboloids exist which determine source location. At large distances, the hyperboloids can be closely approximated by cones formed by rotating the asymptotes about the axis connecting the hydrophone pair (Schau and Robinson, 1987). While this approach has been used successfully in marine mammal tracking, localization accuracy decreases quickly with distance. Figure 3.1 illustrates this, using the two-dimensional case of an array of three hydrophones. As the sound source moves further away from the array, accurately pinpointing the intersection of the hyperbolae becomes extremely difficult. Using the hyperbolic TDOA method, a source can only be effectively localized within distances on the order of 5 times the hydrophone spacing (Lashkari, 1997).

This approach to the localization problem was abandoned for a number of reasons. The most important of these is the porpoise’s acoustic directionality. The classical localization problem involves an omnidirectional source. Unfortunately, the main lobe of a harbor porpoise’s transmitting beam is extremely narrow. Au (1993)
Figure 3.1: 2-D Hyperbolic Localization at Short and Long Ranges
determined that the -3dB beamwidths for *Tursiops truncatus* were approximately 10 degrees in both horizontal and vertical directions. Beam patterns for the beluga whale (*Delphinapterus leucas*) are even narrower, on the order of 6 degrees. If we want to localize an animal 20 meters away, the hydrophones would need to be spaced at least 4 meters apart. At this spacing it is entirely possible that a nearby porpoise could be echolocating and yet not be received by some of the hydrophones depending on the animal’s orientation. Also, the echolocation signals of a harbor porpoise are of relatively low source level (on the order of 160 dB re 1 μPa at 1 meter) and therefore have much smaller detection range than a bottlenose dolphin (>220 dB) operating in the same general frequency band (Au, 1993). In addition to the acoustic difficulties, issues of cost and practicality arise. Large spacing between hydrophones would require separate cable runs and amplification circuitry at each of the receiver locations.

In lieu of this approach, we opted to use another technique arising from radar and sonar called line of position fixing (LOP). First, the incoming wavefronts are assumed to be planar. As a result, the cosine of the bearing angle measured relative to two receivers is simply the speed of sound $c$ multiplied by the time delay estimate divided by the distance between the receivers (Carter and Robinson, 1993). This is covered in greater detail in sections 3.4 and 3.5. With a three-dimensional spatial array of four hydrophones, an unambiguous estimate of direction to the source in azimuth and elevation can be calculated. Each such direction estimate determines a line of position coinciding with the assumed straight ray path between the source and the receiver axis. With at least two arrays of this type, the intersection of two lines of
position marks the location of the source; this position can be computed from simple triangulation. Quazi (1991) described some of the sources of error that affect the estimations of bearing and range, i.e. limited signal to noise ratio, uncertainty in receiver positions, loss of coherence of the signal, Doppler effects, and amplitude and phase errors from the plane wave assumption. In the case where directionality prevents the signal from reaching one (or more) of the arrays, a single array can still provide an accurate bearing angle estimate (an improvement over the hyperbolic TDOA method).

3.2 Time Delay Estimation.

Time delays can be difficult to estimate accurately. Watkins and Schevill (1972) determined delays through visual inspection of oscilloscope traces. This is impractical and useless in cases of low signal-to-noise ratio. Instead, a method for estimating time of arrival differences that has become standardized is known as cross correlation. Assuming a signal emanating from a distant source, the arrivals at two separated receivers are represented as

\[
x_1(t) = s(t) + n_1(t) \\
x_2(t) = s(t - D) + n_2(t)
\]

where \( D \) is the delay being estimated, \( s(t) \) is the signal, \( n_1(t) \) and \( n_2(t) \) are uncorrelated Gaussian white noise functions. The cross correlation function \( R_{x_1x_2}(\tau) \) is:
\[ R_{x_1 x_2}(\tau) = \int_{-\infty}^{\infty} x_1(t)x_2^*(t - \tau)dt \] (3-3)

The peak of the cross correlation occurs at the time lag \( \tau \) that minimizes the mean square error between the two signals; this value of \( \tau \) is used as the estimate of delay \( D \).

For finite data records sampled digitally, some adjustment in the calculation of cross correlation functions is required. The continuous time variable \( t \) is replaced by the discrete time variable \( k \), and the linear cross correlation function estimate for a record of length \( K \) is evaluated as

\[ R_{x_1 x_2}[j] = \sum_{k=1}^{K} x_1[k] x_2^*[k - j] \] (3-4)

As the length of data records becomes large, calculation using (3-4) becomes time consuming; a more efficient method of calculating the cross correlation function makes use of calculations in the frequency domain. The dual of the convolution operation in the time domain is simply multiplication in the frequency domain. Additionally, the dual of time reversal is complex conjugation in the frequency domain; as a special case of convolution, cross correlation of two time domain signals is implemented by first performing Fourier transforms upon the signals, then multiplying one signal's Fourier transform by the complex conjugate of the second. For two functions \( x_1(t) \) and \( x_2(t) \) with Fourier transforms \( X_1(f) \) and \( X_2(f) \), the cross correlation function \( R_{x_1 x_2}(\tau) \) is then simply the inverse Fourier transform of the cross spectral density \( S_{x_1 x_2}(f) \):
\[ R_{x_1, x_2}(\tau) = \int_{-\infty}^{\infty} S_{x_1, x_2}(f) e^{j2\pi f \tau} df = \int_{-\infty}^{\infty} X_2(f) X_1^*(f) e^{j2\pi f \tau} df \] (3-5)

Equation 3-5 is part of a set of equations known as the Wiener-Khinchine relations (Bendat and Piersol, 1986).

Given two discrete data records \( x_1[k] \) and \( x_2[k] \) of length \( 2^N \), where \( N \) is an integer, the cross correlation function can again be determined as a special case of convolution. This can be implemented as before using either a linear correlation operation (equation 3-4) or frequency domain (circular) method. In the circular method the correlation is implemented just as in the continuous case; the FFT of one signal is multiplied by the complex conjugate of the FFT of the second signal, then the inverse FFT is performed. One important point to note is that the linear convolution of two sequences of length \( N \) produces a result of length \( 2N-1 \). In circular convolution the sequence length remains \( N \) and the result "wraps around" the ends of the inverse FFT transformed sequence. In order to implement linear convolution (correlation) using the FFT, the data sequences are zero-padded to lengths of at least \( 2N-1 \) (typically to the next power of two) before the FFT operations. The wrapping effects of the inverse FFT operation, as well as differences in output sequence length, need to be accounted for in comparing the two approaches.

In the case of the data used for this project, each sequence was 1001 points long. Matlab's linear cross correlation "xcorr" function produces a sequence 2001 points long, but a computationally efficient circular correlation was applied by zero padding the sequences to 2048 points before the FFT, multiplication and inverse FFT.
operations. Figure 3.2 displays the results of both methods using Matlab. A synthetic signal (windowed pulse at 135 kHz) is cross-correlated with an identical delayed signal. When scaled properly as shown in the figure, the results are consistent using both “xcorr” and the circular correlation procedure.

In order to improve the time delay estimates, prefiltering schemes have been used to attempt to minimize the variance of the time delay estimate (e.g. Knapp and Carter, 1976). All of these schemes are built on an assumption that the signal is a stationary Gaussian random process. They also require knowledge or estimates of the coherence of the signal at different frequencies. Given that the signal generated by the porpoise is in fact a narrowband continuous wave (CW) pulse it was decided to instead simplify matters by using a bandpass filtering scheme (admittedly non-optimal) to reduce the effect of the noise on the time delay estimation.

Knowing that the harbor porpoise echolocation signals are typically centered around 130-140 kHz, a 6th order Butterworth bandpass filter was implemented in Matlab with -3dB points at 100 and 150 kHz. For the data used in this thesis, the signals were filtered in the time domain; a more efficient approach (that will be used with subsequent analysis) applies the filter in the frequency domain. To begin, the Butterworth filter was applied to a discrete-time impulse function using the “filter” command. The resulting function is h[k], the filter’s impulse response, which is transformed into the frequency domain function H[f] using the FFT. H[f] is multiplied by its complex conjugate; the result is W[f], the magnitude of the frequency response of the filter. This weighting function is applied to (multiplied by) the cross-spectral density \( S_{12}[f] \) before the inverse FFT operation to produce the cross correlation.
Figure 3.2: Cross Correlation: Time- and Frequency-Domain Methods
Early in the process of designing this experiment, it was thought that computer data acquisition equipment would be used in the field for sampling the data. However, systems that are capable of adequately sampling multiple channels of high (>150 kHz) frequency signals were prohibitively expensive at the time. For narrowband signals that are to be sampled, it can be beneficial to perform complex demodulation on the signal to shift the spectrum of the signal into a frequency band better suited for data retrieval. A real-valued signal \( x(t) \) with corresponding Fourier transform \( X(j\omega) \) is modulated with a complex exponential:

\[
e^{j\omega_c t} x(t) \Leftrightarrow X[j(\omega - \omega_c)]
\]  

(3-6)

If \( x(t) \) has a narrowband spectrum centered on \( \omega_n \), the effect of the modulation is that the spectrum of the input is shifted to frequencies \( (\omega_c - \omega_n) \) and \( (\omega_c + \omega_n) \). Low-pass filtering removes the high frequency component and the resulting output is a replica of the complex envelope of the original signal centered on a low frequency carrier. This allows the signals to be sampled at a much lower rate, yet retain the information contained in the original signal. The envelope of the signal is unchanged and can be found from the combined magnitude of the real (in phase) and imaginary (quadrature) components of the new signal, downshifted in frequency. Figure 3.3 depicts the demodulation operation. The Fourier transform of the original narrowband signal [3.3(a)] is convolved with the Fourier transform of the modulating signal [3.3(b)]. The result is the frequency-shifted spectrum in 3.3(c). A low pass filter removes the high frequency component.
the proper time lag and give an erroneous time delay estimate. Using the envelope for correlation rather than the peak value will give an incorrect value more often, but the deviations are typically less drastic.

Instead of cross correlating two complex envelope functions, it requires no more effort to compute the complex envelope of the cross correlation function as calculated above. From the relationship $G_{x_1 x_2}(f) = 2S_{x_1 x_2}(f)$ for $0 \leq f < \infty$, we can substitute the one-sided cross spectral density $G_{x_1 x_2}[f]$ before inverse Fourier transforming. In the previous case, inverse transforming the two-sided cross spectrum produced the real cross correlation function in the time domain. Performing the inverse transformation on the one sided cross spectrum produces an additional imaginary component. The absolute value of the complex exponential correlation function provides the envelope of the signal. This is accomplished simply by replacing the two-sided cross spectral density $S_{x_1 x_2}[f]$ with the one-sided cross spectral density $G_{x_1 x_2}[f]$ (by multiplying $S_{x_1 x_2}[f]$ by two and setting the negative-frequency half equal to zero) before performing the inverse FFT. The absolute value of the result is the envelope of the cross correlation function.

Getting a quantitative measure of how "good" an estimate of time delay is relatively straightforward when using peak of the envelope of the cross correlation.

The estimated standard deviation of the time delay estimate $\sigma_T$ is given by

$$
\sigma_T \approx \frac{1}{2\pi W_{nn} d}
$$

(3-7)
where $W_{\text{rms}}$ is the rms bandwidth of the signal and $d$ is the square root of the signal-to-noise ratio (Helstrom, 1975; cited in Spiesberger and Fristrup, 1990). The rms bandwidth is calculated from the following equations (Bracewell, 1978; cited in Au, 1993):

$$f_0 = \frac{\int_{0}^{\infty} f |S(f)|^2 df}{\int_{0}^{\infty} |S(f)|^2 df} \quad (3-8)$$

$$\beta^2 = \frac{\int_{0}^{\infty} f^2 |S(f)|^2 df}{\int_{0}^{\infty} |S(f)|^2 df} - f_0^2 \quad (3-9)$$

where $\beta$ is the rms bandwidth of the signal $s(t)$. For the discrete time case, the integrals are replaced by summations over the length of the record, frequency ranges from zero to half the sampling frequency and the one-sided cross-spectral density is used as the argument. For a conservative estimate of the signal-to-noise ratio $d^2$ (nomenclature from the aforementioned article by Spiesberger and Fristrup), the mean square value of the cross correlation record is divided by the variance of the noise (computed using portions of the record distant from the central region containing the correlation function). An alternate estimate of signal to noise ratio that is simple to implement is the peak value of the correlation function divided by the median of the absolute value of the entire correlation function (Miller, 1997). The standard
deviations for each time delay estimate are squared, and the resulting variances are
used for weighting the least-squares solution described in the next section.

3.3 Receiver Baseline.

In approaching the problem of straight-line bearing angle estimation, two
different schemes for measuring time delay arise. *Ultra-short-* and *short-baseline*
tracking systems use different receiving array geometries and hence require different
processing. The terms come from the arena of ship navigation; a pinger or transponder
is moored and receiving arrays attached to the moving vessel provide range and/or
bearing to the stationary sound source. There are numerous distinctions between the
two methods; among these are such things as transducer size and spacing (Milne,
1983). However, the fundamental difference between the two approaches is a matter of
scale. *Ultra-short-baseline* systems operate by measuring the phase difference between
the signals at two receivers. This requires that the receivers be spaced less than one
wavelength apart. *Short-baseline* systems have receivers spaced far enough (or the
signals are short enough in duration) that the time delay between arrivals of the signal
is measured instead of phase difference.

At 150 kHz (comparable to echolocation frequencies) the wavelength in
seawater is nominally 1 centimeter. This makes an ultra-short baseline approach
impractical for two reasons. First, it would require multiple hydrophones (of sufficient
sensitivity) concentrated in an area less than 1 centimeter across. Secondly, it is
unlikely that the ambient noise can be considered uncorrelated at distances on the order
of a centimeter. It was decided to implement a short-baseline array. Deciding on the spacing between hydrophones is a tradeoff of numerous factors. A shorter spacing reduces the length of the required data records, as the incoming signals are closer together in time. However, for a given sampling frequency, there is a finite set of time delay values that can occur between any two hydrophones that depends on the spacing; for a shorter spacing there are fewer time delays, reducing angle resolution capabilities.

3.4 Direction Angle Calculation.

As mentioned earlier, the localization method used in this system works on cross fixing lines of position determined by computing bearing angles. In the case of two hydrophones, the relation between bearing angle and time delay is shown below:

![Diagram](image)

Figure 3.4: Geometry for Bearing Determination

\[ L_{21} \cos \theta = c(t_2 - t_1) \]  

(3-10)
where $c$ is the sound speed, $L_{21}$ the distance between the pair of receivers, $\theta$ the bearing angle and $t_2-t_1$ the time-of-arrival difference.

The extension to three dimensions requires the use of the three direction cosines. An arbitrary incoming plane wave is defined to move in the direction of the vector $\langle p,q,r \rangle$. The cosines of the angles $\alpha$, $\beta$, and $\gamma$ that vector $\langle p,q,r \rangle$ makes with the $x$, $y$, and $z$-axes, respectively are the direction cosines $u, v,$ and $w$ (Figure 3.5).

\[
\begin{align*}
u &= \cos \beta \\
w &= \cos \gamma
\end{align*}
\]

**Figure 3.5: Representation of Bearing with Direction Cosines**

Now, consider a pair of hydrophones located at arbitrary positions $(x_1,y_1,z_1)$ and $(x_2,y_2,z_2)$. The travel time between phones can be found from the projection of $\langle p,q,r \rangle$ along the inter-phone baseline $L_{21} = \langle x_2-x_1, y_2-y_1, z_2-z_1 \rangle$, which is simply the dot product of the two vectors:

\[
\langle p, q, r \rangle \cdot L_{21} = \sqrt{p^2 + q^2 + r^2} \left\| L_{21} \right\| \cos \theta \\
= p(x_2 - x_1) + q(y_2 - y_1) + r(z_2 - z_1) \tag{3-11}
\]
As we defined the plane wave vector \( <p, q, r> \),

\[
p = \langle p, q, r \rangle \cdot \hat{i} = u\sqrt{p^2 + q^2 + r^2}
\]
\[
q = \langle p, q, r \rangle \cdot \hat{j} = v\sqrt{p^2 + q^2 + r^2}
\]
\[
r = \langle p, q, r \rangle \cdot \hat{k} = w\sqrt{p^2 + q^2 + r^2}
\]

Dividing both sides of (3-11) by the length (norm) of vector \( <p, q, r> \),

\[
c(t_2 - t_1) = \|L_{21}\| \cos \theta = u(x_2 - x_1) + v(y_2 - y_1) + w(z_2 - z_1) \tag{3-12}
\]

For the idealized case (no noise), a set of \( N \) receivers will provide \( N-1 \)
independent time delay measurements. For a three-dimensional localization system,
four receivers at known (not coplanar) positions will satisfy the minimum
requirements, giving six time delay measurements between individual pairs, of which
three are independent. Three linear equations similar to (3-12) can be solved to
determine the unknown direction cosines. The problem is complicated by the presence
of noise and signal variation at each receiver that have the effect of raising the number
of "independent" equations to six (in the ideal case, the time delay between receivers 1
and 3 (\( r_3 \)) is equal to the sum of \( r_{12} \) and \( r_{23} \)). In practice, there is enough noise that \( r_{31} \)
cannot be considered dependent on \( r_{21} \) and \( r_{23} \). The result is six measured time delays
of uncertain independence that form an overdetermined system. Multiple solutions will
satisfy the problem; the "best" solution can be determined using a least-squares
approach, i.e. one that minimizes the mean square error. The derivations below for
basic unweighted and weighted least squares matrix solutions are reviewed in Strang (1986). Equation (3-12) is applied to the six hydrophone pairs and the equations are arranged in the form $\mathbf{A} \mathbf{x} = \mathbf{b}$ as below. The matrix $\mathbf{A}$ represents the geometry of the hydrophone array, vector $\mathbf{b}$ represents the time delay estimates multiplied by the local speed of sound, and we want to solve for vector $\mathbf{x}$, the direction cosines.

\[
\begin{bmatrix}
-x_2 - x_1 & y_2 - y_1 & z_2 - z_1 \\
x_3 - x_1 & y_3 - y_1 & z_3 - z_1 \\
x_4 - x_1 & y_4 - y_1 & z_4 - z_1 \\
x_3 - x_2 & y_3 - y_2 & z_3 - z_2 \\
x_4 - x_2 & y_4 - y_2 & z_4 - z_2 \\
x_4 - x_3 & y_4 - y_3 & z_4 - z_3
\end{bmatrix}
\begin{bmatrix}
\mathbf{u} \\
\mathbf{v} \\
\mathbf{w}
\end{bmatrix}
\times
\begin{bmatrix}
t_2 - t_1 \\
t_3 - t_1 \\
t_3 - t_2 \\
t_4 - t_2 \\
t_4 - t_3
\end{bmatrix}
\]

(3-13)

Multiplying both sides of $\mathbf{A} \mathbf{x} = \mathbf{b}$ by the transpose of $\mathbf{A}$, the result is $\mathbf{A}^T \mathbf{A} \mathbf{x} = \mathbf{A}^T \mathbf{b}$, in which the invertible $3 \times 3$ matrix is produced. The solution is found by multiplying both sides of the equation by the inverse of $\mathbf{A}^T \mathbf{A}$.

\[
\mathbf{x} = (\mathbf{A}^T \mathbf{A})^{-1} \mathbf{A}^T \mathbf{b}
\]

(3-14)

Equation (3-14) provides the simple least-squares solution to the vector $\mathbf{x}$ of direction cosines. If the accuracy of the time delay estimates varies between hydrophone pairs, the least squares system of equations can be modified with different weights depending on the confidence in the estimates. For a given diagonal weighting matrix $\mathbf{W}$,
\[ WAx = Wb. \] In order to make the matrix multiplied by \( x \) square, both sides are multiplied by the transpose of \( WA \), resulting in the following equation:

\[ (WA)^TWAx = (WA)^TWb. \]

This equation can be rewritten as \( A^TWTWAx = A^TWTWb. \) The combination \( W^TW \) is often renamed \( C \). The solution to the weighted least squares problem \( A^TCAx = A^TCb \) is

\[ x = \left( A^TCA \right)^{-1} A^TCb \quad (3-15) \]

which reduces to the ordinary least squares problem [equation (3-14)] when \( C \) is an identity matrix. If we assume the errors in time delays are independent of each other, then \( C \) is a diagonal matrix, where each element \( C_{ii} = 1/\sigma_i^2 \). The variances of the individual elements \( b_i \) of time delay vector \( b \) are computed using equation (3-7). The solution direction cosine vector is found using the Matlab function “lscov” (least squares with known covariance).

Errors in bearing angle estimation will be discussed in detail in section 3.6.

3.5 Cross Fixing Lines of Position.

In order to compute a sound source's position, direction vectors from at least two different spatially separated receivers (or arrays) are required. These can be computed directly from the direction cosines for each receiving array. However, it is more intuitive to estimate positions using a spherical coordinate system. The direction cosines are defined in terms of the spherical coordinates \( \theta \) and \( \phi \) as follows:
\[ u = \cos \alpha = \sin \phi \cos \theta \]  

\[ v = \cos \beta = \sin \phi \sin \theta \]  

\[ w = \cos \gamma = \cos \phi \]  

\[ \theta = \tan^{-1} \frac{v}{u} \]  

\[ \phi = \tan^{-1} \frac{\sqrt{u^2 + v^2}}{w} \]  

Figure 3.6: Representation of Bearing with Spherical Angles

Equivalently, \( \theta \) and \( \phi \) are calculated from the direction cosines:

By separating the horizontal component of direction angle from the vertical, we can determine a horizontal position relative to the arrays using triangulation of the azimuth angles (for the purposes of this project "azimuth" and \( \theta \) are interchangeable;
"elevation" is measured from the horizontal, i.e., $90^\circ - \phi$. In Figure 3.7 below, two receivers are separated by distance $L$. The azimuth angles to the target are $w$ and $e$.

![Figure 3.7: Determining Horizontal Range from Azimuth Angles](image)

The range $R$ from the leftmost ("west") receiver to the source is expressed as:

$$ R = \frac{L \sin(\pi - |e|)}{\sin(|e - w|)} $$  \hspace{1cm} (3-21)

Once the horizontal range and bearing to the source are known the depth can be calculated from simple trigonometry given the elevation angle $\phi$.

3.6 Sensitivity Analysis.

For any measurement system it is important to know how reliably the desired quantity (e.g., position) can be estimated given variability in other parameters. The localization system described in this thesis provides position estimates that are subject to errors in range, bearing and elevation. These errors arise from a combination of
sources. Among these are uncertainty about sensor position, array directionality, background noise, multipath environment, etc. Since a complete description of the local topography and acoustic environment are beyond the scope of this project, this section will investigate the error sensitivity of the arrays assuming straight line propagation without reflections.

The system described in this thesis consists of two tetrahedral arrays of four hydrophones apiece, placed along a baseline and separated by some distance. Within each array, the hydrophones are equidistant from each other at 1 meter. Three of the hydrophones are situated in the XY plane separated by angles of 120°. The fourth hydrophone is centered above the others. Figure 3.8 depicts a schematic of one array. For each array, measurement of the time of arrival differences between hydrophones produces a bearing estimate, converted to azimuth and elevation angles. For a given signal arriving on both arrays, the azimuth angles measured from each array determine lines of position. The final estimate of horizontal range is determined from the intersection of these lines. Elevation distance is then calculated from the horizontal range and elevation angle. To get a sense of performance, we need to look at the system at different scales: (1) pairs of hydrophones, (2) individual arrays, and (3) the multiple array system.

For the case of a simple hydrophone pair with straight-line propagation, variations in the local sound speed $c$ and the spacing $L$ between the phones lead to variations in the measured time-of-arrival differences. In turn the time difference variations affect the accuracy of the estimate of the angle of incidence $\theta$. 

55
Figure 3.8: Schematic of Tetrahedral Hydrophone Array
The time difference between the arrival of the wave front at the phones was expressed in equation (3-10) and Figure 3.4 as:

\[ t = \frac{L \cos \theta}{c}. \]

(3-22)

Ignoring sign, the time delay can fall between a minimum of 0 seconds for broadside \((\theta = \pm 90^\circ)\) signal arrivals and a maximum of \(L/c\) seconds for end-fire \((\theta = 0^\circ, \theta = 180^\circ)\) signal arrivals.

The sensitivity of time delay \(t\) to variations in \(L\) and \(c\) is dependent on \(\theta\).

Differentiating (3-22) with respect to baseline length \(L\),

\[ dt = \frac{\cos \theta}{c} dl. \]

(3-23)

For \(L = 1\) meter and \(c = 1500\) m/s, we assume baseline length errors will be on the order of 1 cm; this leads to a maximum \(dt\) of 6.7 \(\mu\)sec. As the time difference error depends on \(\cos \theta\), the maximum error occurs for end-fire and reduces to zero at broadside.

Similarly, differentiating 3-22 with respect to sound speed \(c\),

\[ dt = -\frac{L \cos \theta}{c^2} dc \]

(3-24)

As before, the cosine term causes variation of \(t\) to approach zero as \(\theta\) approaches 90\(^\circ\) (broadside). From Medwin's sound velocity equation (Urick, 1983), we roughly
estimate that the sound velocity in Maine surface waters in August varies from 1474 m/sec (temperature = 7.5°C, salinity = 30ppt, depth = 20 m) to 1514 m/sec (temperature = 17.5°C, salinity = 35ppt, depth = 20 m). From (3-24), a variation in c of 20 m/sec from the nominal mean value of 1494 m/sec leads to a maximum time delay error of 9μsec.

To illustrate the directional sensitivity to these errors, take the case where the true sound speed is actually 1514 m/s. End-fire arrivals (θ = 0°) will be separated by 1/1514 seconds, or t = 661μsec. If a sound speed of 1495m/s is assumed, solving (3-22) for θ gives the result θ = 9.1°. Obviously, for broadside arrivals, t = 0 sec, so the variation of sound speed has no impact on the solution for θ. In cases where the true sound speed is slower than assumed; i.e. c = 1474 m/s, an end-fire t = 1/1474 sec or 678μsec. If c is assumed to be 1495 m/s, cos θ > 1, obviously an unacceptable result.

This problem is remedied in the transition to the three-dimensional case. The matrix equations in section 3.4 are solved for the direction cosines u, v, and w. When overall scaling errors (e.g., c differing from the assumed value) are applied to the solution, the resulting values of u, v, and w are scaled as well. While they are no longer considered direction cosines since the sum of their squares is no longer 1, this doesn't affect the estimation of azimuth and elevation. The bearing angles are computed from ratios of u, v, and w rather than the values themselves; the scale factor cancels (see equations 3-19 and 3-20).
The three dimensional bearing angles determined by the arrays are subject to both bias and random errors. The bias errors arise when the array is not positioned exactly as assumed. For example, misalignment of the array by a rotation of 1° about its Z-axis leads to a constant 1° error in the azimuth measurement. X- and Y-axis misalignments lead to varying bias errors in the elevation measurement. For example, an array tilted 1° towards north will produce elevation angle bias errors of +1° for signals arriving from the north, -1° from south, and zero error for east and west.

While these bias errors can be accounted for with careful calibration, the case is not so simple for random errors. These errors primarily arise from the presence of ambient noise and electronic noise, as well as random variations in sensor position.

Rather than attempt to describe the result of random error on the bearing angle estimation analytically, a Monte Carlo-type simulation approach is useful. The varying parameter, (i.e. time delay error) is modeled as a random process. Many trials of the simulation with randomly generated parameters are conducted, and the results described statistically.

Given the nominal dimensions of the array, it is straightforward to generate a set of nominal time delays for any given input bearing angle. The bearing is converted to direction cosines and the direction cosine vector $\mathbf{x}$ is then multiplied by the geometry matrix $A$ and divided by sound speed $c$, resulting in the vector of nominal time delays $t$. A set of random errors is applied to the nominal time delays and the inverse equation (3-14) is solved for $u$, $v$, and $w$. If this process is repeated many times, the mean and standard deviation of the resulting bearing angles can be estimated. In order
to get a sense of the directionality of the array, this analysis is repeated for a full circle of azimuth angles at various elevations.

The random error in estimation of time delay between two sensors was characterized in equation 3-7, reiterated here:

\[
\sigma_T \approx \frac{1}{2\pi W_{\text{rms}} d}
\]  

(3-7)

For the case of this system, it is assumed that errors in the six measured time delays between hydrophone pairs are independent of each other. Assuming that the porpoise echolocation signals have an rms bandwidth of 5 kHz and a signal-to-noise ratio of 20 dB, the result is a standard deviation of the time delay estimate \(\sigma_T\) of approximately 10 \(\mu\)sec. In figure 3.9, a set of azimuth measurements (full 360° in 1° increments) was used with various elevation angles (0°, 60° and 80° above the horizontal). The nominal array geometry of a regular tetrahedron with 1-meter spacing was used. For each bearing direction, 100 repetitions were conducted with different sets of randomly generated time delay errors of standard deviation \(\sigma_T = 10 \mu\)sec. In each plot, the radius corresponds to standard deviation of the angle error estimate (in degrees). The top plot shows that the error in azimuth is independent of azimuth (hence the circular patterns), but is heavily dependent on elevation (hence the different radii). The bottom plot shows that error in elevation is constant over all incoming bearing angles. The angle errors for these parameters are generally on the order of 1 degree (approximately 0.6° for horizontal incidence), only increasing significantly for azimuth angle errors near vertical incidence.
Standard deviation $[\sigma_\theta]$ of azimuth angle $\theta$
for different values of $\phi$, $\sigma_\tau = 10\mu$sec, $N = 100$

Standard deviation $[\sigma_\phi]$ of elevation angle $\phi$
for different values of $\phi$, $\sigma_\tau = 10\mu$sec, $N = 100$

Figure 3.9: Variation in Bearing Estimates with Elevation
Figure 3.10 shows the linear variation of angle error with time delay error at horizontal incidence; values for $\sigma_T$ range from 5 to 20 $\mu$sec.

In Figure 3.11, the signal noise has been eliminated ($\sigma_T = 0$). Instead, the hydrophone positions have been subjected to random deviations $\sigma_x$, $\sigma_y$, and $\sigma_z$. This is to simulate the random variation in position arising from ocean currents and the structure's flexibility. The standard deviations in position are assumed on the order of 1 cm. The deviations in angle are also on the order of 1° (horizontal incidence).

Figure 3.12 depicts the results of (knowingly) changing the overall spacing between hydrophones in the array. The standard deviation of bearing error is inversely proportional to $L$: doubling the distance between all the hydrophones reduces the error in bearing estimation by half, however there is a tradeoff in increasing the size of the array where weight, ease of deployment, conspicuousness, etc. are concerned.

Once the variation in bearing angle is determined, this information can be used to determine the errors in range estimation through triangulation from two arrays, illustrated in figure 3.7 and equation 3-21. In the experiment performed in August 1997, two tetrahedral arrays were deployed 60 meters apart along an East-West baseline. Figure 3-13 depicts the results of a range sensitivity simulation using this array geometry. A hypothetical sound source moves in a full circle (at 10° increments) around the West array at a constant distance of 30 meters. The elevation is the same as the array ($\phi = 90^\circ$). For each nominal azimuth angle from the West array, the corresponding nominal azimuth from the East array is computed so the lines of position intersect properly on the 30-meter circle. Using the value of $\sigma_\theta$ computed previously
(roughly 0.6°), a large set of random perturbations are applied to both the west and east nominal azimuth measurements. The perturbed azimuth measurements are used to calculate a set of range estimates, using equation (3-21). Rather than computing a mean and standard deviation, a scatter plot (Figure 3.13) shows the set of perturbed line-of-position intersections surrounding the west array. For angles approaching the east-west baseline (end-fire), small variations in the azimuth measurements can cause the lines of position to intersect at extremely large distances, and in some cases there is no convergence at all. Localization accuracy is typically much higher between the two arrays than outside them. For azimuths on the order of ±20 to ±80 degrees from the West array, the range estimates tend to vary only on the order of 1 meter. Obviously, as the error in bearing angle increases, the error in range increases as well.

Figure 3.14 illustrates what happens when an unaccounted-for bias error is introduced to the system. In this simulation, the east array has been rotated 1° clockwise about its Z-axis; a signal approaching the east array from an azimuth of 150° is treated as if it approaches from a random spread of angles surrounding 151°. The result is that (for west array azimuths of about +20° to +120°) the intersections typically fall 1–3 meters outside the 30-meter radius. South of the baseline the intersections fall within the 30-meter radius by the same amount. For signals arriving from the west, the results vary wildly. Just north of the line, the erroneous range estimates approach infinity. Just south, they approach zero meters from the West array.

This simulation illustrates the probable cause of some of the variability in the results of the experiment that will be discussed in the next section.
Standard deviation \( \sigma_\theta \) of azimuth angle \( \theta \) for different values of \( \sigma_T \), \( \phi = 90^\circ \) (horizontal), \( N = 100 \)

\( \sigma_T = 5 \mu \text{sec} \)
\( \sigma_T = 10 \mu \text{sec} \)
\( \sigma_T = 20 \mu \text{sec} \)

Standard deviation \( \sigma_\phi \) of elevation angle \( \phi \) for different values of \( \sigma_T \), \( \phi = 90^\circ \) (horizontal), \( N = 100 \)

\( \sigma_T = 5 \mu \text{sec} \)
\( \sigma_T = 10 \mu \text{sec} \)
\( \sigma_T = 20 \mu \text{sec} \)

Figure 3.10: Variation in Bearing Estimate Due to Time Delay Error
Standard deviation [σ_θ] of azimuth angle θ
for different hydrophone position errors σ_x = σ_y = σ_z, σ_T = 10μsec, φ = 90° (horiz.), N = 100

Standard deviation [σ_φ] of elevation angle φ for different hydrophone position errors σ_x = σ_y = σ_z, σ_T = 10μsec, φ = 90° (horiz.), N = 100

Figure 3.11: Variation in Bearing Estimate Due to Hydrophone Position Error
Standard deviation $[\sigma_\theta]$ of azimuth angle $\theta$
for different values of $L$, $\sigma_T = 10\mu$sec, $\phi = 90^\circ$ (horiz.), $N = 100$

Standard deviation $[\sigma_\phi]$ of elevation angle $\phi$
for different values of $L$, $\sigma_T = 10\mu$sec, $\phi = 90^\circ$ (horiz.), $N = 100$

Figure 3.12: Variation in Bearing Estimate with Overall Length Scale
Figure 3.13: Scatter Plot of Range Estimations, Random Errors in Bearing
Figure 3.14: Scatter Plot of Range Estimations, Random and Bias Errors in Bearing
4. Experiment.

The experimental testing of the porpoise tracking system was conducted in two phases during August 1996 and August 1997. Both phases took place in the vicinity of Harbor Island in Penobscot Bay, south of the town of Stonington, Maine. The area is a heavily traveled shipping route with a sizable lobster fishing community. It is also a known site of concentrations of harbor porpoise during the late summer.

![Map of the experimental area](image)

*Figure 4.1: Location of Experiment (reprinted from Brodie, 1995)*

4.1 Pilot Study, August 1996.

The initial phase of the experiment was a study to test the feasibility of recording porpoise vocalizations on a short-baseline hydrophone array. Two
tetrahedral space arrays were constructed of PVC plastic tubing. At the four corners of the tetrahedron were Sparton Electronics model 8094-001 hydrophones. The spacing between hydrophones was set at 50 cm. The arrays were mounted on steel poles that were attached to the bow and stern of RV Puffin’ Pig, the 22’ ship that Potter and his group use for survey work. The arrays extended approximately 14 feet beneath the surface. The hydrophones were connected by 50’ cables to a Teac XR-7000 instrumentation recorder. Eight channels (four for each of the two arrays) were recorded; one of the channels was monitored using a simple envelope detector circuit that provided audible output of echolocation clicks.

Subsequent analysis of the data recorded during this phase established that the echolocation signals of the animals could be detected, although they were not always present on all of the hydrophones, even within a given array. There were also problems with radiofrequency interference. The interference was reduced significantly after covering most of the cable with a jury-rigged shield made of aluminum foil and duct tape. However, a strong interference component (continuous sine wave near 100 kHz, possibly LORAN-C transmissions) remained, and made the correlation of signals difficult. Also, the small baseline between hydrophones and motion of the boat made accurate localizations impossible.

4.2. Operational Test, August 1997.

After consideration of the problems of the first phase and budgetary limitations, a plan for the following summer’s full experiment was formulated. The hydrophones
and instrumentation recorder used in the 1996 study were again employed. Features of the 1997 experiment:

- The operation was shore-based. A base camp on Harbor Island was constructed with electric power for the recording equipment and a good vantage point for visual survey work.

- The two hydrophone arrays were deployed on the bottom in fixed locations, positioned approximately 250 meters north of the base camp on the island in 20 meters of water.

- The tetrahedral hydrophone arrays were larger and of sturdier construction than those used in the 1996 study. Each array was designed for multiple days of deployment, including an aluminum pressure case that contained circuitry and batteries for driving the signals along 300+ meters of cable to the shore station.

- The spacing between hydrophones was increased to 1 meter to improve angular direction resolution for a given sampling rate. The two arrays were positioned on the bottom with a baseline of 60 meters separating them to improve the range estimates of the triangulation.

![Schematic of the Receiving System](image)

**Figure 4.2: Schematic of the Receiving System**
4.3. Equipment Used in the Experiment.

4.3.1. Hydrophones.

The basic element of the tracking system is the receiving transducer. The choice of a hydrophone and other equipment depends on source characteristics and operating conditions. Important parameters can be estimated using the sonar equations (Urick, 1983). For one-way propagation and passive detection,

\[
SL - TL = NL - DI + DT 
\]

where

- \( SL \) = Source level of the signal
- \( TL \) = One-way transmission loss
- \( NL \) = Ambient noise level
- \( DI \) = Directivity index
- \( DT \) = Detection threshold

For the echolocation clicks of a harbor porpoise, a source level of 162 dB re 1\( \mu \)Pa at a distance of one meter is assumed (Au, 1993). The one-way transmission loss assuming spherical spreading is \( TL = 20 \log R + \alpha R \), where \( R \) is the range in meters and \( \alpha \) is an absorption coefficient of approximately 0.1 dB/m in seawater at a frequency of 100 kHz. Extrapolation of the shallow-water noise spectrum level curves in Urick (1983) provides a NSL of approximately 25 dB re 1\( \mu \)Pa/\( \sqrt{\text{Hz}} \) at 100 kHz. For 50 kHz of bandwidth between 100 and 150 kHz (the frequency range of echolocation...
clicks), the noise level \( NL = NSL + 10 \log BW = 72 \text{ dB re } 1\mu Pa \). The directivity index of an omnidirectional hydrophone is 0 dB. For a signal detection threshold of at least +10 dB above the noise, the sonar equation is

\[
162 - 20 \log R - .1R = 72 + 0 + 10,
\]

which gives an effective maximum detection range of \( R \approx 300 \text{ meters} \). For a source level of 150 dB re 1\mu Pa @ 1 m, the detection range reduces to 200 meters. In practice, the highly directional transmitting beam pattern of the porpoise and an electronic noise floor will further reduce the detection capability.

For this project the Sparton Electronics model 80994-001 hydrophone was selected for the receiving arrays. These are small (3/4" diameter) spherical hydrophones originally designed for use in sonobuoys.

![Sparton Electronics Hydrophone with Preamplifier](image)

**Figure 4.3: Sparton Electronics Hydrophone with Preamplifier**

The hydrophones are omnidirectional, working well at frequencies up to 150 kHz. The phones operate on 12VDC battery power, to supply the integrated preamplifiers. With
the preamps, the effective free-field voltage sensitivity is nominally \(-160\) dB re \(1\text{V/\mu Pa}\). High sensitivity was required due to the low source levels of the porpoise's vocalizations. Assuming the \(162\) dB source level of the animal, this receiving sensitivity should provide output of tens to hundreds of millivolts at ranges of tens of meters, without saturating at close range.

4.3.2. Arrays.

The tetrahedral hydrophone arrays were constructed by Craig Mallen of the URI Department of Ocean Engineering. A schematic of one array appeared in Figure 3.8 and a photograph of one of the actual arrays used during the experiment, complete with cabling is shown in Figure 4.4. The arrays are constructed such that three of the hydrophones are arranged in the X-Y plane, radiating from the origin at 120° intervals and distances of 57.75 centimeters (\(1/\sqrt{3}\) meters). The fourth hydrophone is located 81.65 centimeters (\(\sqrt{2}/\sqrt{3}\) meters) above the origin of the array. This insures that the spacing between any two hydrophones is nominally 1 meter. Early acoustic tank tests with the 1996 model of the array showed that there was some concern about attenuation in the instance where pipe sections shaded the hydrophones. The new arrays were designed to minimize the amount of PVC piping between any two hydrophones (i.e., the hydrophones are raised above the horizontal arms and the central hub by about 4 inches). The piping was perforated to allow water to flood the array, minimizing any acoustic reflection due to trapped air.
The arrays are designed to be lowered from a vessel and adjusted by a diver once on the bottom. The arrays are mounted on a triangular base with a mounting bracket with locking bolts that allows fine adjustment of the vertical and horizontal alignment of the array. The arrays are positively buoyant and were equipped with lead weights for anchoring.

Figure 4.4: Tetrahedral Hydrophone Array and Cable

Included on the arrays are aluminum pressure cases (economics dictated this decision—future systems should use hardware enclosures that present less of an impedance mismatch to the seawater). The cases contain line driver circuitry, batteries for the hydrophone preamps and line drivers, and underwater connectors for the hydrophones and cables. The line driver circuit (see Appendix) was designed by Keith
Von Der Heydt of the Woods Hole Oceanographic Institution. The circuit takes the hydrophone output signal which has a maximum range of ±6 volts sitting on 6VDC and converts it from single-ended (ground referenced) to differential. When a signal is driven differentially, instead of one ground line and one signal line, both conductors are allowed to float relative to the ground; the signal is determined by the potential difference between the two lines. This has the advantage of increased immunity to electronic interference. The circuit also matches the hydrophone output impedance to the characteristic impedance of the cable to minimize losses. The 300 meter Quabbin 6175 cables contained six twisted pairs with individual shielding, of which four were used for a given hydrophone array. As the cable was to be run along a rocky bottom in high tidal currents, the cable came equipped with a tough high-density polyethylene (HDPE) jacket to minimize damage due to abrasion.

4.3.3. Recording and Digitization.

The collection of acoustic data during the experiment was made possible by the participation of Khosrow Lashkari and Steve Lowder of the Monterey Bay Aquarium Research Institute. On the island, a tent was set up to shelter their Teac XR-7000 instrumentation recorder. The Teac is capable of recording 8 channels of acoustic data simultaneously, with an operational bandwidth of 150 kHz. It records on high quality VHS cassettes at speeds ranging from 1.2 to 76.2 cm/sec. At 76.2 cm/sec, a cassette containing enough tape for three hours of SP mode video recording lasts a total of eight
minutes. Approximately 35 tapes were recorded over the course of four days at the site.

Input and output ranges are adjustable from ± 0.3 to ± 5.0 V. Unfortunately, we were not able to finish construction on the 20 dB gain amplifier circuits which were designed to convert the differential signals back to single-ended. This caused a reduction in signal-to-noise ratio and dynamic range.

During the recording process, two hydrophone channels were monitored. One channel provided raw hydrophone output in audible ranges that indicated the presence of boats in the area. Another channel was filtered through an envelope detector circuit consisting of a diode in series with a resistor-capacitor pair. The circuit traces the envelope of the incoming echolocation signal and produces audible clicks that can be monitored. In many instances during the experiment, harbor porpoises were detected acoustically, invariably followed by visual sightings.

After the experiment, one set of recordings was digitized with the assistance of Tom Weber of the URI Ocean Engineering Department. The recordings were played back at 1/16 of the original recording speed and the eight channels were simultaneously sampled at 50 kS/sec, for an effective sampling rate of 800 kS/sec, or roughly six times the peak frequency of the echolocation signals. At 16 bit resolution in the analog-digital conversion, this equates to roughly 12.2 megabytes per second of real-time recording. The data to be digitized were hand selected by monitoring the spectrogram output of the recorder (run at 1/8 speed) using the program software Spectra Plus. After digitizing a sine wave signal on all eight channels, it was discovered that the tape
recorder inherently delays the odd numbered channels approximately 15 μsec relative to the even numbered channels. The deviations have been noted and the time delay estimates adjusted accordingly.

8 channels of acoustic data, recorded on TEAC XR-7000, tape speed of 76.2 cm/sec. → Playback at 1/16 normal speed (4.8 cm/sec) → PC data acquisition card digitizes 8 channels at 50kS/s (effectively sampling at 800 kS/s).

FTP 8MB data files to Sparc workstation → Look for signals above minimum threshold. Save data in two sets of 4 channels, 1,000 data points, surrounding echolocation clicks. → Apply digital bandpass filter → Read data from binary files into Matlab in 100,000 point segments.

Figure 4.5: Data Reduction Chain

The data processing was performed on a Sun Sparc20 workstation using Matlab 5.1. Typically the analysis progressed as follows: the data were filtered with Butterworth bandpass filters with passbands between 100 and 150 kHz to improve signal-to-noise ratio. Once a candidate click of sufficient amplitude was found, the time series were reduced to two separate 4×1000 data point records, one for each array.

The six correlation functions for each array were performed by calculating the 2048-point FFT for each hydrophone signal, multiplying conjugates of the transforms together, then inverse FFTing to the time domain for determination of the time lag at

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the maximum peak of the correlation function. Rough variances of the time delay
estimates were calculated from the peak values and medians of the envelope
correlations (these were the most conservative). The time delays and variances were
used in the least squares solution along with the following array geometry matrix A.

\[
\begin{bmatrix}
  x_2 - x_1 & y_2 - y_1 & z_2 - z_1 \\
  x_3 - x_1 & y_3 - y_1 & z_3 - z_1 \\
  x_4 - x_1 & y_4 - y_1 & z_4 - z_1 \\
  x_3 - x_2 & y_3 - y_2 & z_3 - z_2 \\
  x_4 - x_2 & y_4 - y_2 & z_4 - z_2 \\
  x_4 - x_3 & y_4 - y_3 & z_4 - z_3 \\
\end{bmatrix} =
\begin{bmatrix}
  0.5 & -0.866 & 0.0 \\
  -0.5 & 0.866 & 0.0 \\
  0.0 & -0.5774 & 0.8165 \\
  0.0 & 0.0 & 0.0 \\
  0.5 & 0.2887 & 0.8165 \\
  0.5 & 0.2887 & 0.8165 \\
\end{bmatrix}
\]

The direction cosine solutions were calculated using equation (3.15). The nominal
value for sound speed c was assumed to be 1500 m/sec, as no actual CTD data was
available at the time of analysis. As discussed in Section 3.6, the sound speed
variations do not compromise the bearing estimation; the azimuth and elevation are
computed from the ratios of the direction cosines, not the values themselves equations
(3-19) and (3-20). The azimuth angles are used for triangulation based on equation
(3-21). Elevation distance z can be computed as the horizontal range R divided by the
tangent of the spherical angle \( \phi \) (\( \phi = 90^\circ \) corresponds to \( z = 0 \)).
5. Results.

Over the course of four days in Maine, approximately 35 eight-minute tapes were recorded. These recordings were made under a variety of current and sea state conditions at all hours of the day as well as at night. Some of the tapes were annotated with a voice channel to mark the surfacing of an observed porpoise with the hopes of correlating surface behavior with acoustic data. To date, one tape that was known to have an abundance of echolocation clicks has been digitized. It was recorded during a morning interaction in which a pair of porpoises (mother and calf) had been observed approaching the island. Khosrow Lashkari and I digitized this tape during November, 1997. One hydrophone channel from each array was monitored both for the occurrences of echolocation clicks in the 100–150 kHz band and low frequency tones between 15 and 20 kHz. Each time that a clear vocalization was evident, the tape count was noted for later digitization. Dozens of echolocation clicks occurred during the first half of the tape, yet were conspicuously absent in the second half. There were also a large number (> 100) of the low frequency (18 kHz) tones occurring throughout the 8 minute tape.

In order to extract the echolocation clicks, the 8 megabyte, 1.25 second-long binary data records were read in segments of 0.25 seconds. This produced time series long enough (100,000 data points long) to ensure that all the hydrophones had signals in the same data record, yet short enough not to overload the Sun workstation's resources.

Each time a segment of data was read, a spectrogram of the time series was generated. If a click was evident, the time series were observed to see if the click
occurred on all 8 hydrophones. If not, this was noted and the click was eliminated from the localization dataset. Even though the signal might be strong on seven of the eight channels, this was a calculated move to test the 4-hydrophone localization strategy. There was a downside to this approach; because of the directionality of the porpoise’s transmitting beam, the animal had to be in a position to ensonify both arrays. This meant that the porpoise was either (1) oriented along the array baseline or (2) traveling towards the baseline but distant enough for both arrays to fall within the beam. The first case (which seems to characterize most of the signals collected in this data set) is an end-fire condition, where the variability of the bearing estimates greatly reduce the reliability of the range estimate; this was discussed in Section 3.6. In the second case, an animal would most likely have to be hundreds of meters from the baseline. The detection of these animals is probably quite difficult at these distances, because of their low source levels.

Culling the data in this fashion reduced the number of echolocation signals used in this study to 31. Figure 5.1 illustrates one of the cleaner signals that were recorded. Both the waveform (with its characteristic continuous frequency, quick rise and slow decay) as well as its narrowband spectrum near 135 kHz are shown.

Prior to correlation, a 6th order Butterworth bandpass filter with -3dB cutoff frequencies of 100 and 150 kHz was applied to all the signals. Assuming a hydrophone sensitivity of a nominal -160 dB re 1 V/μPa, the loudest of the signals recorded had peak pressures of approximately 20 Pa, equating to a peak sound pressure level of 146 dB re 1μPa.
Time Series of Harbor Porpoise Echolocation Click Recorded on East Array, Center Hydrophone (#4). Tape count 1803 = 234 seconds into tape

Frequency Spectrum of Harbor Porpoise Click
1024 point FFT, sample frequency 800 kS/sec

Figure 5.1: Echolocation Signal and Spectrum from 1997 Experiment
Time series plots and cross correlation functions for all 31 clicks on both arrays appear in the Appendix. The time axes are not consistent between the West and East arrays, but are consistent between all four phones on a given array. These time series also do not reflect the tape recorder delays; the corrections were applied after the cross correlations were performed. From top to bottom, the time series correspond to the following hydrophone positions relative to the array origin: (1) due north, coinciding with the positive y-axis, (2) 120 degrees southeast (east is the positive x direction), (3) 120 degrees southwest, and (4) centered above the origin at a distance of 81.65 cm along the positive z-axis. For most of the clicks, the signals are louder with less distortion on the West array. More importantly, the signal consistently arrives first at West array hydrophone 3. The delay between phones 3 and 2 decreases as the tape progresses, hence the bearing angle can be expected to change from nearly due west to southwest.

One noticeable feature affecting some of the signals is a highly variable echo structure. In a multiple path environment, small changes in the orientation of the animal can have profound effects on the incoming signals. For example, in Figure 5.2 two clicks occur at phone 3 on the West array during the same second; note the time difference between the first and second signal peak.

In several instances the waveforms were anomalous. In Figure 5.3, the top plot illustrates a click at $t = 184$ seconds in which the later signal (assumed to be the reflected pulse) is of higher amplitude than the first (direct path). In the bottom plot, the waveform at 235 seconds is highly distorted; this may be due to destructive interference between the direct and reflected path or, more likely, simply indicates a
Figure 5.2: Illustration of Reflection Problem
Figure 5.3: Anomalous Waveforms
non-porpoise signal that passed the screening process. In some of the time series there also appears to be crosstalk between the channels.

The time lags at the maxima of the cross correlation functions are usually somewhat different depending on whether the raw correlation peaks or the envelope peaks are used. Four different approaches to the least-squares bearing solutions were used. Two of these approaches used the peaks of the raw cross correlation functions to indicate the time differences. The other two used the peaks of the cross correlation of the complex envelopes. In each case, raw or envelope, the simple unweighted least squares solution was determined as well as the case where the least squares solution included a diagonal matrix of variances of the time delay estimates (based on SNR). The resulting azimuth and elevation angles from each array as well as the position coordinates relative to the West array are tabulated in the Appendix, Tables A.1 through A.3. The variation in bearing angle using the different methods is not particularly large. However, as was demonstrated in Section 3.6, small errors in the angle measurement lead to increasingly large errors in the line of position range estimate as the bearing angle nears the end-fire condition.

Figures 5.4 through 5.7 on the following pages show the x-y coordinates of the localizations that were computed for two of the four cases, the unweighted solution using raw signal correlations and the weighted solution using the envelopes. Initially, three-dimensional plots including the depth dimension were generated, but they were non-intuitive and difficult to interpret; the two-dimensional plots shown here are the result.
Localization positions relative to west array.

'.' denotes localizations using envelope correlation and weighted least squares
'+' denotes localizations using raw signal correlation and unweighted least squares

Figure 5.4: West - East Array Localizations, Long Range
Figure 5.5: West - East Array Localizations, Short Range
Localization positions with time indices and possible tracks, using raw signal correlation and simple least squares.

Figure 5.6: Close Range Localizations and Possible Tracks Using Raw Signal Correlation and Simple Least Squares Bearing Solution.
Figure 5.7: Close Range Localizations and Possible Tracks
Using Correlation Envelope and Weighted Least Squares Bearing Solution
During most of the interactions, the azimuth angles were stable, but small errors in angle caused the range estimates to bounce around significantly. The plots show a high concentration of localizations slightly southwest of the West array.

One curious inconsistency is in the elevation angle data (see Tables A.1 and A.2). From the West array the angle values tend to stay within a few degrees of the plane of the hydrophone array. This is consistent with an animal actively observing the array. However, the time series plots in the Appendix clearly show that the raised (#4) hydrophone on the east array receives the signal much later compared with the west array, and is often the last hydrophone to be ensonified by the signal. This clearly indicates that the sound is approaching from an angle below the horizontal, on the order of 30 degrees. This would seem a steep angle for a bottom reflection, however the bottom in the area is quite hard and the local bathymetry was highly varied, if the RV *Puffin*’ *Pig*’s echosounder was to be believed. Given the small amount of data, I opted to continue the analysis in two dimensions rather than treat the West array’s elevation data as correct and the East array’s as erroneous.

These data were prepared for a presentation of at the 134th Meeting of the Acoustical Society of America in San Diego in December 1997. One matter that caused some confusion concerned two concentrations of clicks, the first around 150 seconds into the tape, and the second around 174 seconds (Figures 5.6 and 5.7). The azimuth estimations were very stable, at least from the West array, and the localizations appear to form nearly straight lines in the direction of the West array. The confusion arises because the localizations at 150 seconds appear to be closer to the
array than the ones at 174. One possible scenario is that the animal scanned the array, then needed to surface for air before returning 20+ seconds later. Another scenario that was suggested was that two different animals traveling together were each echolocating on the array. We did not observe any porpoises surfacing near the array during the time frame of the recording, so neither hypothesis can be substantiated. However, it is probable that the porpoise or porpoises were directly targeting the array, most likely because of the unusual geometry of the array and sharp acoustic impedance contrast from the metal pressure case.

The actual deployment and fine adjustment of the arrays was an admittedly inexact process. For lack of better information, we assumed that the two arrays are separated by 60 meters along the east-west x-axis, at the same depth, both oriented with phone 1 pointing due north (y-axis). We were unable to perform a direction calibration of the system in the field due to a malfunction of the calibration projector. Despite this, given the best available information the geometric solutions seem to indicate that the animal or animals ceased echolocating a few meters away from the array. At the San Diego meeting a discussion with John Potter of the National University of Singapore brought to light the idea that Wood and Evans (1980, cited in Dawson, 1991) offered. Dolphins are often known to cease echolocating as they approach prey (perhaps to avoid frightening it away), and work by detecting the noise the fish makes as it swims. He also theorizes that odontocetes rely heavily on passively monitoring the local noise field. This instinctive behavior may explain why the clicks approach within a few meters of the array and then stop.
As a final addendum to this section, some of the low frequency (roughly 18 kHz) tones were considered. It would be highly desirable to be able to localize the animals using these tones due to their omni directional propagation. However, the signals are so weak, narrowbanded and long in duration that cross-correlation is all but useless as a means of time delay estimation. Any successful approach to using these signals would probably require ultra-short baseline phase comparison techniques.
6. Conclusions and Recommendations

The results of this experiment indicate that the properties of the harbor porpoise's echolocation system (that may be ideally suited to the porpoise) are anything but ideal for the person attempting to acoustically track them at a distance. The low source levels effectively limit the detection distances to tens of meters, given ambient noise conditions. The correlation characteristics of the simple amplitude-modulated sinusoidal signal are less than ideal; false peaks in the cross correlation function result from the presence of noise. Most importantly, the porpoise focuses acoustic energy into a highly directional beam. This makes detection of an animal dependent on its orientation.

Some limitations to the existing system are obvious. In order to compensate for the directionality of the animals, the arrays should be closer together. This would increase the likelihood of a given echolocation pulse arriving on multiple arrays. I recommend reducing the baseline distances from 60 meters to 30 meters or less.

From the data collected in the experiment, the azimuth measurements were relatively stable, but the uncertainty in bearing angles measured from the East array led to variations in the range estimate. Little was known about the actual orientation of the arrays. They were positioned roughly 60 meters apart, falling approximately along an East/West line, and at roughly the same depth. The alignment of the arrays with hydrophone 1 pointing due north cannot be guaranteed. This was compounded with end-fire signal arrivals that are the most difficult to range accurately. Still, the repeatability of the azimuth measurements is encouraging. An improvement to offset that problem would be the addition of a third array, positioned perpendicular to the
other two. In this way, least-squares estimates of range and depth can be computed that would be less sensitive to end-fire and other error-prone conditions. Naturally, any additional hydrophones within a given array increase the reliability of the bearing estimate from that array. If practical, a network of individual hydrophones spread out over some distance could serve as a detection net and provide additional information to the arrays.

At least one piece of data already exists that has not been exploited, and could be used as a check of the range estimate. The system already uses time delays within an array to determine lines of position from each array. However, when both arrays receive the same signal, the time difference (milliseconds) between arrays defines a hyperbola that serves to constrain the position estimate.

A necessity for any future deployment is extensive calibration with a known signal source. The source should be moved around the arrays at known ranges and bearings so the system performance can be evaluated. Any corrections for bias errors arising from array positioning can then be implemented. This would also give the user a sense of the reverberation characteristics in the area. Another useful adaptation would be the inclusion of sources on the arrays that could be triggered intermittently, to confirm relative array positions.

The arrays need to be more sturdy, easier to deploy, and less likely to get snagged in floating debris. They also need to be made less interesting to inquisitive porpoises (and other animals). Using materials with acoustic impedances closer to that of the water will be less likely to draw a porpoise’s attention and distract it from its natural behavior. I recommend increasing the height of the arrays to minimize shading
any of the hydrophones by foreign objects near the bottom. Future deployments will also probably be in deeper water than the Harbor Island experiment, requiring specialized equipment (beyond a dry-suited diver with a compass) for proper array orientation.

If the information is available or can be obtained without difficulty, knowledge of things like the sound speed and local bathymetry can be used to make inferences about the acoustic propagation characteristics in the area.

Future experiments are in the early planning stages. The next phase of the project has been conceived as a semiautonomous system, in which the equipment operates continuously, reporting data back to a personal computer only when an interaction with an animal occurs. In order for the system to be efficient, the acoustic signals need to be processed immediately on-site. The downside to any work done using the existing procedure is the time- and computation-intensive nature of the signal analysis. Because of the expense and processing demands of digital data acquisition systems capable of multichannel sampling at hundreds of kilohertz, alternative means will be used to calculate and then pass on the time difference data to the computer. One way to estimate those delays is to demodulate or shift the signals' frequency spectrums toward the baseband using analog front-end circuitry before sampling at a lower rate. Another way is using threshold detection, where an acoustic signal of sufficient level (limited to a narrow frequency band) triggers a timing circuit. Such a system could be implemented using electronic components without the need of a digital data acquisition system. If the time delays (and any other pertinent information) are transmitted to a computer, the analysis can then be conducted to generate bearing and range estimates.
A few researchers in the U.K have been working on similar porpoise tracking 
problems. A group from the International Fund for Animal Welfare (Chappell, et. al., 
1996) developed a system that automatically detects the presence of clicks, using a 
simple envelope detector circuit. Another group from the University of Loughborough 
(Connelly, et. al., 1997) used a similar circuit with multiple hydrophones. A look-up 
table of bearings calculated for numerous time delay combinations was constructed and 
is used to track the animals.

The eventual goal David Potter has in mind is an autonomous system. One 
system concept was that the equipment would be deployed near a set gill net and left in 
place unattended for extended periods of time, recording interactions with the animals, 
including all the time delay information and capable of downloading the data when 
requested. The data could be transmitted by cable up to a surface buoy equipped for 
telemetry to a remote PC by radiofrequency ethernet link.

In closing, this project has always proved both challenging and rewarding, and 
not a little humbling. For every bit of insight we gained into how these animals 
operate, many more questions arose. Despite the complex set of tasks left to be 
accomplished, most of the project goals were met successfully; this is quite 
encouraging.

Also encouraging is the continuing work of a large number of people of various 
backgrounds, involved in this and many other projects, who continue to pose these 
questions and investigate novel ways to find the answers.
Literature Cited


Smith, T., Palka, D., and Bisack, K., “Biological Significance of Bycatch of Harbor Porpoise in the Gulf of Maine Demersal Gillnet Fishery,” NOAA/NMFS/NEFSC,


Table A.1: Bearing Angles Measured From West Array, Coordinates [0,0,0]

RU = raw signal correlation, unweighted least squares
RW = raw signal correlation, weighted least squares
EU = correlation using complex envelope, unweighted least squares
EW = correlation using complex envelope, weighted least squares
Azimuth increases clockwise from positive x-axis (East)
Elevation increases downward from positive z-axis (Up)

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Table A.2: Bearing Angles Measured From East Array, Coordinates [60,0,0]

RU = raw signal correlation, unweighted least squares
RW = raw signal correlation, weighted least squares
EU = correlation envelope, unweighted least squares
EW = correlation envelope, weighted least squares

Azimuth increases clockwise from positive x-axis (East)
Elevation increases downward from positive z-axis (Up)

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Table A.3: Position Relative to West Array, Coordinates \([0,0,0]\)

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Figure A.1.1: Click Time Series and Spectra, Tape Count 875, 114 Seconds
Figure A.1.2: Click Time Series and Spectra, Tape Count 940, 122 Seconds
Figure A.1.3: Click Time Series and Spectra, Tape Count 1110, 144 Seconds
Figure A.1.4: Click Time Series and Spectra, Tape Count 1132, 147 Seconds
Figure A.1.5: Click Time Series and Spectra, Tape Count 1155, 150 Seconds
Figure A.1.6: Click Time Series and Spectra, Tape Count 1156, 150 Seconds
Figure A.1.7: Click Time Series and Spectra, Tape Count 1158, 150 Seconds
Figure A.1.8: Click Time Series and Spectra, Tape Count 1160, 150 Seconds
Figure A.1.9: Click Time Series and Spectra, Tape Count 1162, 151 Seconds
Figure A.1.10: Click Time Series and Spectra, Tape Count 1202, 156 Seconds
Figure A.1.11: Click Time Series and Spectra, Tape Count 1204, 156 Seconds
Figure A.1.12: Click Time Series and Spectra, Tape Count 1229, 159 Seconds
Figure A.1.13: Click Time Series and Spectra, Tape Count 1339, 174 Seconds
Figure A.1.14: Click Time Series and Spectra, Tape Count 1541, 1/4 Seconds
Figure A.1.15: Click Time Series and Spectra, Tape Count 1342, 174 Seconds
Figure A.1.16: Click Time Series and Spectra, Tape Count 1343, 174 Seconds
Figure A.1.17: Click Time Series and Spectra, Tape Count 1344, 174 Seconds
Figure A.1.18: Click Time Series and Spectra, Tape Count 1345, 174 Seconds
Figure A.1.19: Click Time Series and Spectra, Tape Count 1349, 175 Seconds
Figure A.1.20: Click Time Series and Spectra, Tape Count 1350, 175 Seconds
Figure A.1.21: Click Time Series and Spectra, Tape Count 1420, 184 Seconds
Figure A.1.22: Click Time Series and Spectra, Tape Count 1422, 184 Seconds
Figure A.1.23: Click Time Series and Spectra, Tape Count 1464, 190 Seconds
Figure A.1.24: Click Time Series and Spectra, Tape Count 1521, 197 Seconds
Figure A.1.25: Click Time Series and Spectra, Tape Count 1522, 197 Seconds
Figure A.1.26: Click Time Series and Spectra, Tape Count 1570, 204 Seconds
Figure A.1.27: Click Time Series and Spectra, Tape Count 1600, 208 Seconds
Figure A.1.28: Click Time Series and Spectra, Tape Count 1656, 215 Seconds
Figure A.1.29: Click Time Series and Spectra, Tape Count 1803, 234 Seconds
Figure A.1.30: Click Time Series and Spectra, Tape Count 1814, 235 Seconds
Figure A.1.31: Click Time Series and Spectra, Tape Count 2092, 271 Seconds
Figure A.2.1: Hydrophone Sensitivity
S/N: NTK-1A  Date: 23/July/96
Sample Gate: 4.0 ms  Receive Delay: 1.7 ms
Water Temp: 70 F  Depth: 2.74 m
Spacing: 2.0 m  Tested by: DRB

FFVS vs FREQ

FREQUENCY in kHz

-190
-185
-180
-175
-170
-165
-160
-155
-150

0.0  20.0  40.0  60.0  80.0  100.0  120.0  140.0  160.0  180.0

NRL STD: H52-148  PROJ: F89-A126  INCR: 1 kHz

Sparton Electronics

11-NLR-15-RFV 1098
Figure A.2.2: Hydrophone Sensitivity—Sparton Electronics # EB-4
Figure A.2.3: Hydrophone Sensitivity—Sparton Electronics # 10

FFVS vs FREQ.

S/N 10   DATE 23/July/96
SAMPLE GATE 1.0 ms RECEIVE DELAY 1.7 ms
WATER TEMP 70 F DEPTH 2.74 m
SPACING 2.0 m TESTED BY DAB

0.0 20.0 40.0 60.0 80.0 100.0 120.0 140.0 160.0 180.0
FREQUENCY in kHz

Sparton Electronics
Figure A.2.4: Hydrophone Sensitivity—Sparton Electronics # 10E
FFVS vs FREQ.

S/M. 9     DATE 23/JULY/96

SAMPLE GATE 1.0MS RECEIVE DELAY 1.7MS

WATER TEMP 70F DEPTH 2.74M

SPACING 2.0M TESTED BY DRB

Figure A.2.5: Hydrophone Sensitivity. Spartan Electronics #9
FFVS vs FREQ.

S/N 4
DATE 23/JULY/96

SAMPLE GATE 1.0ms RECEIVE DELAY 1.7ms
WATER TEMP 70 F DEPTH 2.74m
SPACING 2.0m TESTED BY DRB

Figure A.2.6: Hydrophone Sensitivity-Sparton Electronics #4
Figure A2.7: Hydrophone Sensitivity, Sparton Electronics # NTK-10A

FFVS vs FREQ.

S/N NTK-10A DATE 22/July/98
SAMPLE GATE 1.0MS RECEIVE DELAY 1.7MS
WATER TEMP 70 F DEPTH 2.74m
SPACING 2.0M TESTED BY DBB

FFVS vs FREQ.

FREQUENCY in kHz

-130 -135 -140 -145 -150 -155 -160 -165 -170 -175 -180

0 20 40 60 80 100 120 140 160 180
Figure A.2.8: Hydrophone Sensitivity—Sparton Electronics # NTK-6A
Differential line driver circuit

- **V+ = 12 volts (nominal)**
- **All 1% precision resistors**
- **C2 and C3 are 16V tantalum capacitors**
- **C1 and C4 are ceramic**

**Figure A.3: Differential Line Driver Circuit Schematic**

- **U1A**
  - 4.99K
  - 49.9Ω
  - 10k
  - 10k
  - 10k
  - 10k
  - 10k
  - 6
  - 5
  - 4

- **U1B**
  - 10k
  - 10k
  - 10k
  - 10k
  - 10k
  - 6
  - 5
  - 4

- **MiniCircuits**
  - RF Transformer
  - P/N T1-6T
  - Impedance ratio 1:1
  - Style X65
  - 8 pin DIP

- **Quabbin 6175 cable**
  - 1 of 12 twisted pairs
  - with individual shield
  - 1000 ft. long

- **C1 3.3nF**
- **C2 10μF**
- **C3 10μF**
- **C4 0.1μF**

- **10k**
- **49.9Ω**

- **Input**

- **To TEAC instrumentation recorder**

- **U1** is National Semiconductor LM6218N
  - Dual Operational Amplifier
  - 8 pin DIP
MULTIPAIR CABLE
PAIRS SHIELDED 20 AWG

**Application:** Direct Bural Roadway Loop, Control Cable

**Construction:** 20 AWG tinned copper as listed below, insulated with polypropylene and paired. Each pair shielded with aluminum/polyester tape and tinned copper drain wire. Shielded pairs cabled and jacketed with black high density polyethylene.

**Listing/Ratings:** Mfr's Suggested Working Voltage: 350 Volts

<table>
<thead>
<tr>
<th>Part Number</th>
<th>No. of Pairs</th>
<th>Strand</th>
<th>Drain Wire AWG</th>
<th>Insulation Thickness</th>
<th>Jacket Thickness</th>
<th>Nominal Diameter</th>
<th>Nom. Cap. pF</th>
<th>Color Code</th>
<th>1000' pchg</th>
<th>Weight Lbs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>6183</td>
<td>1</td>
<td>Solid</td>
<td>22 Solid</td>
<td>.013</td>
<td>.035</td>
<td>.89</td>
<td>.189</td>
<td>4.80</td>
<td>25</td>
<td>48</td>
</tr>
<tr>
<td>6170</td>
<td>3</td>
<td>10/30</td>
<td>22 7/30</td>
<td>.013</td>
<td>.033</td>
<td>.049</td>
<td>1.02</td>
<td>.330</td>
<td>9.38</td>
<td>20</td>
</tr>
</tbody>
</table>

a: Capacitance between conductors.
b: Capacitance between 1 conductor and other conductors connected to shield.

**Figure A.4: Quabbin 6175 Cable**
Instrumentation Data Recorders... Video cassette Data Recorders

**XR-5000**  
**XR-7000**  
**XR-9000**  
**XR-5000WB**

- Menu-driven electro-luminescent (EL) display for interactive operation of various measurement conditions.

- Dual display modes: bar-graph for all data channels or 2CM waveform display.

- XR-5000, XR-7000 and XR-9000 offer FM Wide Band Group-I recording, plus High Band recording, which doubles Wide Band Group-I response to DC 40kHz.

- XR-5000WB offers Wide Band Group-II, with DC to 125kHz.

- ID information recording and search functions speed data processing.

- Recording/reproduction is possible for up to 5 hours 44 minutes with the XR-5000, XR-7000, and XR-9000 and 11 hours 28 minutes with XR-5000WB.

- Available options include: a GPIB board with A/D converter (all models); Super FM amplifier for response equivalent to FM High Band x 2 (Wide Band Group-I X 4); DR amplifier; and PCM amplifier (XR-5000/XR-7000)

![XR-7000](image)

Figure A.5: TEAC XR-7000 Instrumentation Recorder

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Bibliography


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