# Underwater Threat Neutralization: Swimmer Defense

Gary Koopmann
157 Hammond Building, University Park, PA 16802
phone: (814) 865-2761 fax: (814)863-7222 email: ghk1@psu.edu

Chris Rahn
157 Hammond Building, University Park, PA 16802
phone: (814) 865-6237 fax: (814)863-7222 email: cdrahn@psu.edu

Grant Number: N0014-06-1-0191

## LONG-TERM GOALS

The long term goal of this project is to demonstrate the efficacy of a swimmer deterrent system that focuses high intensity, low frequency sound at a sector of a harbor containing a swimmer. The system integrates swimmer location data from high frequency sonar detectors with control templates to drive a multiplicity of sound sources. Focusing is achieved by driving each of the sound sources with optimal magnitude and phase based on measured transfer functions between source and harbor sectors. These measurements are obtained from the acoustic calibration of the harbor.

## OBJECTIVES

(1) Develop a strategy to measure source/receiver transfer functions for a given harbor geometry that considers sound propagation influenced by daily and seasonal changes (temperature, tides, etc.) and the presence of transient reflectors (movement of ships).

(2) Develop a source control algorithm that, when given a sector of the harbor containing a swimmer, will automatically energize high intensity sources to focus sound at that sector.

(3) Develop a user-friendly graphics interface (GUI) that permits a non-technical person to operate the swimmer deterrent system by simply clicking the sector of the screen that portrays the presence of the swimmer at a particular sector of the harbor.

(4) Test the calibration algorithm and the GUI in various situations leading up to a final, FNC demonstration of the swimmer deterrent system.

(5) Develop and validate a digitized acoustics model for large, acoustic spaces with embedded reflectors to assess the sensitivity of source/receiver transfer functions to the presence of transient reflective bodies (e.g., ships) in the harbor.

## APPROACH

This project can be divided into four main parts: (1) the characterization of the harbor’s acoustics that provides templates that store source/receiver transfer functions, (2) the development of control algorithms to focus high amplitude, low frequency sound on specifed harbors sectors, (3) the

| | |
|---|---|
| **Report Documentation Page** | *Form Approved*<br>*OMB No. 0704-0188* |

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

| | | |
|---|---|---|
| 1. REPORT DATE<br>**30 SEP 2008** | 2. REPORT TYPE<br>**Annual** | 3. DATES COVERED<br>**00-00-2008 to 00-00-2008** |

| | |
|---|---|
| 4. TITLE AND SUBTITLE<br>**Underwater Threat Neutralization: Swimmer Defense** | 5a. CONTRACT NUMBER |
| | 5b. GRANT NUMBER |
| | 5c. PROGRAM ELEMENT NUMBER |
| 6. AUTHOR(S) | 5d. PROJECT NUMBER |
| | 5e. TASK NUMBER |
| | 5f. WORK UNIT NUMBER |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)<br>**Pennsylvania State University ,157 Hammond Building,University Park,PA,16802** | 8. PERFORMING ORGANIZATION REPORT NUMBER |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) | 10. SPONSOR/MONITOR’S ACRONYM(S) |
| | 11. SPONSOR/MONITOR’S REPORT NUMBER(S) |

12. DISTRIBUTION/AVAILABILITY STATEMENT

**Approved for public release; distribution unlimited**

13. SUPPLEMENTARY NOTES

**code 1 only**

14. ABSTRACT

**The long term goal of this project is to demonstrate the efficacy of a swimmer deterrent system that focuses high intensity, low frequency sound at a sector of a harbor containing a swimmer. The system integrates swimmer location data from high frequency sonar detectors with control templates to drive a multiplicity of sound sources. Focusing is achieved by driving each of the sound sources with optimal magnitude and phase based on measured transfer functions between source and harbor sectors. These measurements are obtained from the acoustic calibration of the harbor.**

15. SUBJECT TERMS

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| a. REPORT<br>**unclassified** | b. ABSTRACT<br>**unclassified** | c. THIS PAGE<br>**unclassified** | **Same as Report (SAR)** | **22** | |

**Standard Form 298 (Rev. 8-98)**
Prescribed by ANSI Std Z39-18

development of a GUI-based controller that can be operated by non-technical personnel and (4) the development of a digitally-based acoustic model for assessing source/receiver sensitivity to reflectors.

(1) To characterize the acoustic transmission characteristics of a given harbor, low frequency sound sources are used along with an array of hydrophones to determine transfer functions from each of the sources to each sector of the harbor. Using these transfer functions, an algorithm has been developed in the software program LabVIEW to calculate the phase required to maximize the sound pressure in each sector.

(2) With the above characterization, phase templates are generated and stored as ‘look up’ tables within the control algorithm. When a swimmer is detected in a particular sector, the controller nearly instantly recalls the corresponding template for that sector and energizes the sound sources to focus the sound field at that sector.

(3) To operate the controller, a user-friendly GUI has been developed in LabVIEW. A map of the harbor’s sectors is to be projected on the monitor as an overlay of the map of the harbor. When the position of the swimmer is identified and transmitted to the controller, the position of the swimmer will appear within the designated sector. At any point, the controller operator can energize the sound sources to focus energy at a sector simply by clicking a button – LabVIEW will calculate the appropriate sector to energize by the swimmer location.

(4) The control templates (transfer functions) could vary due to physical changes in operating conditions within the harbor. These include daily and seasonal changes (temperature, salinity, tides, etc) along with the presence of time dependent reflecting boundaries, i.e. ships. A set of control templates might need to be acquired for each of these conditions that captures the particular characteristics of each harbor under consideration, however, preliminary data suggests fewer sets of templates will be necessary.

Preliminary to the projected harbor demonstrations, the development of the LabVIEW controller software was done in air in an anechoic chamber using loudspeakers and microphones. This effort was completed the end of December 2007. To test the controller in a marine environment, smaller scale underwater tests were conducted at Jacksonville Quarry near the Penn State University Park Campus. Further refinement of the equipment and controller algorithms was carried out at the Jacksonville Quarry prior to the field tests and final FNC demonstration in June 2008.

Concurrently with this testing and the development of the controller algorithm and supporting instrumentation described above, the acoustic modeling program continued to be refined and validated with theoretical and experimental data. Ultimately, the results of the model will be used to interpolate and extrapolate against experimental data as the model is progressed, to allow for uncharacterized sectors of the harbor.

Prof. Gary Koopmann, the PI for this project, is the acoustics and sound propagation specialist for the group, focusing on the acoustic modeling program and project logistics. Prof. Christopher Rahn, a co-PI, is the controls and instrumentation specialist for the group, focusing on the algorithms and controlling the sources. Andrew Kankey is a Ph.D. candidate focusing on the development and implementation of the control algorithms. He is also responsible for writing LabVIEW codes, developing the graphical user interfaces, and integrating the acoustics modeling program with the experiments.

## WORK COMPLETED

During this past year, multiple iterations of a LabVIEW GUI were developed and tested in the Applied Research Laboratory's Water Tank and the local Jacksonville Quarry for ease of GUI use and accuracy in the focusing algorithm.

An acoustic finite element program was completed and validated with simple geometries as well as more complex, realistic geometries. Methods for adequately modeling the harbor bottom were investigated to replicate experimental results numerically.

The year of testing culminated in June at Coddington Cove in Newport, RI, where the effectiveness of the second generation of our phase-searching algorithm was investigated. Input to the algorithm consisted of measuring transfer functions between an array of 7 main hydrophones (distributed at 10 degree intervals in a line simulating the approach of a diver) and each source in a three-source and a four-source array. The algorithm was tested by focusing the sources on selected sectors of the harbor containing a hydrophone. The results from this round of testing were successful, illustrating our ability to indeed focus the low frequency sound at different sectors within the harbor. These results were also compared to classic array theory as a baseline and the maximum pressures were similar for both cases.

## RESULTS

1. The acoustic finite element code was created and validated using three simple enclosures shown in Figure 1: (1) a rigid duct, (2) a rigid walled box, (3) a rigid walled box with a pressure release surface. The first few theoretical eigenvalues were compared to FEM results and they agreed to within 4% as shown in Table 1.

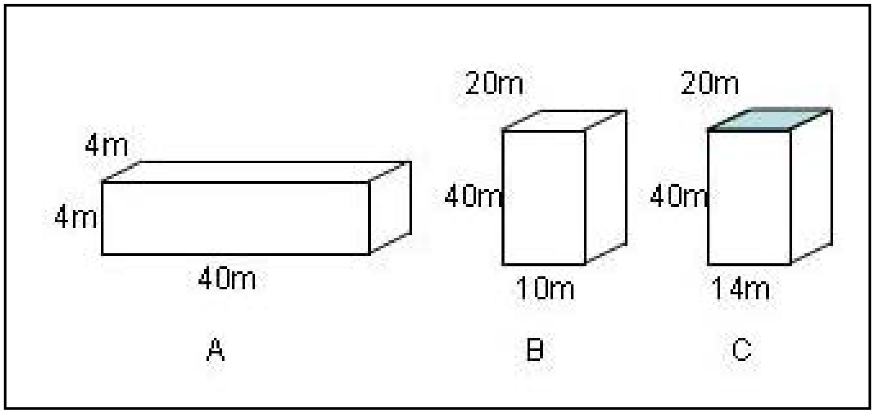


***Figure 1: Basic eigenvalue problems. Rigid-walled duct(A), rigid-walled rectangular solid(B), rigid-walled rectangular solid with pressure release top(C).***

***Table 1: Eigenvalue comparison for basic problems. Values are natural frequencies in rad/s.***

| Rigid-Walled Duct (A) | | | Rigid-Walled Box (B) | | | Rigid - Press. Release Box (C) | | |
|---|---|---|---|---|---|---|---|---|
| *Theory* | *FEM* | *% Diff.* | *Theory* | *FEM* | *% Diff.* | *Theory* | *FEM* | *% Diff.* |
| 117.8 | 117.9 | 0.08 | 117.81 | 117.93 | 0.10 | 168.30 | 168.65 | 0.21 |
| 235.62 | 236.6 | 0.42 | 235.62 | 236.59 | 0.41 | 205.44 | 205.80 | 0.18 |
| 353.43 | 356.7 | 0.93 | 263.43 | 264.35 | 0.35 | 289.55 | 290.55 | 0.35 |
| 471.24 | 479 | 1.65 | 333.22 | 334.59 | 0.41 | 312.60 | 313.57 | 0.31 |
| 589.05 | 604.3 | 2.59 | 353.43 | 356.71 | 0.93 | 373.30 | 374.69 | 0.37 |
| 706.86 | 733.2 | 3.73 | 424.77 | 428.04 | 0.77 | 391.45 | 394.56 | 0.79 |

2. To illustrate the accuracy of our boundary condition modeling, the simple case of an impedance tube, for which an analytic solution exists, was used with different boundary impedances. The FEM program uses the factor β which is the ratio of the characteristic fluid impedance to the boundary impedance. An impedance tube is a duct with rigid walls, a piston with prescribed velocity at one end and a wall of a defined impedance on the other end, see Figure 2. The FEM results for several different boundary impedances were compared and agreed well. A few of those results are shown in Figures 3 through 6.

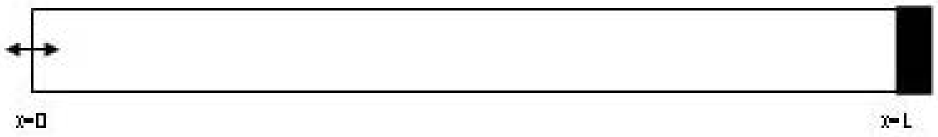


***Figure 2: Impedance Tube. The left edge consists of a piston vibrating with a prescribed velocity. The right edge has a known impedance.***

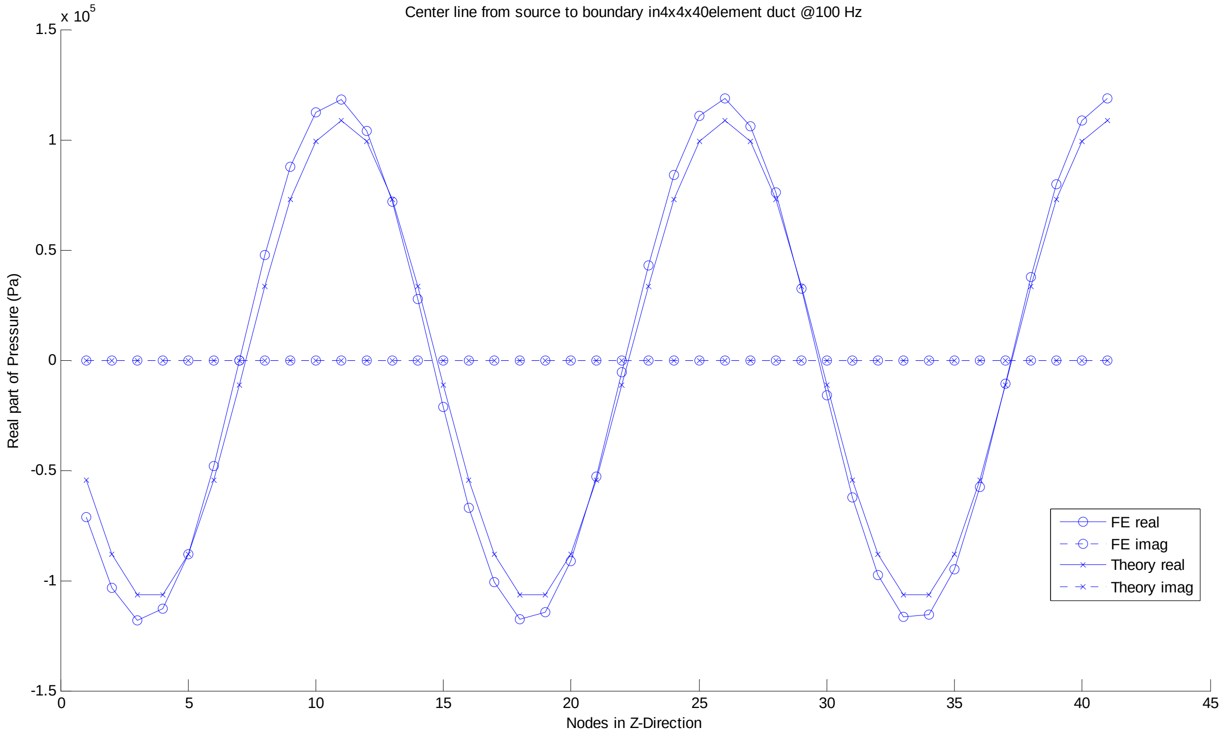


***Figure 3:  Impedance tube results, real and imaginary pressure vs. distance (node number). Boundary is a Rigid Wall with β =0.  [Both real parts and imaginary parts agree well, with real parts simulating a sine wave and imaginary parts equal to zero.]***

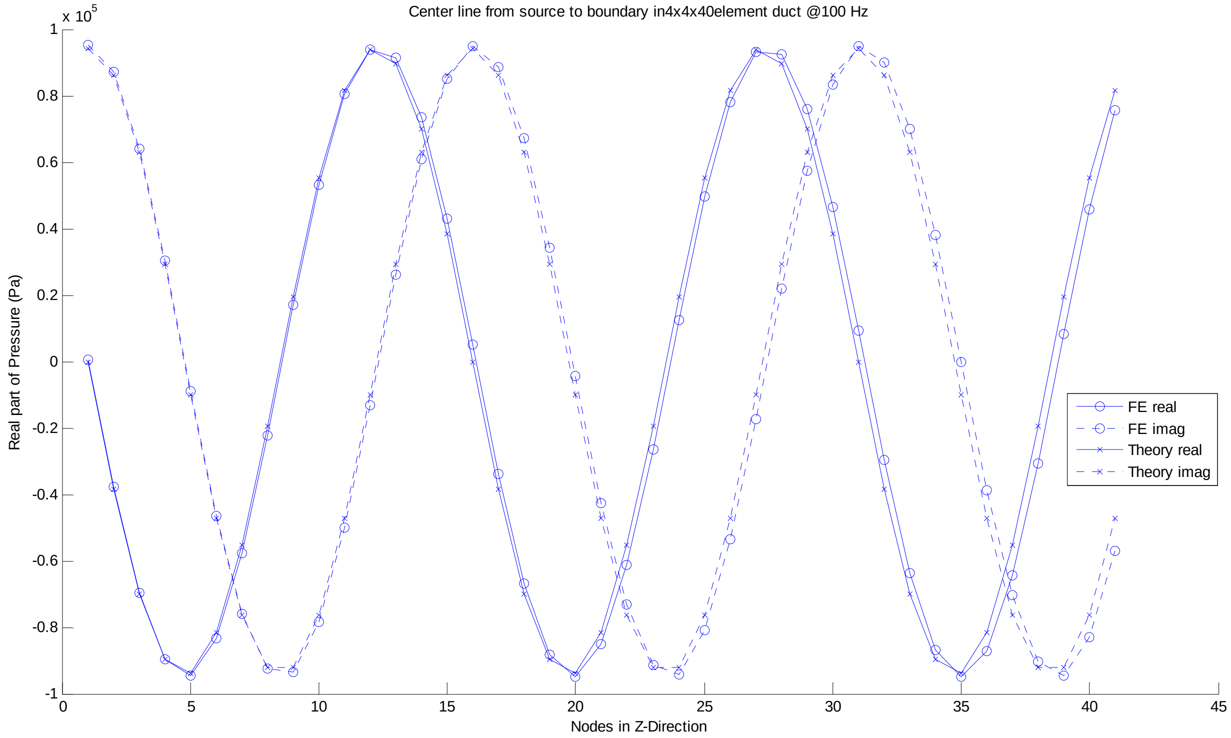


***Figure 4: Impedance Tube results, real and imaginary pressure vs. distance (node number). Boundary has a ρ-c condition with β =1. [Both real parts and imaginary parts agree well, with real and imaginary parts simulating sine waves which are about 90 degrees out of phase.]***

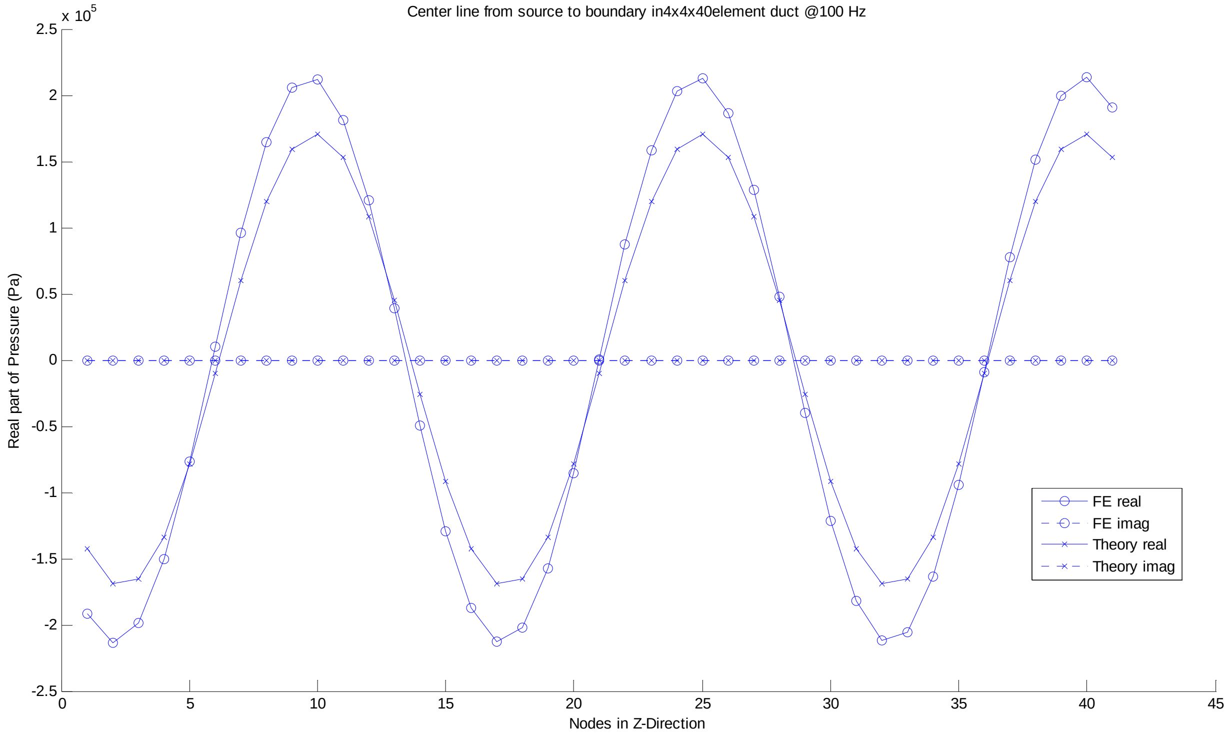


***Figure 5: Impedance Tube results, real and imaginary pressure vs. distance (node number). Boundary has an imaginary impedance with β =0.5 i. [Both real parts and imaginary parts agree well, with real parts simulating a sine wave and imaginary parts equal to zero.]***

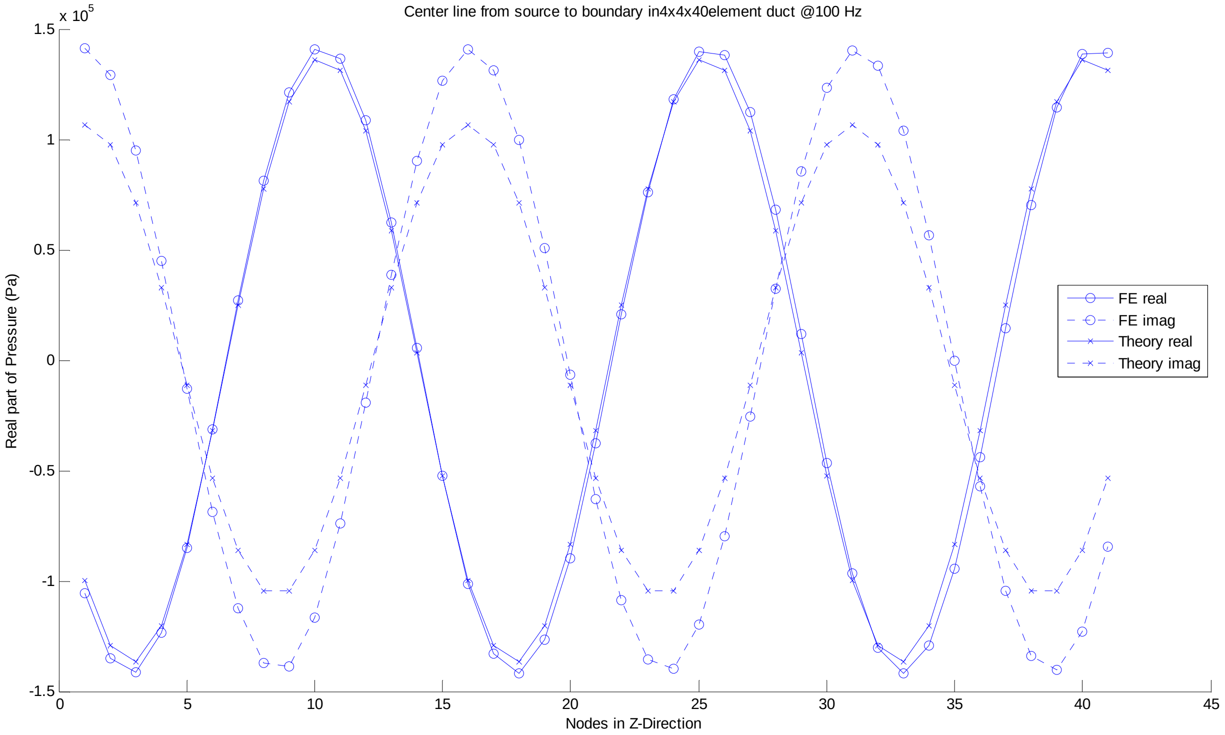


***Figure 6: Impedance Tube results, real and imaginary pressure vs. distance (node number). Boundary has a complex impedance with β =0.5+0.5 i. [Both real parts and imaginary parts agree well, with real and imaginary parts simulating sine waves which are about 135 degrees out of phase. Real parts agree better than imaginary parts.]***

3. An underwater wedge, shown in Figure 7, was used to validate the FEM code for a more complex geometry. The underwater wedge used had a pressure release top and bottom surface. This type of boundary condition was used because there was an analytical solution to the problem to which the FEM model could be compared. The FEM results for the wedge as viewed in ParaView are shown in Figure 7 for three different frequencies. The comparisons with theory for each frequency are shown in Figures 8 through 10. The FEM results agree very well with theory in both magnitude and location of the minimums. The sources were located 100m deep in a portion of the wedge which was 200m deep. The distance from the source to the tip of the wedge is about 1km.

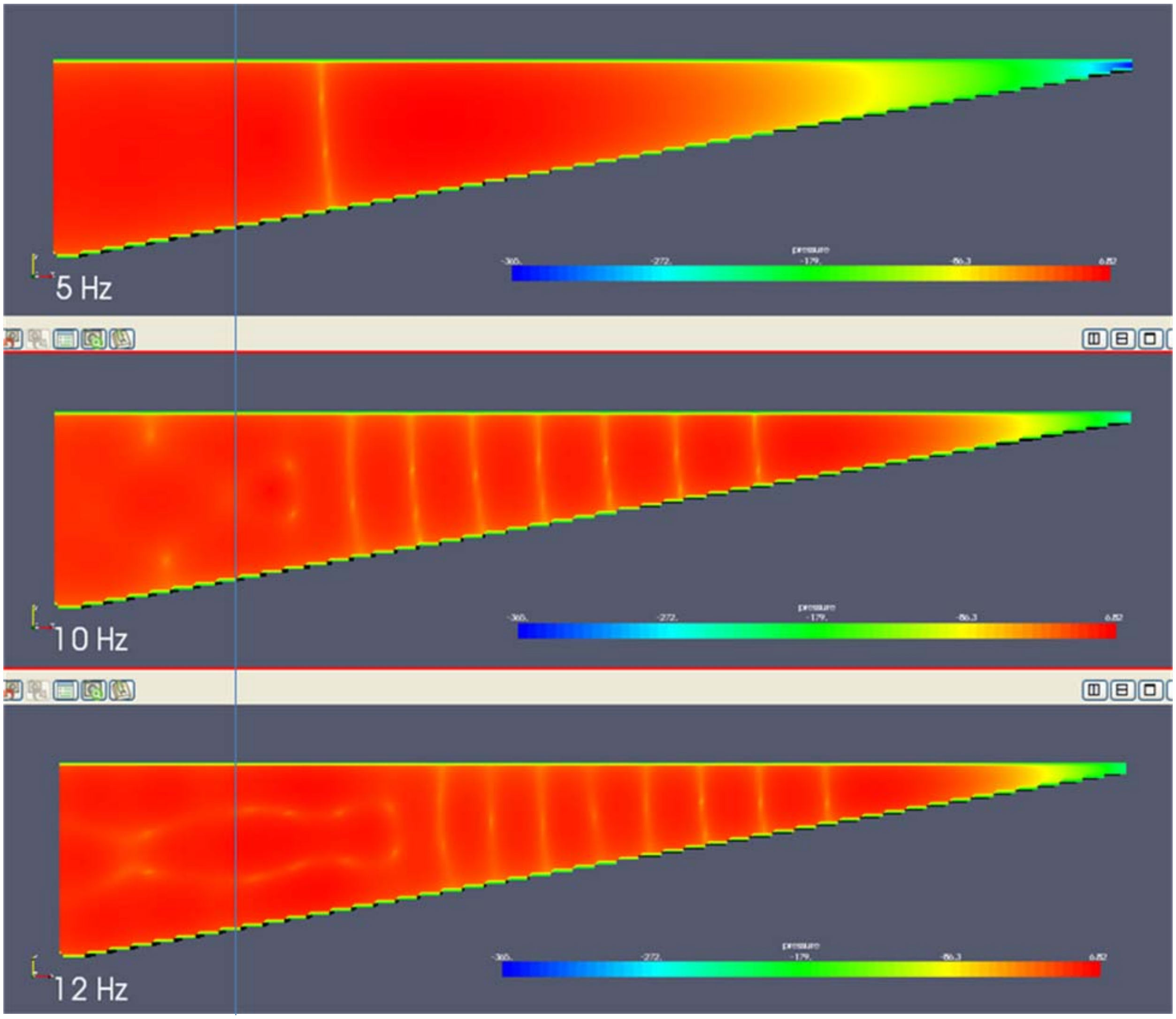


***Figure 7: Wedge solutions from Acoustic FEM. Source is 100 m deep on vertical line which is approximately 1 km from tip of wedge. Depth at Source location is 200 m. Pressure release surfaces on top and bottom and rho-c on the left most side. [Results for three frequencies, 5, 10, and 12 Hz. Modes cut off as the sound propagates towards the wedge tip.]***

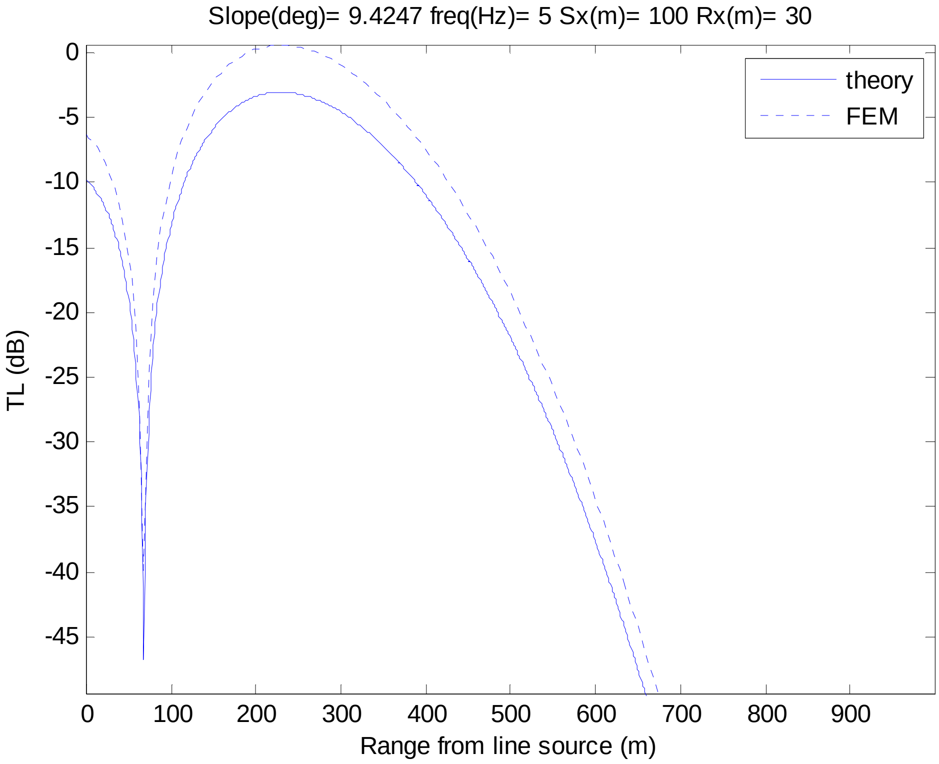


***Figure 8: Wedge results from FEM compared to analytical theory. Source is at 100 m depth excited at 5 Hz, receiver is at 30 m depth. [Slope of wedge is 9.4247 degrees. First null is around 75m.]***

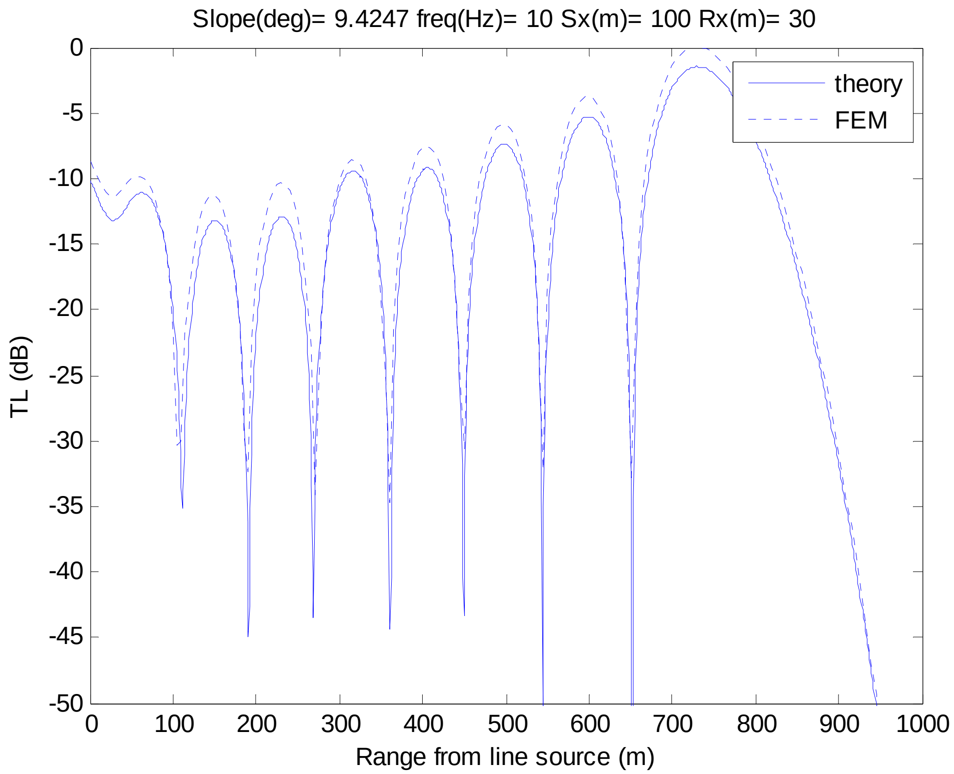


***Figure 9: Wedge results from FEM compared to analytical theory. Source is at 100 m depth excited at 10 Hz, receiver is at 30 m depth. [Slope of wedge is 9.4247 degrees. First null is around 110m.]***

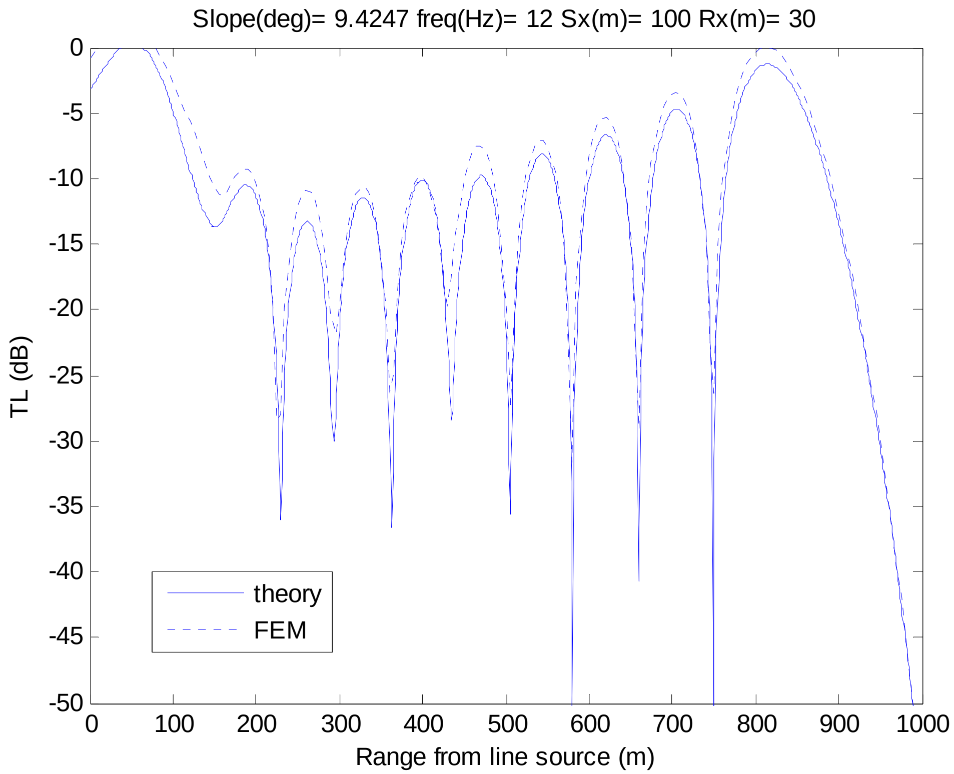


***Figure 10: Wedge results from FEM compared to analytical theory. Source is at 100 m depth excited at 12Hz, receiver is at 30 m depth. [Slope of wedge is 9.4247 degrees. First null is around 220m.]***

4. The final demonstration in Coddington Cove was performed in early June 2008. From the end of a finger pier, a linear array of 7 acoustic sources was suspended 2 meters from the harbor bottom. The mean water depth in the harbor was 11 meters with surficial sediments characterized by silts, sandy silts, and clay. The acoustic field was measured by an array of 11 hydrophones oriented in a cross pattern in the harbor. The phones ranged from 100 meters to 325 meters from the center of the array and were placed in ten degree increments along an line from a peninsula on the coast to the second pier in the harbor. Figure 11 shows the layout of the hydrophones in the harbor. An Optimal Phase Search (OPS) method involving the calibration of the harbor was used along with classic array theory to determine the phasing of the sources to focus energy on each of the hydrophone locations. Both the J15-3 array and the HLF1 array were tested at 100 and 200 Hz for the phasing and 100 to 600 Hz for transmission loss measurements in the harbor. Figure 12 shows the graphical user interface created in LabVIEW.

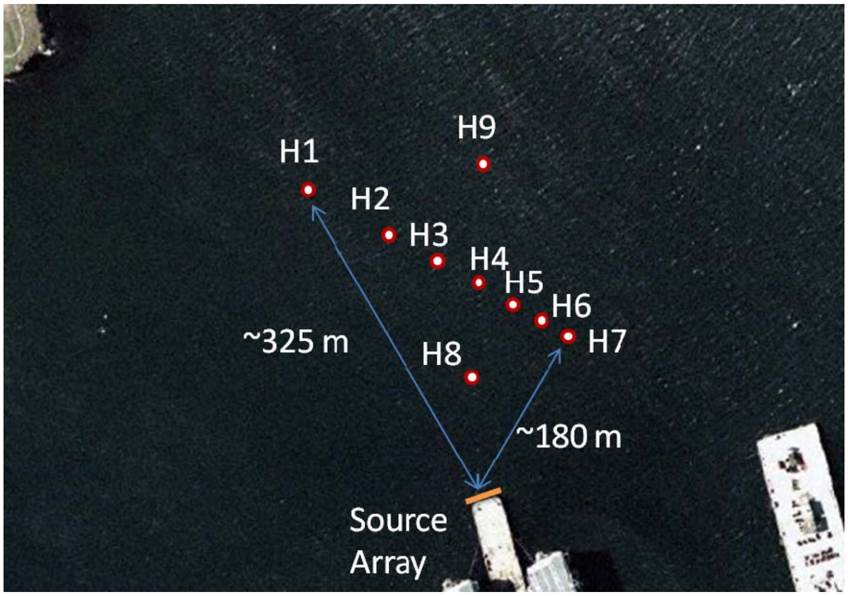
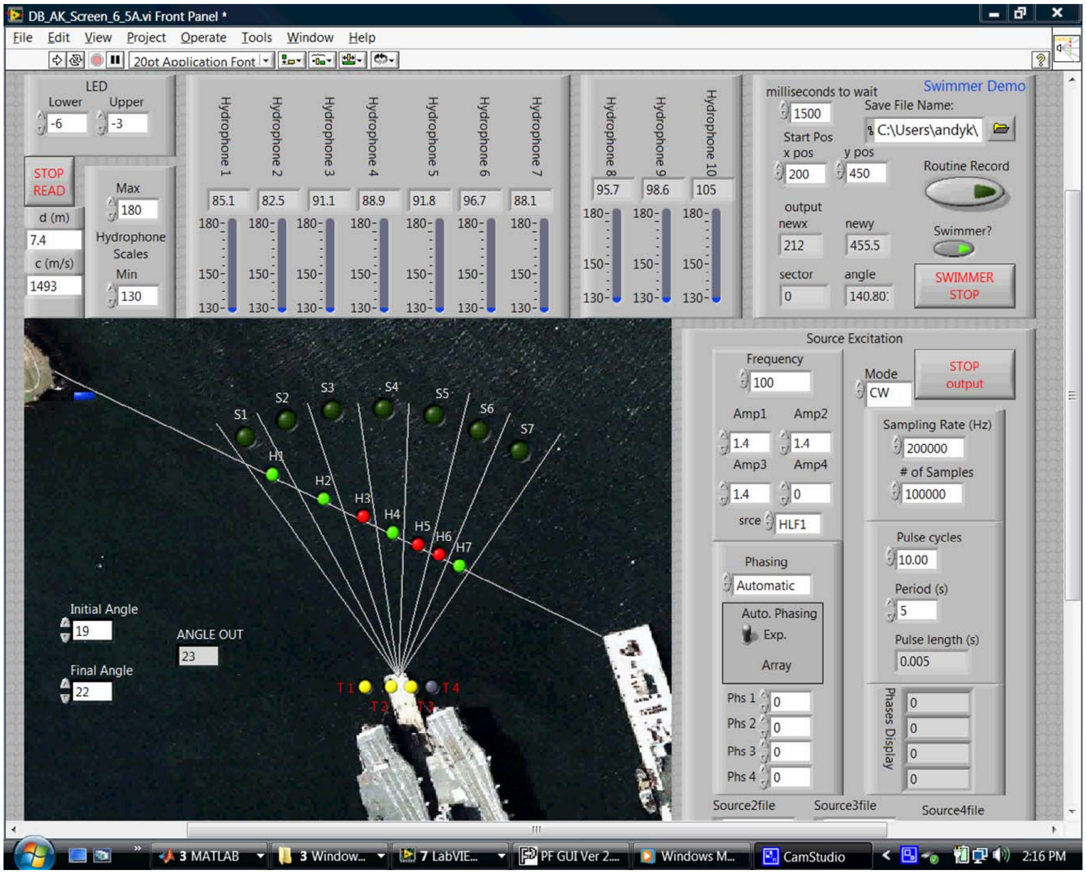


***Figure 11: Hydrophone layout in Coddington Cove June 2008. Two more hydrophones were in a vertical array with hydrophone 4. [Hydrophones 1 through 7 are evenly distribued angularly in a line from the shoreline to the pier next to the working pier, Hydrophones 8 and 9 form a radial with Hydrohpone 4, Hydrophone 7 is 180m from the pier while Hydrophone 1 is 325m from the pier.]***



Lower -6
Upper -3

Max 180
Min 130

d (m) 7.4
c (m/s) 1493

| Hydrophone 1 | Hydrophone 2 | Hydrophone 3 | Hydrophone 4 | Hydrophone 5 | Hydrophone 6 | Hydrophone 7 | Hydrophone 8 | Hydrophone 9 | Hydrophone 10 |
|---|---|---|---|---|---|---|---|---|---|
| 85.1 | 82.5 | 91.1 | 88.9 | 91.8 | 96.7 | 88.1 | 95.7 | 98.6 | 105 |

milliseconds to wait 1500
Save File Name: C:\Users\andyk\
Start Pos x pos 200 y pos 450
output newx 212 newy 455.5
sector 0
angle 140.80

Frequency 100
Mode CW
Amp1 1.4
Amp2 1.4
Amp3 1.4
Amp4 0
srce HLF1
Sampling Rate (Hz) 200000
# of Samples 100000
Pulse cycles 10.00
Period (s) 5
Pulse length (s) 0.005
Phasing Automatic
Phs 1 0
Phs 2 0
Phs 3 0
Phs 4 0
Phases Display 0 0 0 0

Initial Angle 19
Final Angle 22
ANGLE OUT 23

***Figure 12: Graphical user interface developed in LabVIEW for the Coddington Cove demonstration. The lights change color and blink as the pressure is increased at each hydrophone, while the meters help to visualize the beam pattern.***

5. Results show that the classic array theory and the OPS method both lead to similar phasing in Coddington Cove. Figures 13 and 14 show some typical results for the phasing. The sound pressure level at the hydrophones for both phasing methods was similar as well. These results are shown in Figures 15 through 18 for both source arrays at 100 and 200 Hz. The main discrepancies in the pressure correspond to discrepancies in the phasing, i.e. when the phasing for the OPS method was very different from the classic array theory, the pressure resulting from the OPS phasing was reduced at that hydrophone from the classic array theory results. This could be due to a bad hydrophone or inconsistencies in the area of the hydrophone location.

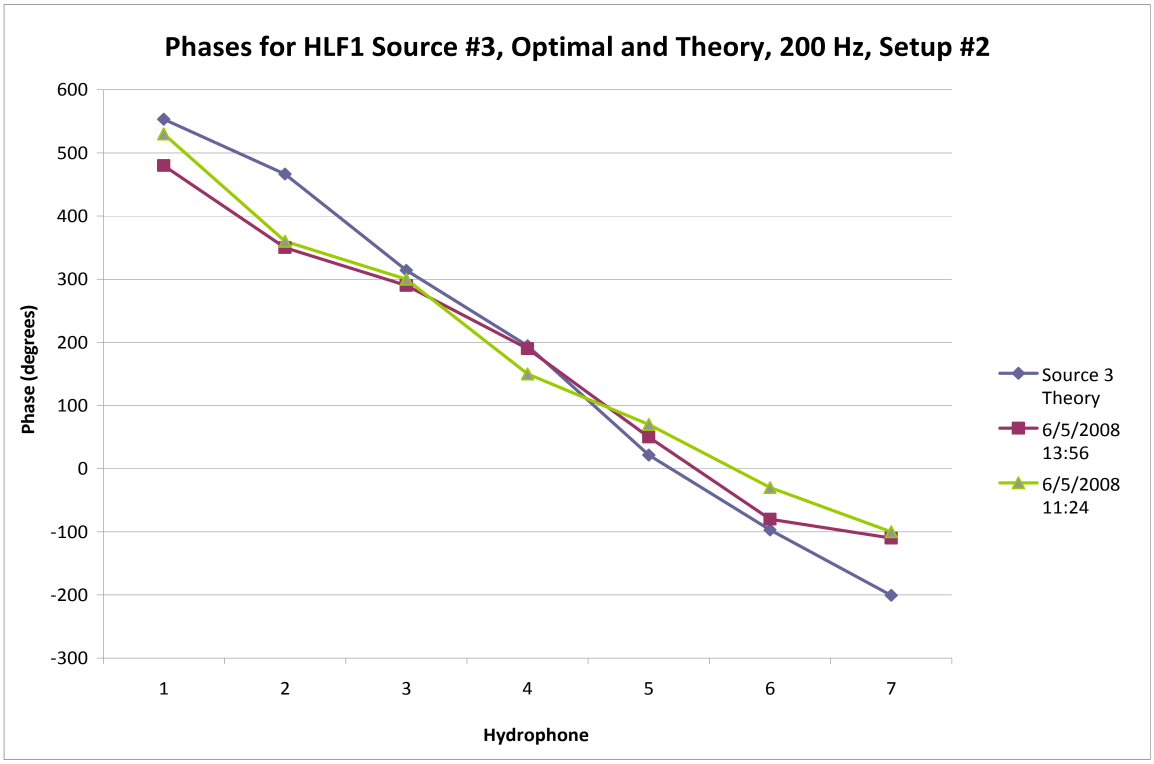


***Figure 13:  Unwrapped phase results from two Optimal Phase Search runs compared with classic array theory for HLF1 Source #3 at 200 Hz.  [Values are similar as are slopes, with a little more than -100 degrees per hydrophone (10 degrees).]***

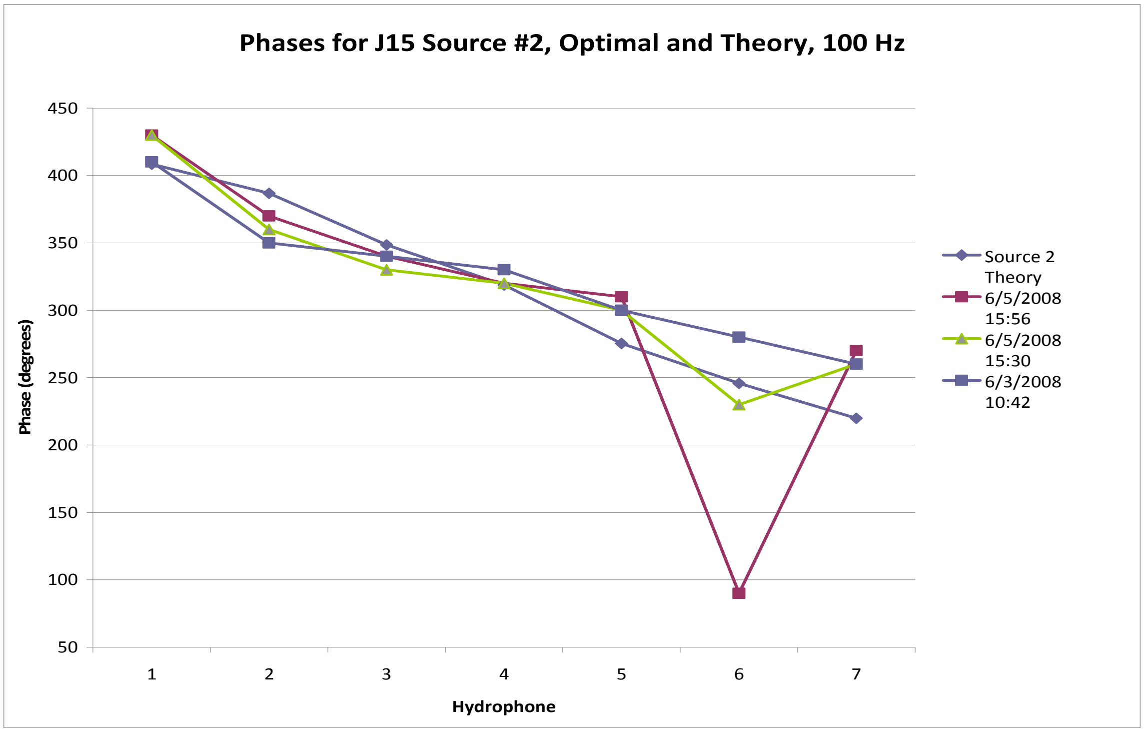


***Figure 14: Unwrapped phase results from three Optimal Phase Search runs compared with classic array theory for J15 Source #2 at 100 Hz. [Values are similar as are slopes except for Hydrophone 6, with about -25 degrees per hydrophone (10 degrees).]***

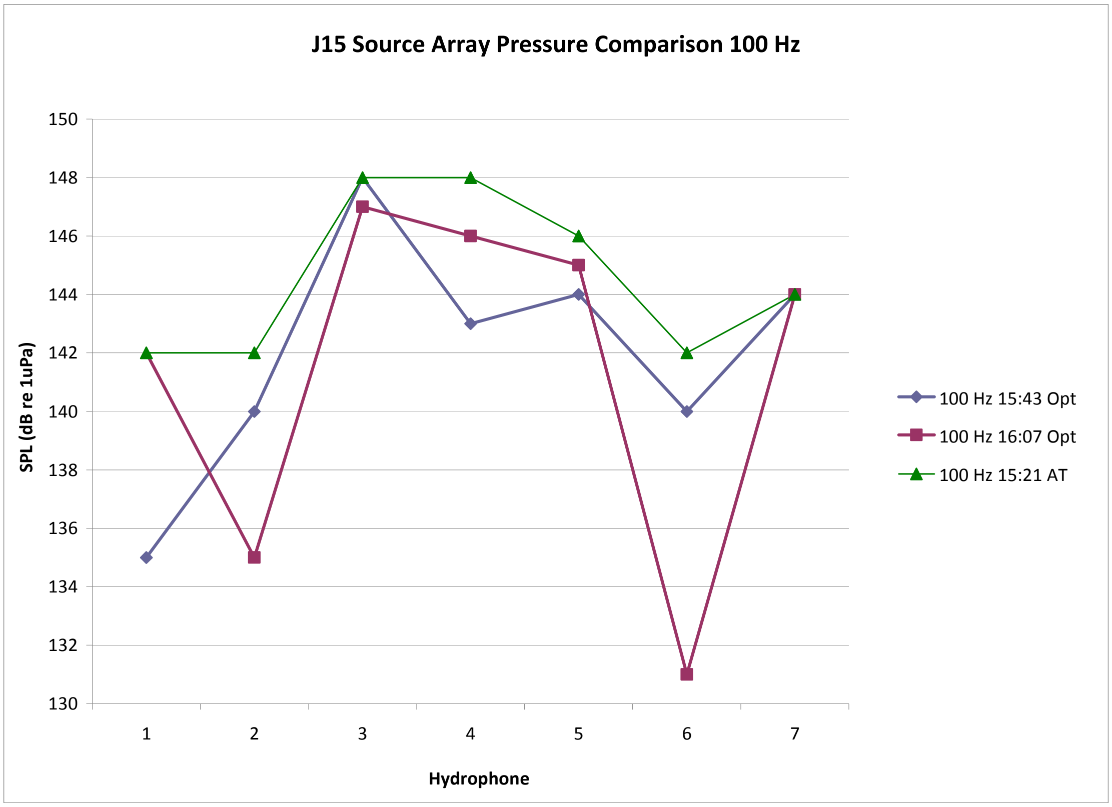


***Figure 15: Sound Pressure Level at each hydrophone with phasing via the Optimal Phase Search method and the classic array theory at 100 Hz for the J15 Source Array.***

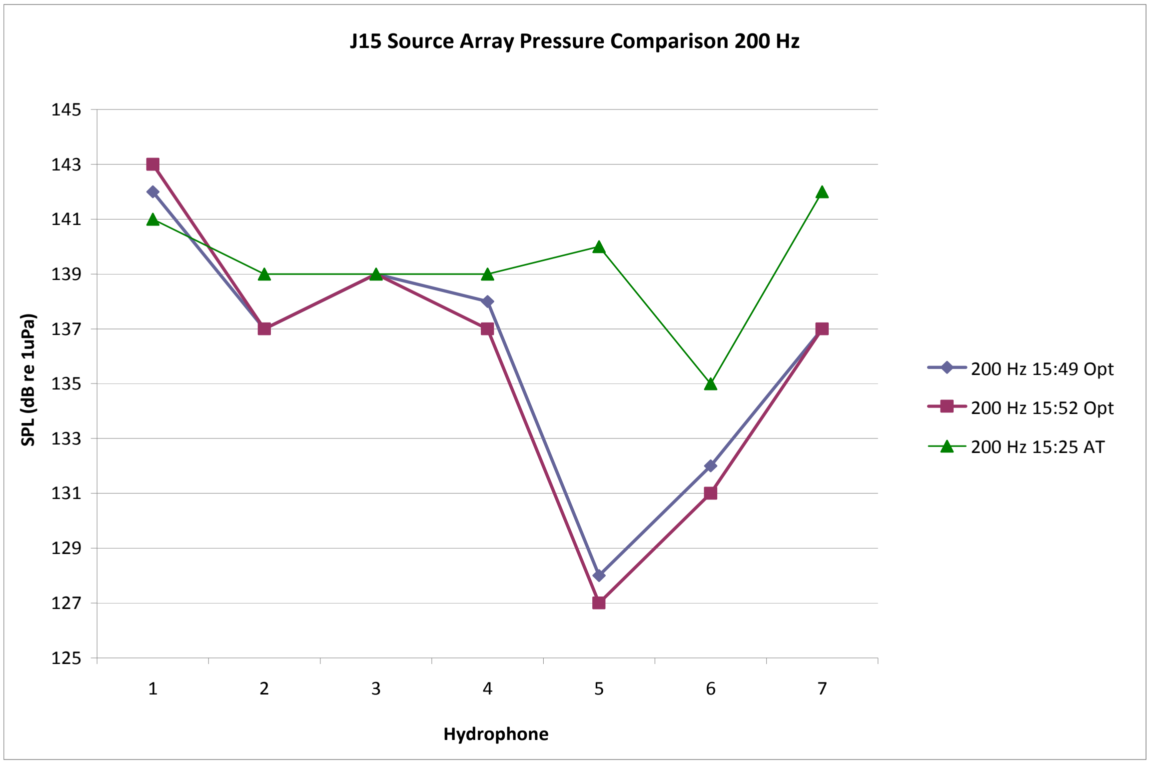


***Figure 16: Sound Pressure Level at each hydrophone with phasing via the Optimal Phase Search method and the classic array theory at 200 Hz for the J15 Source Array.***

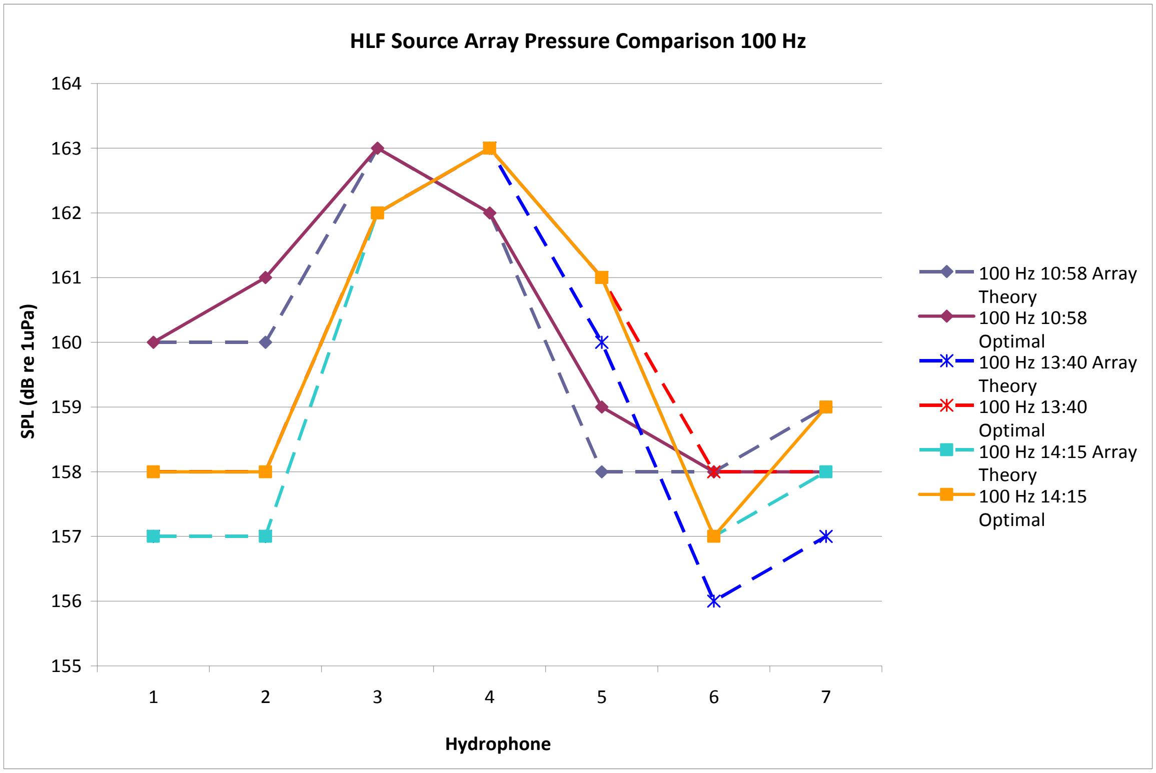


***Figure 17: Sound Pressure Level at each hydrophone with phasing via the Optimal Phase Search method and the classic array theory at 100 Hz for the HLF1 Source Array.***

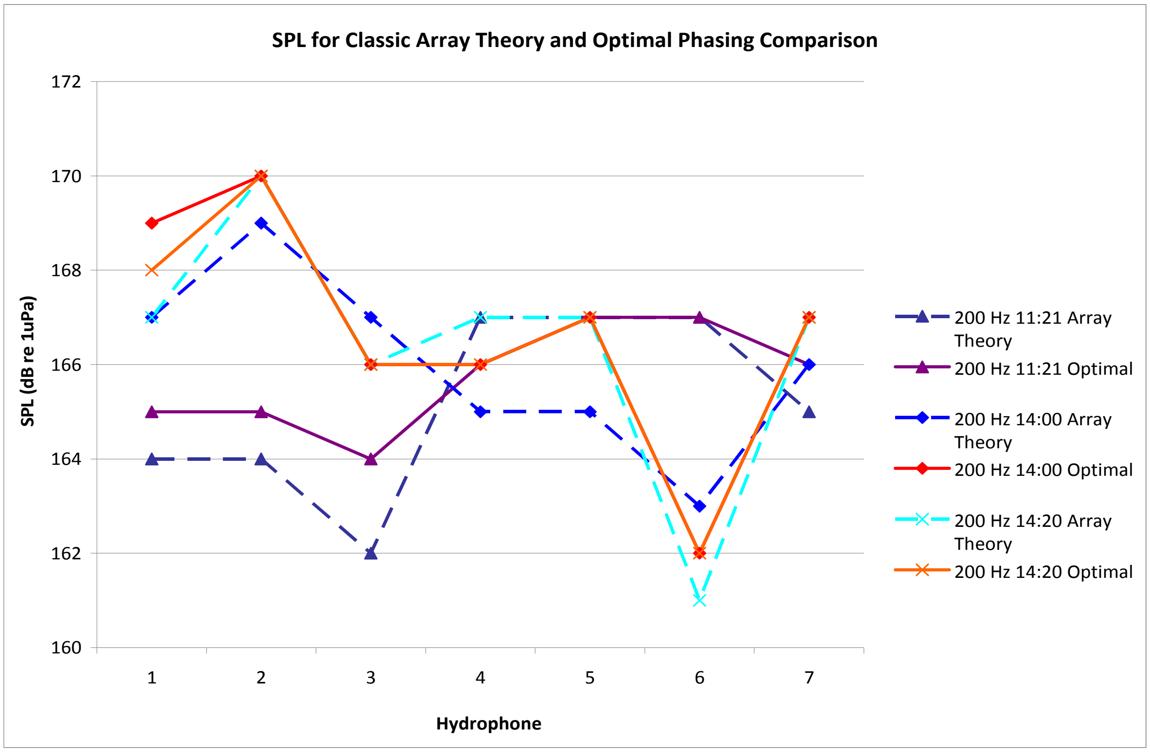


***Figure 18: Sound Pressure Level at each hydrophone with phasing via the Optimal Phase Search method and the classic array theory at 200 Hz for the HLF1 Source Array.***

6. A simplified, waveguide form of the harbor was modeled (10 meters deep 200 meters long) to compare FEM transmission loss results to experimental data. Using a bottom impedance value that varied with distance from the source according to a numerically approximated reflection coefficient, the model was able to accurately predict transmission loss within the spread of experimental data, see Figure 19. It could be possible, using different adaptive techniques to use the FEM program to predict the bottom impedance values for a harbor instead of measuring them directly.

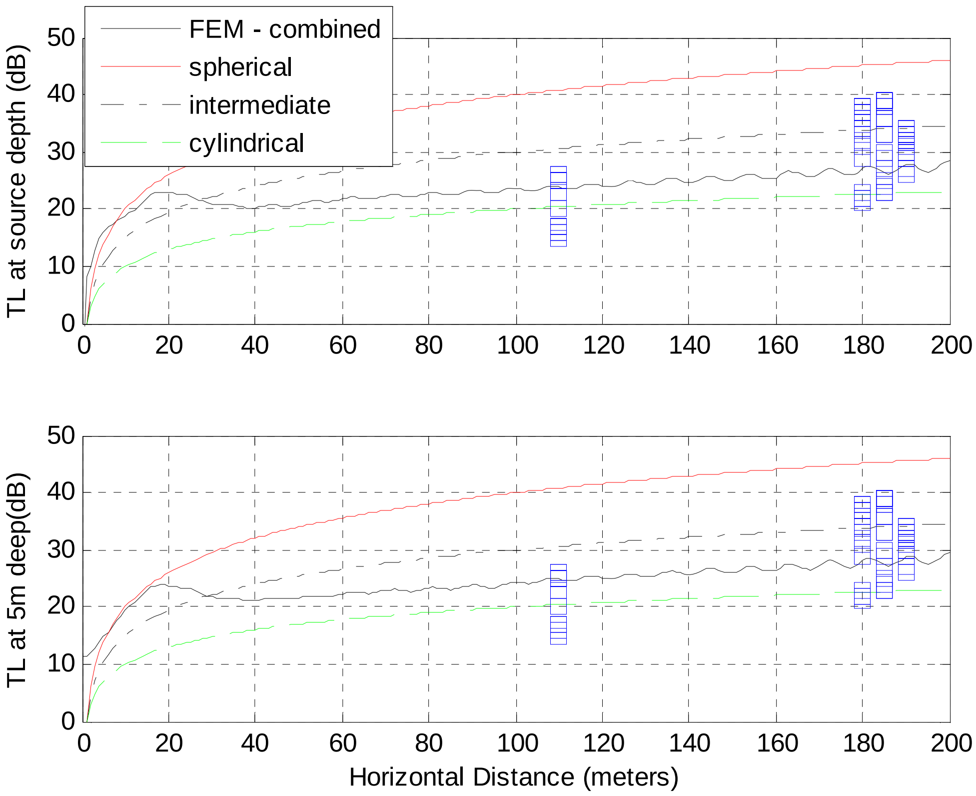


***Figure 19: Transmission loss from the Acoustic FEM code at source depth and 5m deep in a 10m waveguide model of a harbor. The solid black line is the FEM results, while the red, black dot-dashed, and green dashed are theoretical spherical, intermediate, and cylindrical spreading. The blue squares are experimental data points from Coddington Cove over the course of one day. [Transmission loss plot increases similar to spherical until about 20 meters then matches more closely to cylindrical spreading.]***

7. In summary, with proper source array spacing we are able to focus energy in a desired direction using two different methods: Optimal Phase Search (OPS) and classic array theory. Both lead to similar results in Coddington Cove. The OPS method allows for different sources in a single array and will compensate for nearby reflective surfaces whereas the classic array theory requires all sources to be similar and is meant for open water. The OPS method is dependent on *a priori* interrogation of the harbor, although these phases did not change drastically over the course of the days we were testing. The acoustic FEM program successfully modeled a portion of the harbor and could predict transmission loss values within the spread of experimental data.

## IMPACT/APPLICATIONS

As a means of deterring swimmers from intruding our harbors, the impact of this project is highly significant. By focusing high intensity, low frequency sound at a sector of a harbor containing swimmers, the physiological and psychological effects on the swimmers will be such to impede their mission in a controlled, non-lethal manner.

## RELATED PROJECTS

We are closely coordinating our project with that of the PSU/ARL group (D. Bradley, K. Becker, and M. Zucker)   Much of our work is complementary and thus, our field trips to the Jacksonville Quarry near Penn State and Coddington Cove were combined.  In addition, The ARL group is providing valuable input (e.g., acoustic characterization of the harbor) to our control modeling program.