Design and Implementation of a Monopulse Sonar Transmitting Array

Submitted To

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EXECUTIVE SUMMARY

Monopulse sonar processing is an important branch of sonar research that explores methods for calculating the arrival angles of underwater sound waves. This paper documents my senior design project, which explored the implementation of monopulse processing techniques in a sonar transmitter. The application of monopulse technology in the transmitter rather than the receiver, referred to as “transmit-monopulse,” is a new extension of existing monopulse theory that has not, until now, been explored by the research community. I begin by explaining the motivations for pursuing transmit-monopulse technology, and define the requirements of a monopulse sonar transmitter design for a number of real-world applications. I continue by summarizing basic existing monopulse techniques, and then showing how these techniques can be applied in transmit-monopulse. I then illustrate how I implemented a design for a monopulse transmitter in both software and in a functional prototype. I later discuss the results predicted by my software simulation and the implications of those predictions on the actual data obtained through in-water experimentation. Finally, I recommend ways in which future research can extend the ideas developed in my project.

In addition to presenting an itemization and summary of the design and implementation process, I discuss challenges that arose over the course of the project. Issues like time and economic constraints, as well as difficulties in prototype construction caused an eventual need to reformulate my project plans. In this paper I briefly explain how these issues affected the final outcome of the project. At the end of the paper I discuss the ethical and safety concerns involved in my project, and provide a list of references used to research monopulse technology. Appendices A, B, and C include source code for my software simulation, prototype schematics, and the source code for software I developed to automate experiments.

1.0 INTRODUCTION

This report comprehensively documents the design and implementation of a monopulse sonar transmitting array. In the work presented here I discuss my design process, detail my design's implementation, and analyze the performance of my final design solution.

I performed this project as an undergraduate student employee of the Applied Research Laboratories, University of Texas at Austin (ARL-UT). Monopulse sonar processing research is an exciting branch of work performed at ARL, and the monopulse transmitter I designed is a novel application of monopulse theory developed at the lab. Dr. T. L. Henderson developed the bulk of the theory implemented in my project, and it was under his supervision that my work was performed. The work presented here is a natural extension of existing monopulse sonar research, and with its completion, the potential arises for many new applications of monopulse sonar technology.

I begin my report by discussing the design problem that my project addresses, and I illustrate example applications of my final design. I then develop basic monopulse processing principles and describe the application and implementation of those ideas in my design solution. Finally, I present the results of a series of in-water experiments conducted with a prototype of my design. I assess the validity of these results with respect to theoretical values, and conclude by recommending future extensions of my work.

2.0 DESIGN PROBLEM STATEMENT

Sonar applications such as target tracking and underwater surveying have motivated the development of a number of techniques for making high-resolution calculations of the arrival angle of an incoming sound wave. When employing most of these techniques, the system's resolution is determined by the beamwidth achieved by the system's transducer array. A small beamwidth allows for higher resolution measurements, and the beamwidth is inversely proportional to the physical size of the array. For my project, I wanted to develop a system that was small enough to lend itself to numerous applications while maintaining a high enough resolution to remain useful. Because my design required a small physical array dimension, which in turn limited the system's resolution, I chose to research and implement monopulse processing techniques, which allow angle measurements to be made at higher resolution than the system's beamwidth [1].

Existing research on monopulse techniques concentrates on systems in which the burden of monopulse processing performance must be placed on the sonar system's receiver—a restriction that severely limits the application of this technology. The limitations of this type of monopulse processing can be seen, for example, when trying to land a small underwater vehicle on the back of a submarine. In this situation, the vehicle's operator requires an accurate measurement of the angular offset of his vehicle with respect to the submarine. A standard monopulse receiver implementation would require extensive processing hardware to be placed in the small vehicle. In my project I devise a method for performing monopulse processing in the sonar system's transmitter rather than in the receiver, which allows simple receivers to make high-resolution angle measurements. The application described here and those similar to it will benefit greatly from a monopulse transmitter implementation.

3.0 DESIGN PROBLEM SOLUTION

3.1 MONOPULSE SONAR PROCESSING

Because my final solution stems directly from traditional monopulse theory, I will present the basics of a monopulse receiver implementation before discussing the method used to implement monopulse processing in a transmitter.

3.1.1 Traditional Monopulse Receiver Implementation

In a receiver implementation, monopulse techniques dictate that the receiver simultaneously process the recorded sounds of a linear hydrophone array twice - the first time with a typical array element weighting that minimizes sidelobes, and the second time with an element weighting that is the derivative of the first. A unique property of these derivative matched weightings is that the arrival angle of an incident plane wave of sound can be calculated simply by taking the ratio of the two sets of outputs [2, p.183]. To prepare the outputs for the ratio calculation, a filter must process the outputs of each weighting function. In order to resolve the derivative-matched relationship of the monopulse weighting functions, the filter for the first monopulse function output must be the derivative of the filter used for the second monopulse function output. Figure 1 depicts a model of a monopulse sonar receiver implementation.

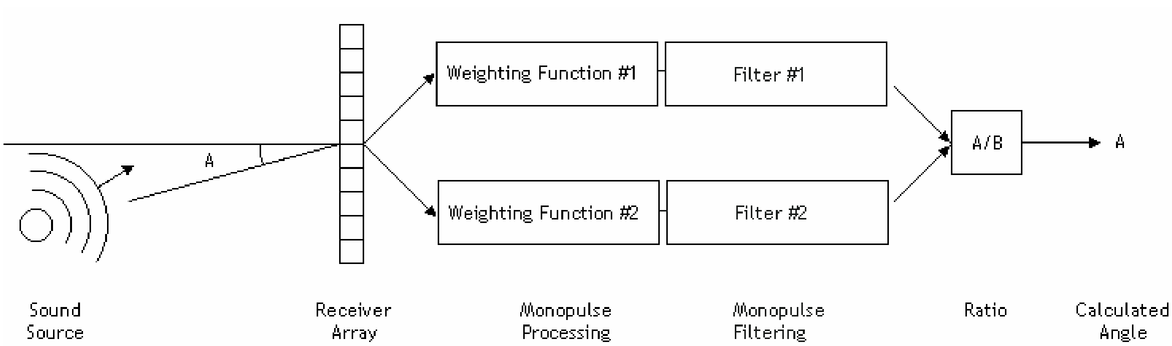

Figure 1. Monopulse receiver system diagram.

When a discrete-element receiver array is employed, the angle indicated by the ratio calculation will actually be an "inflected" angle measurement, proven in [3, p.45] to be:

$$\tilde{s}(t) = \frac{\tan\left[\left(\pi \dfrac{D}{\lambda}\right)\sin\theta(t)\right]}{\pi \dfrac{D}{\lambda}} \qquad \textbf{(1)}$$

where $\theta(t)$ is the correct angle measurement. For cases in which the source signal is a simple sinusoid, the inflected measurement can be corrected by simply solving for $\theta(t)$:

$$\theta(t) = \arcsin\left(\frac{\arctan\left[\tilde{s}(t)\left(\pi\frac{D}{\lambda}\right)\right]}{\pi\frac{D}{\lambda}}\right) \qquad \textbf{(2)}$$

3.1.2 Transmit-Monopulse Theory

In a transmit-monopulse system, the objective is to transmit a signal using a transducer array such that a single hydrophone receiver with no knowledge of its location in the water can determine its angular offset relative to the transmitting array by recording and processing the transmitted sound wave. Further, a transmit-monopulse system must allow multiple receivers at different locations in the water to record the same transmission and still determine each of their respective angular offsets.

The monopulse receiver is an excellent starting point for devising a monopulse transmitter. Figure 2 illustrates the final diagram of my system, which I will reference as I develop the ideas behind monopulse transmitter design.

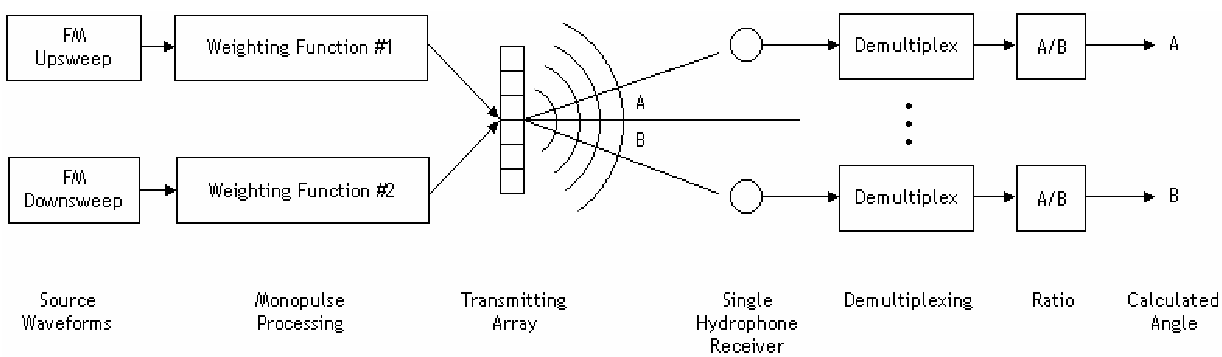

Figure 2. Monopulse transmitter system diagram.

In sonar systems, the processes of transmitting and receiving can be reversed and the resulting system output will be symmetric. For example, if a given receiving transducer array with a certain shading function produces a maximum output for a 100 kHz sine wave produced at a 20-degree offset in front of it, then that same transducer array transmitting a

100 kHz sine wave on all channels would create a sound field with maximum intensity at a 20-degree offset. In the monopulse transmitter, rather than weight a recorded waveform with the two monopulse shading functions described above, the transducer weights source waveforms at each element then transmits the waveforms into the water. However, because both monopulse shading functions apply a weight to each array element, it is impossible to apply both shading functions to on set of source waveforms during the same transmission. To avoid this, two different sets of source waveforms are created. The first set contains linear frequency modulated (FM) upsweeps and the second set contains linear frequency modulated (FM) downsweeps. These waveforms were chosen because FM upsweeps and downsweeps with the same start and end frequencies are nearly orthogonal. The monopulse transmitter applies the two monopulse shading functions to the two sets of source waveforms, as illustrated in Figure 2 above, and then adds the source waveforms together and transmits them.

When a single hydrophone receiver records the transmitted sound wave, it must recover the different monopulse weightings in order to calculate its angular offset with respect to the transmitter. To do this, the receiver demultiplexes the two signals by applying two matched-filters, an FM upsweep and an FM downsweep, to the recorded waveform. The matched-filtering process also performs pulse compression, described in detail by [4], which allows for faster transmission repetition in noisy environments. As in the monopulse receiver, the FM upsweep matched-filter must be differentiated before filtering. The receiver's angular offset is then calculated by taking the ratio of each filter's output at each output's peak value. Another receiver at a different location in the water recording the same transmission will recover a different set of weights from filtering that will produce the proper angle offset calculation for that location.

3.2 SONAR TRANSDUCER ARRAY DESIGN

In a sonar system, both the beamwidth and the operating frequency of the system are determined by the physical characteristics of the system's transducer array. Thus, when designing a system for a certain application, finding an appropriate combination of system parameters is of paramount importance. For my project, the transducer array had to be small enough to be mobile while maintaining high resolution, and therefore my project required the use of a small operating wavelength. Additionally, the hydrophones that constitute the transducer array must be spaced at approximately one-half of the wavelength, requiring very small hydrophones for my application. Lastly, in order to allow monopulse processing to be performed in both the horizontal and vertical dimension, I designed the transducer array as a 6-by-6 element planar array with the corner elements removed. Figure 3 shows a diagram of the transducer array layout along with the element numbering system.

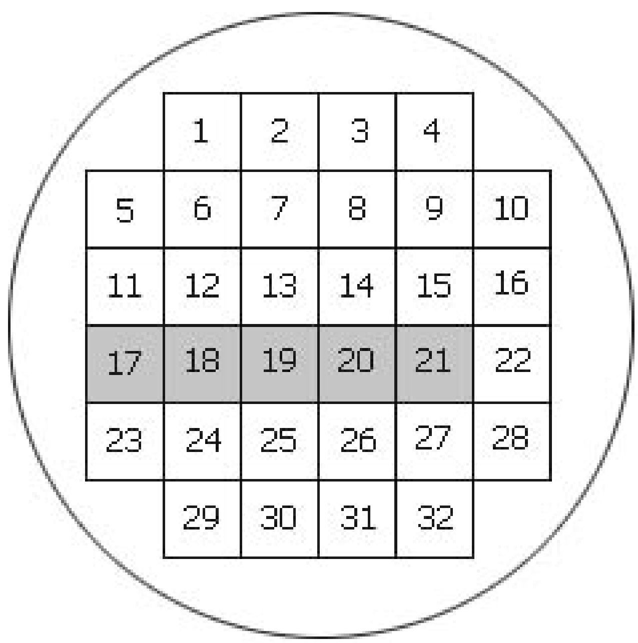

Figure 3. Transducer array layout and numbering system.

Although I designed my array with the layout shown above, fabrication abnormalities caused a number of the 32 elements to malfunction. For this reason, I modified my experiments to measure only horizontal angle offsets using five working elements. The elements used were numbers 17, 18, 19, 20, and 21.

3.3 DESIGN ECONOMIC ANALYSIS

Economic considerations played an important role in determining my final design solution. In order to keep costs low, I designed my system to work with an ICS-625b 32-channel digital to analog converter (DAC) board that was available to me at the Applied Research Laboratories, University of Texas (ARL-UT). This decision determined the number of array elements to be used, which was an important factor in the design of the transducer array. Additionally, I used transducer elements fabricated at ARL, which further reduced construction costs.

4.0 DESIGN IMPLEMENTATION

To prove the concept of the transmit-monopulse design solution described in the previous section, I chose to build both a numerical simulation of the system in MATLAB and a fully functional sonar system prototype. The numerical simulation predicted the performance of the system in varying environmental conditions, and the functional system prototype later confirmed those predicted results. I performed all simulation software development for my project on a Sun Microsystems SunRay workstation. For the in-water experiments with the system prototype, a Linux system running the Fedora Core distribution controlled the transmitter, while a Sun Microsystems data acquisition machine recoded data from the receiving hydrophone.

4.1 MATLAB SIMULATION

The MATLAB simulation of my system included both the transmitter and receiver components of the system, as well as a noisy channel simulating the water in which the system would later be submerged. The simulation modeled all data processes that were performed in the system prototype, including monopulse shading function generation, underwater sound wave propagation, and data post-processing. I originally built the simulation to model the planar array originally intended for my prototype, but I later altered the source code to use only the array elements used in my in-water experiments. The source code for the original and altered simulations is included in Appendix A.

4.1.1 Transmitter Simulation

In order for the simulation to accurately predict the results of a working prototype, the simulation had to closely model the physical characteristics of both the transducer array and the environment in which the experiments were performed. Thus, the transmitter simulation begins by specifying the physical dimensions of the transducer array. For this parameter I used a 0.3-inch element spacing, corresponding to the measured width of ceramic transducer elements available at ARL-UT. As discussed earlier, only the line containing array elements 17, 18, 19, 20, and 21 was used in my experiments, so elements in my simulation were placed side by side at 0.3 inch spacing. The measured resonant frequency of the arrays elements was 85 kHz, which is appropriate for 0.3-inch element spacing, so I created linear FM source waveforms centered around 85 kHz. The source waveforms were sampled at 250 kHz to reflect the sampling rate used by the ICS-625b DAC board.

With the physical characteristics of the array specified, the simulation then calculates the monopulse shading functions that are applied to the array elements during transmission. I will refer to these shading functions as w00[n] and w01[n]. A Taylor shading was used as the base shading function since it minimizes sidelobes in the array beampattern [5]. The first weighting function, w00[n], is calculated by convolving the sequence [1,1] with the base function. The derivative-matched weighting function, w01[n], is calculated by convolving the sequence [1, –1] with the base function, as described in [6]. The calculated values of these weights are given in Table 1, and the weighting functions are plotted in Figure 4 to illustrate the derivative-matched relationship of the two functions.

Table 1. Monopulse shading function element weights.

Element Number [n]	**w00[n]**	**w01[n]**
17	0.5567	0.5567
18	1.5567	0.4433
19	2.0000	0

20	1.5567	-0.4433
21	0.5567	-0.5567

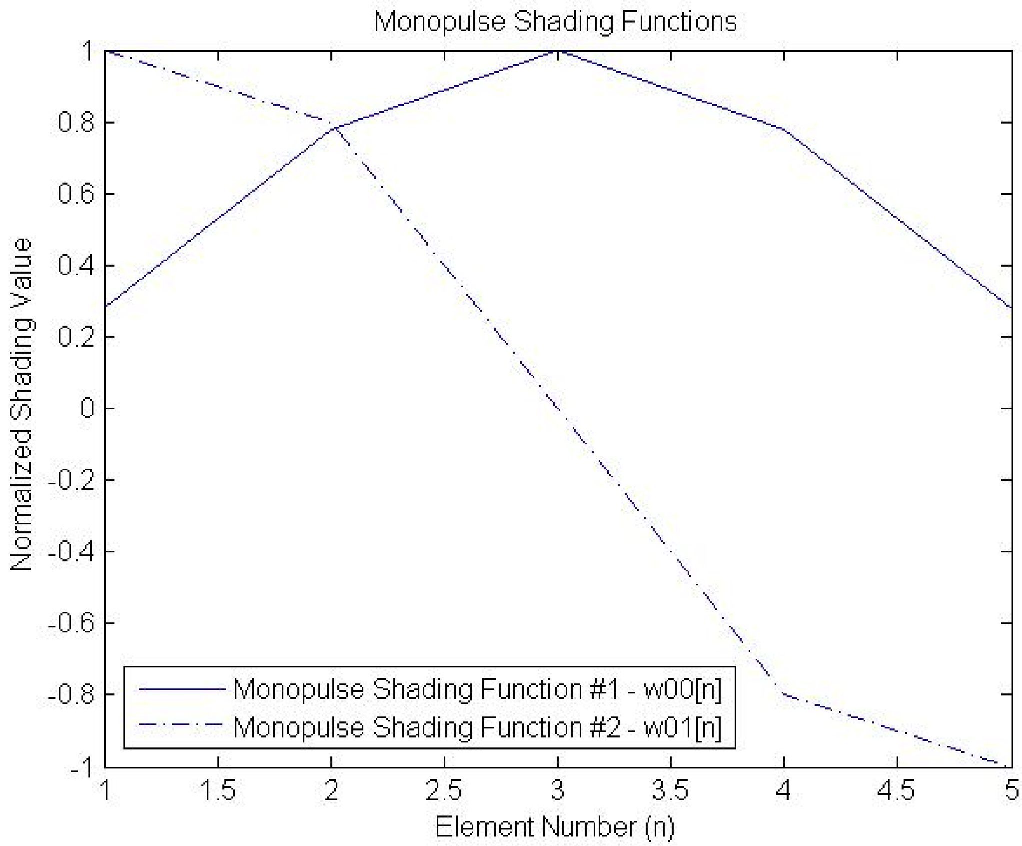

Figure 4. Monopulse shading functions.

The final step in simulating the sonar transmitter is to model the creation and propagation of underwater sound waves. To begin, the simulation applies the monopulse weighting functions to the source waveforms. The w00[n] weights are applied to the linear FM upsweep and the w01[n] weights are applied to the linear FM downsweep. The two FM waveforms for each element are then added together to form the waveform that will be applied to the corresponding element of the transducer array. With the final source waveforms calculated, propagation of the sound waves through the water is simulated using the interpz MATLAB function. The interpz function calculates the sound pressure at some point in the water with respect to the orientation of a transmitting array at some time following transmission. In the case of my simulation, this point is the location of the hydrophone receiver, and the time delay following transmission is determined by the propagation distance and by the speed of sound in water. Additionally, the intensity of the sound at that point is decreased due to sound absorption during propagation. The sound speed is calculated by the soundspeed MATLAB function, employing the equation given in [7, p.113], and the transmission loss is calculated using the soundabsoption MATLAB function. The interpz, soundspeed, and soundabsoption functions are all part of a MATLAB toolbox developed by Dr. T. L. Henderson at the Applied Research Laboratories.

4.1.2 Receiver Simulation

The receiver simulation begins by sampling the data generated by the interpz function in the transmitter simulation at 1 MHz. I chose this sampling rate to match that of the Sun Microsystems data acquisition machine used during the in-water experiments and it is much higher than the required Nyquist rate. At this point, additive white gaussian noise satisfying a specified signal-to-noise ratio (SNR) is added to each receiver. Once sampling is complete, the recorded sound waves are matched-filtered, as described in my design solution. I will refer to the filtered outputs as s00[t] and s01[t]. Next, the receiver locates the time of the peak value in s00[t], noted as t_{peak}, and calculates the following ratio:

$$u(t) = \frac{s01[t_{peak}]}{s00[t_{peak}]} \quad (3)$$

This calculation is then compensated for discrete-element array inflection using (2), and the final angle offset estimation is output to the MATLAB command line.

4.2 PROTOTYPE CONSTRUCTION

The prototype used for my in-water experiments consisted of a transducer array, a PVC enclosure, and a 32-channel cable. The transducer array was made of 32 square ceramic transducer elements, all of which were set in a non-conducting, urethane potting. The array potting was then set in a cylindrical PVC enclosure, where the 32-channel cable was attached to the back of the array using three different 50-pin connectors. The 32-channel cable itself consisted of 32 separate wires, each containing a positive wire, a negative wire, and a grounded shield. Each shield was grounded to the ICS-625b in order to avoid interference between the closely tied wires. The array was later attached to the Tankroom rotating column with an aluminum fitting and hose clamps. Due to the complex nature of sonar transducer array construction, professional employees at ARL who specialize in sonar system construction built the majority of my prototype. Schematics and pin-outs for the prototype are included in Appendix B.

5.0 TEST AND EVALUATION

Once I completed construction of the design prototype, I conducted a set of in-water sonar experiments to verify the system design modeled in my MATLAB simulation. I then compared these results to those predicted by the simulation to quantify how accurate they were with respect to the results calculated for a noise-free environment.

5.1 MATLAB SIMULATION

The main objective of my MATLAB simulation was to first confirm the transmit-monopulse system design, and then to predict the performance of the system prototype. I confirmed the system design concept by programming the simulation with a known receiver angle offset and comparing this value to the one calculated by my receiver model. I then repeated the transmitting and receiving simulation processes while varying both the receiver angle offset and the amount of noise present in the propagation channel. Because the true receiver angle offset was know for each repetition of the process, I simply compared the angle calculated by the monopulse processing to the known value. I then calculated and recorded the error in these results for later comparison. The results of these simulations formed a basis for verifying the accuracy of my in-water experiments. Figure 4 shows the angle calculation root-mean-square (RMS) error for SNR values of ranging from –30 to 30 over a 60-degree, horizontal viewing window in front of the transmitting array.

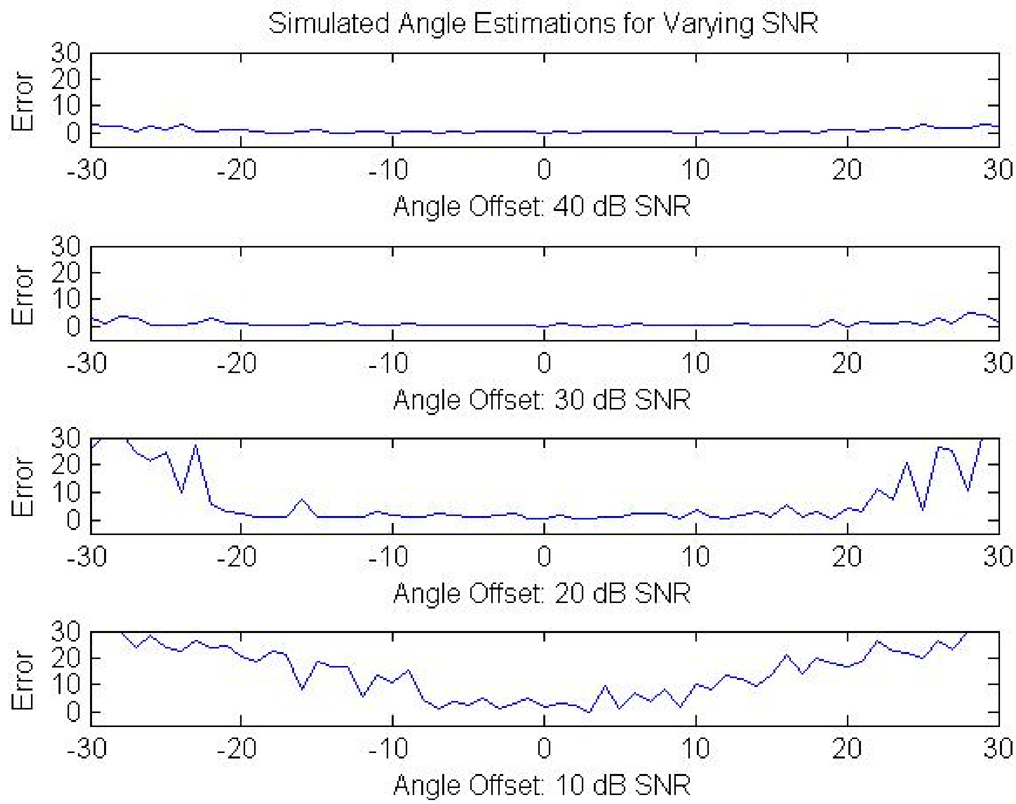

Figure 5. Simulation results for varying SNR.

Additional system parameters used for the experiments illustrated in Figure 5 are given in Table 2. These parameters were determined by varying their values for numerous sets of simulated experiments—a process documented in my lab notebook. These parameters produced the most accurate results in my simulation.

Table 2. Optimal simulation system parameters

Source waveform center frequency:	85 kilohertz
Source waveform bandwidth:	40 kilohertz
Source waveform duration:	5 milliseconds
Distance between Transmitter and Receiver:	1.23 meters

In light of the results presented in Figure 5, I expected my prototype to operate reliably when the receiver was at a horizontal angular offset less than or equal to 20 degrees in magnitude.

5.2 IN-WATER EXPERIMENTS

In order to verify the results predicted by my MATLAB simulation, I performed a set of in-water sonar experiments with my system prototype in the ARL Tankroom. This section details the setup I used for my tests and summarizes the results of the experiments. Over the course of my experiments, I developed a number of MATLAB scripts to automate many repetitive tasks required for the experiments. The source code for these scripts and descriptions for each are included in Appendix C.

5.2.1 Experimental Setup

The Tankroom is an indoor, fresh-water sonar testing facility at the Applied Research Laboratories that is often used to calibrate sonar systems before final deployment. Although it is a controlled environment, the Tankroom is not noise-free and the conditions there reflect those found in a calm natural environment. The only major artificial effects present in Tankroom experiments are the short-range wall reflections that are present due to the small size of the tank itself.

I built the transmitting end of my experimental setup around the ICS-625b DAC board, which was housed in a Fedora Core Linux server. I controlled the output of the DAC board from the Linux terminal using ICS-625b WaveGen software, which reads data samples in from an XConfig file format and outputs the samples with the DAC board. The output of the DAC board was connected directly to the cable that was wired to the individual elements of my transducer array, and the external clock input of the DAC board was connected to my data acquisition's trigger output. The Sun Microsystems data acquisition system coordinated the execution of sequential angle estimation tests by triggering the DAC board and recording the receiver output shortly thereafter. For the receiver I used an omnidirectional Reson hydrophone passed through a 40 dB preamplifier and connected to the data acquisition system. A flow diagram of this system is shown in Figure 6.

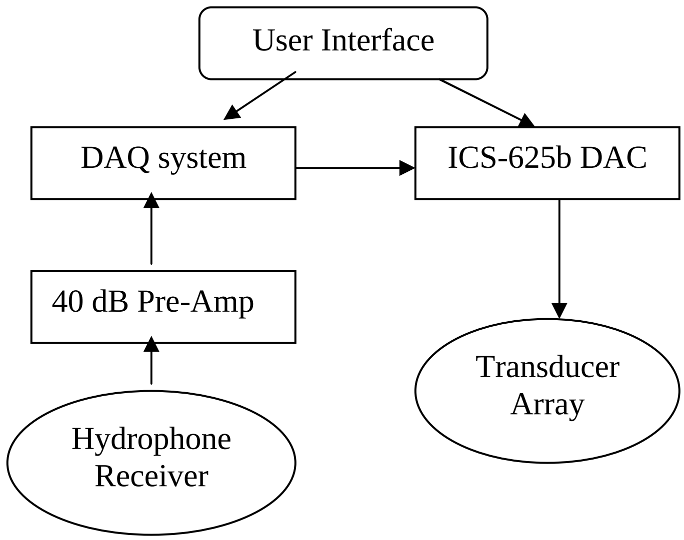

Figure 6. Experimental setup flow diagram.

To perform my angle estimation experiments, I attached the transducer array to the rotating column in the Tankroom and attached the Reson hydrophone to an immobile column a few meters in front of the rotating column. Once lowered into the water, I rotated the column by remote control while the data acquisition system repeatedly executed and recorded transmit/receive sequences. By rotating the transducer array, I varied the offset angle of the receiver as the MATLAB simulation does. During experimentation, the angle readout of the rotating column was fed directly into the data acquisition system, thus allowing me to compare the angle calculated in my receiver to the true value after post-processing.

5.2.2 Experimental Results

I processed the data recorded during my experiments using a MATLAB script similar to the receiver implementation in my numerical simulation. This script is included in Appendix C. In order to determine the best combination of source signal bandwidth and duration, I performed a series of tests in which these values were set to different practical values. I obtained the most accurate results, shown in Figure 7, with a signal bandwidth of 40 kHz and signal duration of five milliseconds. These results very closely reflected those predicted by my simulation.

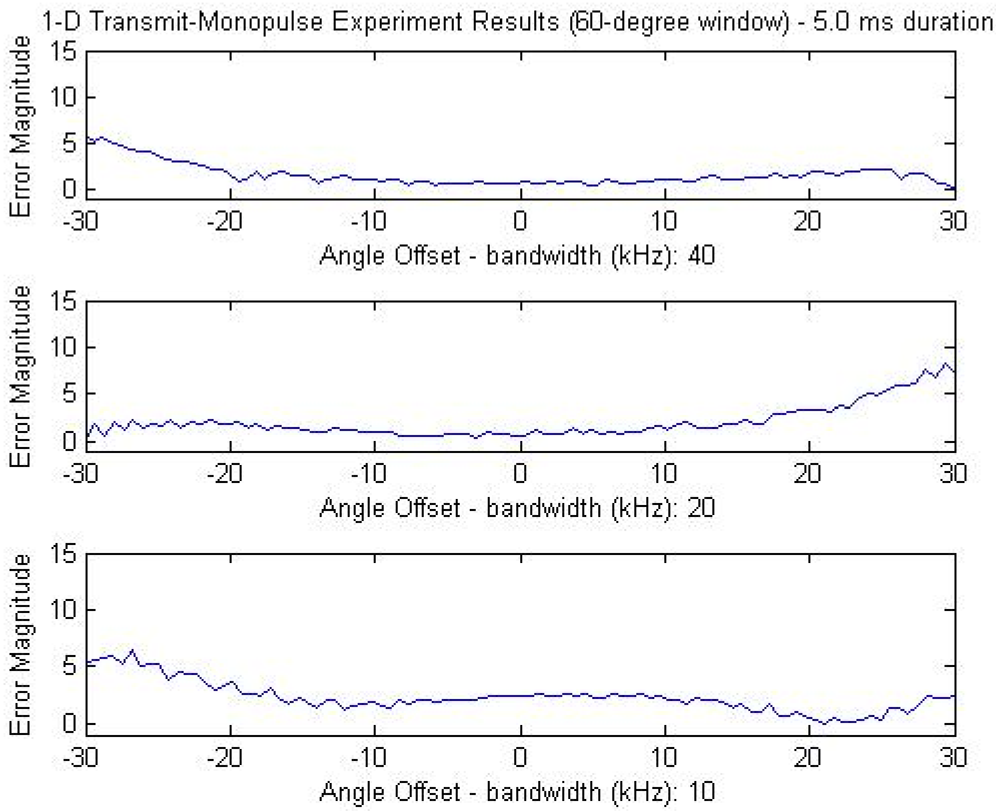

Figure 7. Most accurate in-water experiment results.

The root-mean-square error for each of the graphs shown in Figure 7 is given in Table 3.

Table 3. RMS error for most accurate in-water experiments.

Top Graph:	1.555
Middle Graph:	2.074
Bottom Graph:	2.339

Like the graphs of my simulated results, the graphs in Figure 7 indicate that the receiver estimates its true offset angle most reliably when the offset angle is small. This result is reasonable considering the sine term in the tangent's argument in equation (2). When the sine term is very small, which corresponds to a small receiver, the argument of the tangent function will in turn be very small. Because the tangent of a small value is approximately equal to that small value, the inflected angle estimation is approximately equal to the correct angle estimation. For large offset angles, my receiver did not estimate the angle as accurately. This may be due to the close proximity of the tank's sidewalls. When the array is rotated to angles greater than 30 degrees, it is transmitting a significant amount of power directly toward the wall, which causes strong multipath reflections that distort the recorded waveform.

6.0 TIME AND COST CONSIDERATIONS

By considering the economic aspects of my project from the start, I avoided incurring any unforeseen costs during the course of semester. All of the materials used to construct my transducer array prototype were available for use at ARL, and no special hardware was purchased for my project. The greatest cost associated with my project was the time devoted by myself and other ARL employees who assisted in the construction of the system prototype.

The only deviations from my original project schedule were caused by the prototype construction abnormalities discussed earlier in this paper. Because of the complex nature of sonar array construction, I spent nearly three weeks pinpointing the source of my problems, and once the problems were identified they could not easily be resolved. However, I was able to modify my experimental setup to measure angles in a single dimension using only a subset of the original transducer elements. While this practical modification of the project suffered from lesser-quality experimental results, I was still able to prove the concept of a transmit-monopulse sonar system, which was the true goal of my project.

Lastly, because I spent so much time troubleshooting the transducer array, I was not able to perform in-water experiments at the ARL Lake Travis Test Station. These experiments are a natural extension of those performed in the ARL Tankroom, and I will perform them during future research in transmit-monopulse sonar systems at ARL.

7.0 SAFETY AND ETHICAL ASPECTS OF DESIGN

I spent considerable effort ensuring that my project followed ethical engineering practices. After conducting a patent search on monopulse processing techniques, I found that there are numerous patents protecting specific applications of monopulse technology. However, the derivative-matched processing technique implemented in my project is not protected by patent. Furthermore, the application of these techniques in a sonar transmitter separates this technology even more from its predecessors.

The safety of the sonar system operator and those individuals near the system was also an important consideration in my design. Due to the intense sound waves created by underwater transducer arrays, individuals may suffer injury if they are submerged in water near an operating array. For this reason, my design should not be used in recreational areas such as public pools or lakes.

8.0 CONCLUSIONS AND RECOMMENDATIONS

I feel that the work I completed over the course of this project is a significant addition to field of monopulse sonar research. With my work I have created a foundation for future study in transmit-monopulse system design, and from this point many extensions of my work may be studied more easily.

There are many extensions of the work presented here that future researchers may investigate. One such extension would be to decrease the number of transducer array elements even further and quantify the angle estimation performance for simpler arrays. Additionally, for systems in which an extremely simple receiver is needed, it would be interesting to see how slower sampling rates than the one used in my experiments degrade the quality of angle estimations.

The most obvious extension of my work would be to extend my design to measure vertical angle offsets in addition to horizontal angles. My project was initially designed to make both measurements, but array construction difficulties precluded experimental testing of that functionality. However, the implementation of vertical measuring techniques will follow the techniques presented in my paper almost exactly, and the vertical measuring technique was successfully implemented in my simulation. With this in mind, I feel that my project undoubtedly satisfies project requirements even while making measurements in only one dimension.

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