Digital VHF Direction Finding

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Abstract

Digital Very High Frequency (VHF) Direction Finding (DF) is a solution to some of the Coast Guard's problems in completing its missions of search and rescue and eliminating wasteful spending and undue risk of human life in responding to hoax calls. This semester, working from the prototype system of last year, a toolbox of utilities to analyze and calibrate the system were developed which resulted in an increased knowledge base of DF and a more reliable and robust system.

Introduction

Telephone calls placed on landline phones are able to be traced back to their source via the phone company. However, the technology currently in existence to track the origin of voice transmissions originating from vessels at sea is limited at best and non-existent at worse. This weakness is utilized by those who seek to undermine the missions of the Coast Guard, from an intoxicated pleasure boater to a sinister drug smuggler, via hoax calls.

The problem of hoax calls, the deliberate transmission of fraudulent distress signals, is not a new problem facing the U.S. Coast Guard. However, as the Coast Guard's missions increase and our resources remain stagnant, our ability to do more with less seems to have become the necessity of doing everything with nothing. This equates to no room for the toleration of wasteful spending. However there are 40-60 hoax calls a month in the Fifth District (from New Jersey to the North Carolina-South Carolina border) alone [1]. This directly effects the bottom line as the hourly cost to operate a 41' patrol boat is $313, and for an HH-60 Jayhawk helicopter it is $3,600 [1]. In addition to the monetary cost is the risk imposed on those Coast Guard personnel who respond, as well as the lack of resource availability in the event a real emergency was reported.

One thing the Coast Guard can do to reduce the number of hoax calls is to have those who engage in this senseless and/or dangerous actions prosecuted. In order to arrest them however, we must locate them. This is what a direction finding system assists in doing.

Unfortunately, this task is impaired due to the fact much of the Coast Guard's current communication equipment is 30 years old, when its expected service life at installation was only 15 years [2]. Furthermore, when equipment fails, replacement parts are no longer commercially available and unique solutions on a case-by-case basis must be developed, resulting in a lack of standardization [2]. Over the past 30 years, additional equipment has been added or interchanged on a local level in a semi-successful effort to try to keep our systems from becoming obsolete. This has further made the systems non-standard and incompatible.

The National Distress and Response Modernization Project (NDRSMP) was initiated to respond to the Coast Guard's ailing communications and sensing capabilities. This project is managed by G-AND (my project sponsor), which is an office of the Headquarters Acquisitions Directorate

(G-A). NDRSMP seeks to modernize and upgrade the current National Distress and Response System [2]. To this end, on 2 December 1999, the Coast Guard issued a request for proposal (RFP) for the first phase of NDRSMP, the Design, Demonstration, and Validation phase [3]. Currently the project is in between the functional design and preliminary detailed design sub-phases [3].

There are a total of fourteen functional requirements for the NDRSMP. Some of them include:

- Position Locating. The modernized system must provide a means of determining the location of a distressed vessel or hoax caller by identifying the origin of the communications signal.

- Telecommunications Recording. The modernized system must automatically record and time stamp all voice transmissions.

- Instant Play Back. The modernized system must be capable of immediate play back of incoming voice transmissions.

A Digital VHF Direction Finding System accomplishes all three of these requirements.

Background

Current commercial-off-the-shelf (COTS) direction finding products have various limitations that render them undesirable for installation aboard Coast Guard units. Over the past few years, the Coast Guard Academy has acquired a working knowledge of DF and has set out to develop a system that addresses the shortcomings of COTS systems. Some of the limitations of these currently available analog systems are that they:

- Process VHF-DF signals using sub-optimal methods.

- Cannot discriminate/detect multiple targets at the same carrier frequency.

- Do not improve the intelligibility of the demodulated audio by employing techniques such as beam forming or null steering.

- Employ hardware demodulation, hence weaker signals are inherently lost during the demodulation process.

Digital systems have many advantages over conventional analog systems. They can detect multiple radio calls from different bearings on the same frequency and record the transmissions for analysis at a later time. A digital system is also able to steer the antenna beam in software to eliminate an unwanted signal or home in on weaker or inaudible signals.

In FY99, the Coast Guard Academy developed a digital VHF-DF antenna and receiver set. In the spring of 1999, the dual monopole antenna array and receiver was tested and found to have a precision of ±4°. It was determined that an antenna array of at least three monopole antennas would be required to eliminate the front-to-back ambiguity (caused by the signal being mirrored along the axis parallel to the plane of the antennas) and increase precision.

In FY00, a new antenna array was designed utilizing four monopoles. The digital system developed consisted of the four-antenna array, a four-channel sensor, and two high end Pentium® computers. One computer is the real-time receiver with two analog to digital converter cards (total of eight channels) to read the signals from the antennas. The second computer is the user interface that performs the bearing calculations and post processing. Furthermore, beam forming and null steering techniques were researched and accomplished with limited success. A packet modem system was incorporated to provide ground truth DGPS position information that allows one to verify the accuracy of the bearing compared with the current, actual position. At the end of the project, there were promising results but no clear understanding of how the system was performing. In some sectors, the system was very accurate; however in others it did not work at all and the tools to determine why were not available.

Last semester was spent learning the intricacies of the code and nonlinear function relationships as well as the basics of direction finding. Upon completion of this familiarization, I examined the current status of the project, restored it to its May 2000 condition, identified areas that required analysis, and implemented changes to the user interface to make it more intuitive and provide additional information. Finally, I streamlined some aspects of the code in an effort to improve efficiency and logic.

In addition, I added a delete functionality that allowed the elimination of a transmission via a single button versus manually removing three or more files in three different directories. The packet modem test was not fully functional. I corrected its deficiencies, most notably its lack of time-transmission synchronization.

Objective

The overall goal of this project was to demonstrate the principles of Digital VHF Direction Finding using the phase differences of a four-monopole antenna array in order to gain a greater understanding of direction finding in support of NDRSMP.

❶ This involved a complete analysis of the phase-difference to bearing mappings.
❷ A second objective of this project was to examine the mapping matrix, spanning all of its building stages from data collection to the final 360 x 1000 element array.
❸ This was a five-day process. It then became desirable for an automatic matrix-creation function to ease this work-intensive process and provide a quicker turn-around.
❹ As the project progressed, it became clear due to equipment failure that a new tracking system was required. Hence, the acquisition of a new system was the fourth objective.
❺ Upon becoming sufficiently certain that the code, computers, and sensor were in order, it was decided that some time should be spent analyzing the antennas; both the original short antennas from last year as well as the high-gain longer antennas used last semester.
❻ The final objective was to automate the data collection process by using the packet modem to determine the actual bearing. This can then be used in an airplane or vessel scenario, where all the data is saved together without human intervention.

Originally there were additional objectives laid out, including code conversion to C++ and the investigation of digital down conversion technology. However, lower priority objectives were eliminate due to time constraints, and in many cases those objectives that were not met could not

be until higher priority objectives were accomplished first and a deeper understanding of the technical aspects of the project could be understood and its performance validated. A conscious decision was made not to go to C++ given the time line and limited performance enhancement this would provide. There is no doubt that digital down conversion technology (where the analog sensor is replaced with a single computer card) is the next logical step for this system, once it has proven itself.

Technical Approach

The first objective of this project, analyzing the phase-difference to bearing mappings, was accomplished through a diagnostic GUI (figure 1) and multiple data collection and review iterations. This GUI allows the user to look at the cross correlation function (or phase difference) results between the three antenna pairs (1-2 in green, 1-3 in red, and 1-4 in blue) and visually see what possible bearing these match. The composite plot at the bottom represents the three bearing probability plots overlaid. By collecting 360 degrees of samples, it was then possible to see how the cross correlations changed as a function of bearing. In order to do this, an antenna rotation table had to be constructed. The antenna on the first, simple rotating table can be seen in figure 2. Figure 3 is a close-up of the rotating table.

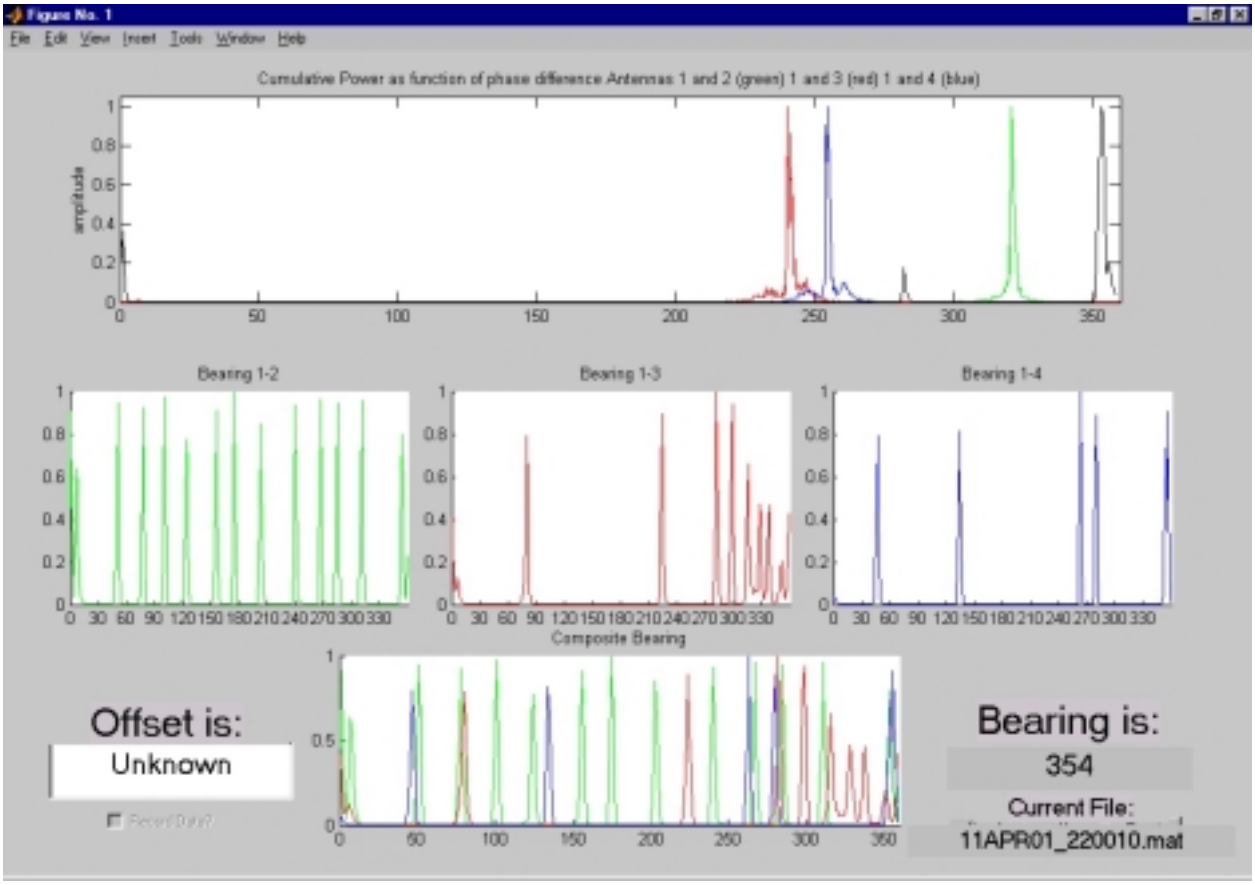


Figure 1 – Diagnostic GUI Screen Shot

Figure 2 – Original Antenna Array for 360° Data Collection

Figure 3 – Close Up of Rotating Stand

This setup provided valuable information as to the nature of phase differences and their behavior in relation to angular differences.

Upon gaining insight as to how the cross correlations were impacted by the geographic orientation of the antennas, the focus of the project shifted to the mapping matrices. The ideal mapping matrices used up to this point in time are provided in figure 4.

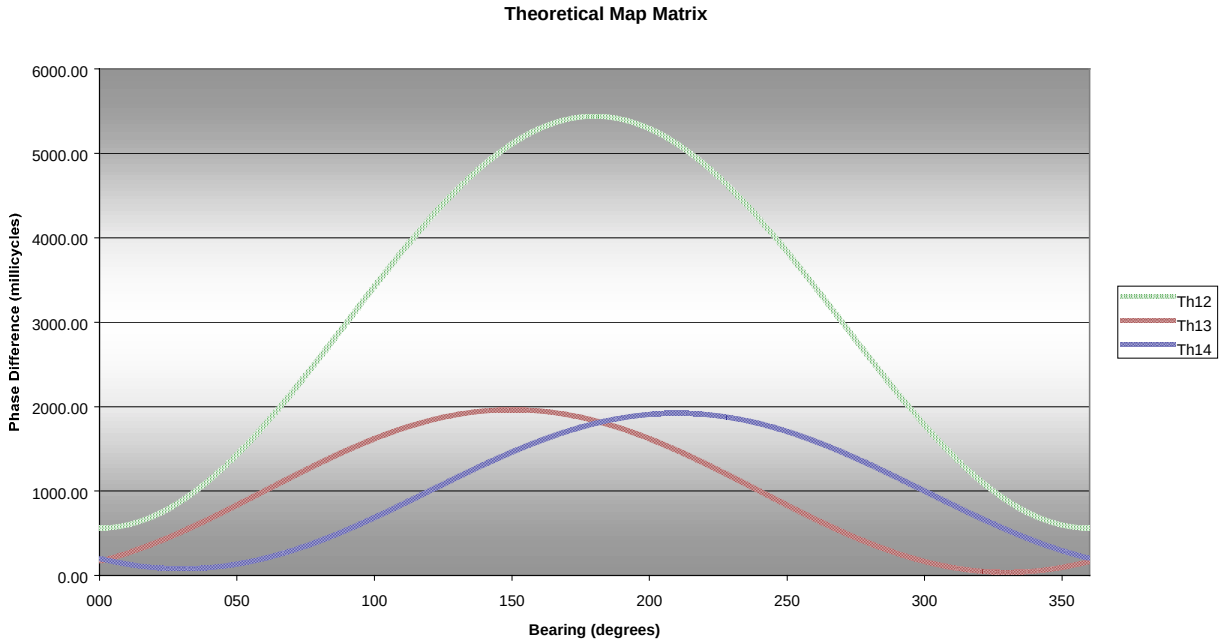


Figure 4 – Unwrapped Theoretical Mapping Matrices

In order to have an adequately calibrated system, it would be necessary to measure a given signal's phase difference among the antenna pairs per a particular bearing. The roof of McAllister Hall is not a pristine site with 360° of open space. On the contrary, it is surrounded by buildings (most notable Chase Hall and Hamilton Hall which all but block the west to north-

west quadrants), hilly terrain, and the Gold Star Bridge off to the south-east. So to model the site, a stationary target was used and the antenna was rotated to simulate all 360° in five degree increments. This data was then manually processed to remove data points that appeared "bad." Then the remaining data was manually processed to average the remaining cross correlations per bearing. The 72 bearings were then interpolated to 360 with each degree having a particular phase difference (in millicycles) assigned. Then this data was interpolated such that every phase difference correlated to at least one bearing. Figure 5 illustrates the resulting, wrapped, plot of this data. Figure 6 shows this data unwrapped and overlaid with the ideal plot.

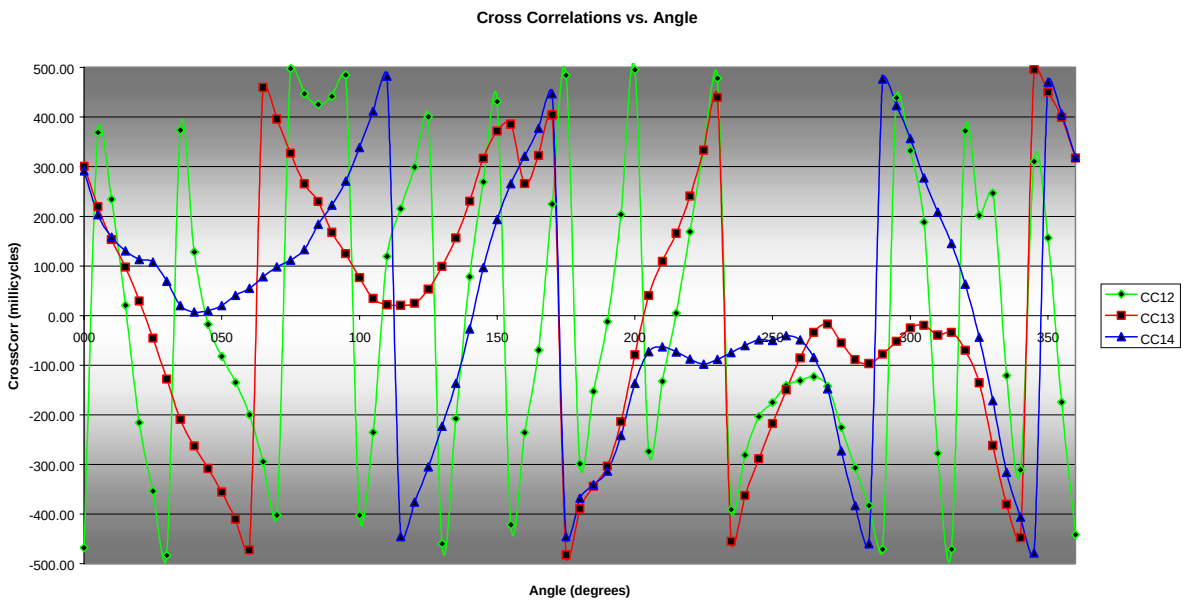


Figure 5 – Measured Data of Original Table, Large Antennas, 35W Transmitter, 360° of Data, Unwrapped

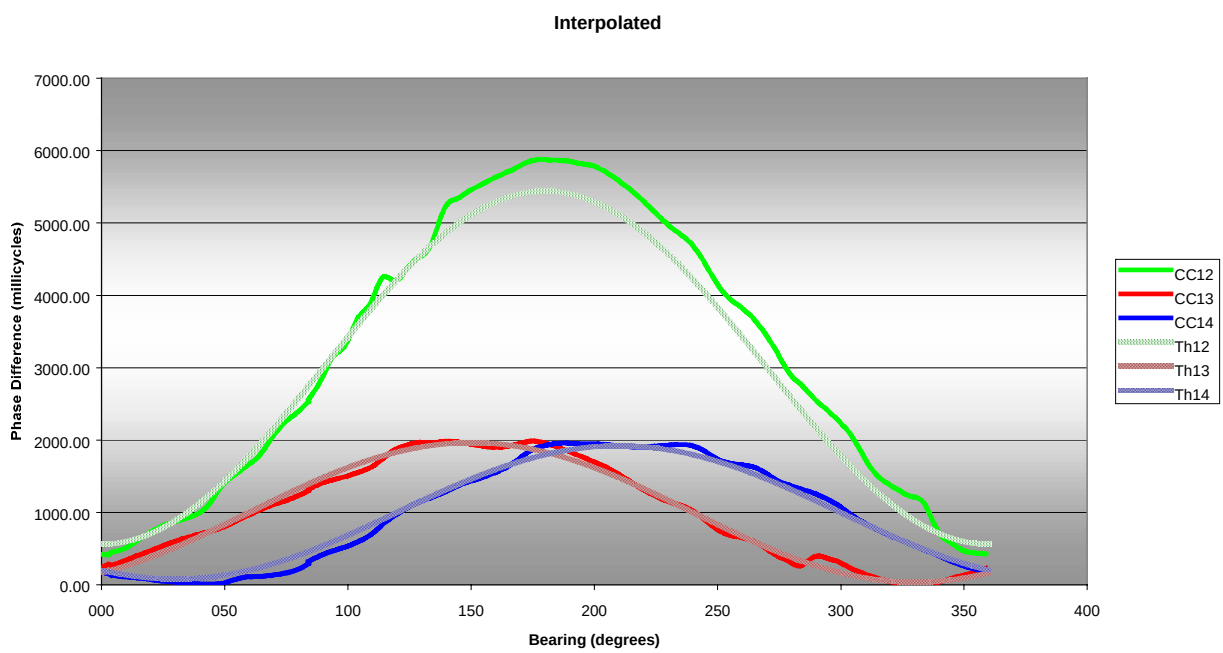


Figure 6 – Ideal and Measured Map Matrices (Large Antennas, 35W Transmitter)

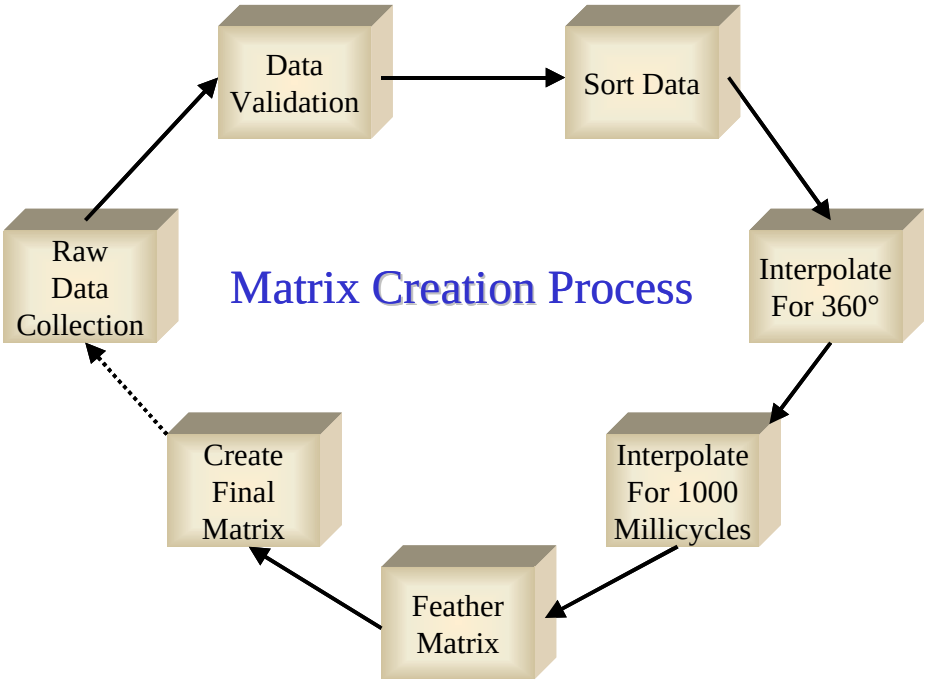
These graphs demonstrated that the 1-3 and 1-4 antenna pairs were behaving very close to what was expected. The 1-2 was considerably different from about 140° on. This corresponded to an apparent larger separation between the antennas 1 and 2. Upon inspection of the array (see figure 7), it became clear that an array base built by a professional carpenter would be necessary in order to ensure the measurements between antennas was accurate.

Figure 7 – Lack of Antenna Precision

The process of creating the mapping matrix was then laid out in order to automate the process. The matrix creation process is illustrated in figure 8. A series of MATLAB functions were coded to complete each of the subtasks. Data collection was conducted by recording the orientation of the table at the time the transmission was sent. The data was later processed and the orientation added to compute the true bearing to the transmission site. Data collection routines involved recording 360 degrees of data in five-degree increments for a total of 72 recorded bearings. At each of the 72 bearings, four to eight transmissions, 20 to 30 seconds apart, were recorded. A single data collection routine lasted from two and a half to five hours, with 500 megabytes to over one gigabyte of data collected.

Upon collection of the data, the next step is to eliminate "bad" data. During the actual rotation of the antenna, the data is unreliable. Furthermore, there may be other transmissions or a myriad of other factors that would undermine the integrity of the transmission. Originally this was done by human estimation.

The data then had to be organized, sorted, and the "definitive" phase differences computed for each given bearing. The resultant B x 4 (where B is the number of distinct bearings and the columns containing the bearing and phase difference for the 1-2, 1-3, and 1-4 pairs) matrix was then linearly interpolated to encompass all 360 degrees. Next the values were interpolated for all



1000 millicycles. Finally, the matrix was “feathered” which gave various weights to phase difference that were close to the phase difference recorded. After all of these functions were called, a final matrix was created and saved for use.

One of the advantages of a digital system is that all of the raw data can be saved and processed at a later time. When creating the map matrices, the digital data allowed me to test newly created matrices with previously collected data runs to see its effectiveness in tracking a moving target.

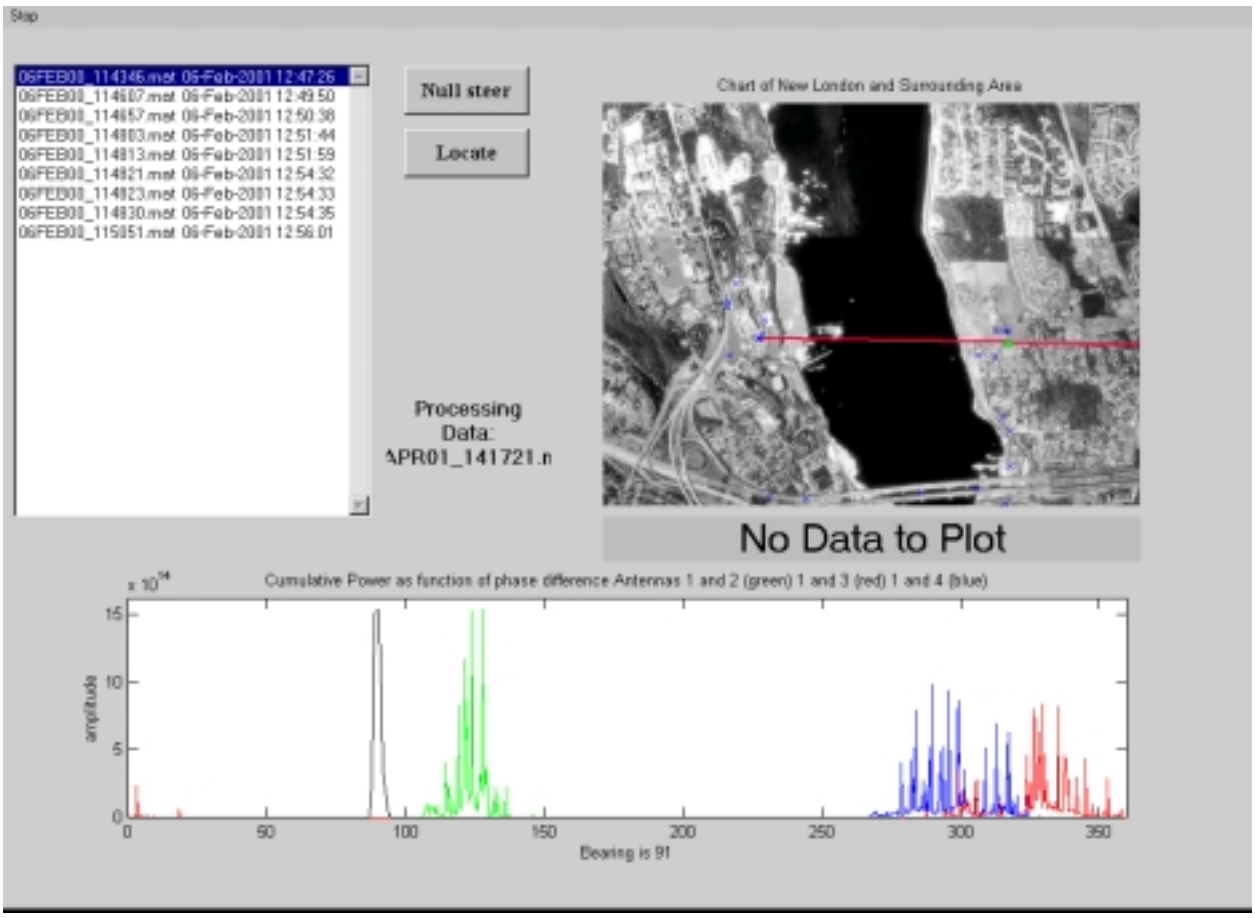


Figure 8 – Digital VHF DF Tracking GUI

This process of tracking is accomplished by having two independent systems. Figure 8 shows the tracking GUI. The first system is the actual DF system that, operating the same as normal, provides the bearing (red line). The second system is used to provide ground truth and is comprised of a transmitting package and a receiving package. On the transmit side is a DGPS receiver, packet radio modem, power supply (12V car battery), DGPS antenna, and transmission antenna (figures 9 and 10).

Figure 9 – Car Equipped with DGPS and Modem

Figure 10 – Close-up of Tracking System

On the receive end is a receive antenna, packet radio modem, and software that controls message reception and actual bearing calculation. The process begins when the DGPS receiver sends at a programmed interval a DGPS position in NMEA format. The packet modem then transmits this message on the same channel the DF system is monitoring. The DF system then calculates the bearing to the source of the transmission. Meanwhile, the receive packet modem picks up the signal. When the GUI computer senses that a signal has been sent, it samples the COM port and reads the data. A function then strips the position from this and the actual bearing is computed. The green asterisk represents the "true" position of the target based on the DGPS position. The blue x's represent previous positions. This data can then be saved and analyzed for matrix performance. The digital data can also be post-processed to recreate the run from beginning to end.

Unfortunately the original tracking system experienced technical problems throughout the semester, from failed memory in the DGPS receiver, a laptop computer with a screen that was prone to blank or simply restart itself to batteries drained beyond recharge and a blown transmission packet modem (the modems were multiple decades old). These problem lead to the acquisition of a new tracking system (figure 10) with new components and great decrease in weight and complexity with the reduction of a controlling computer at the transmission end.

After the code was streamlined, the sensor calibrated, and data runs conducted, the attention of the project shifted to the antennas themselves. Last year, small antennas with a metal ground planes (figure 12) were used and then abandoned in favor of long antennas with internal gain (figure 11). The larger antennas were hypothesized to be interacting with each other, with their re-radiation affecting the ability to DF. In order to gain insight as to what was happening in the array, NEC modeling was then turned to. Figure 13 demonstrates the magnitude response of the monopole antenna we used. A model of the array was then constructed (figure 14) and data was produced and analyzed. NEC was further used to examine how the phase if affected by the interactions of the four antennas. The results of this analysis is pictured in figure 15.

Figure 11 – Tall Antenna (First Half of Semester) **Figure 12 – Small Antenna (Second Half of Semester)**

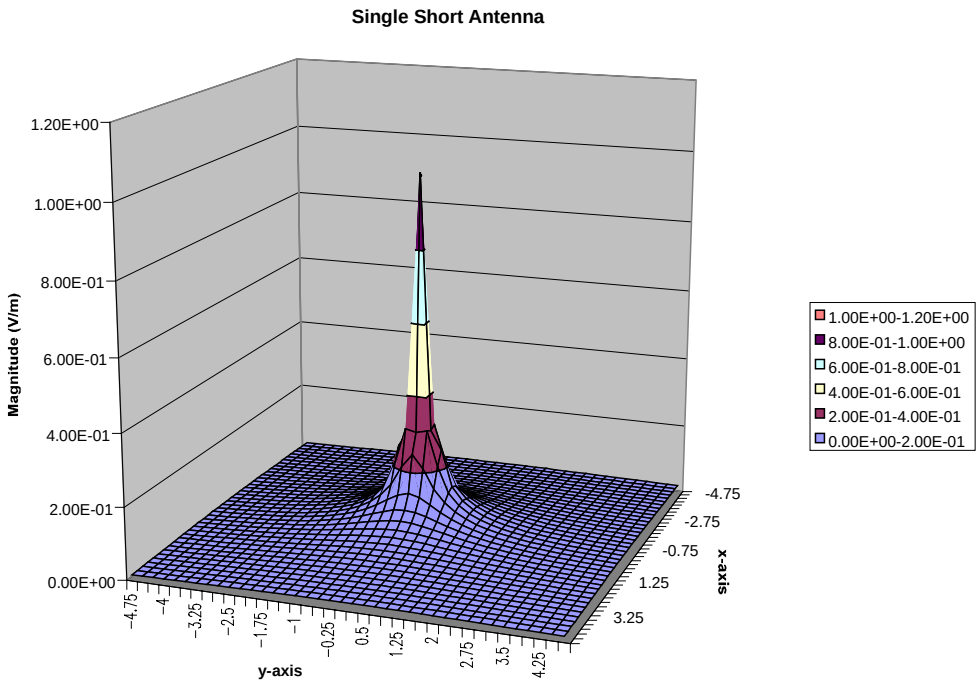


Figure 13 – Magnitude Response for a Single, Short Antenna

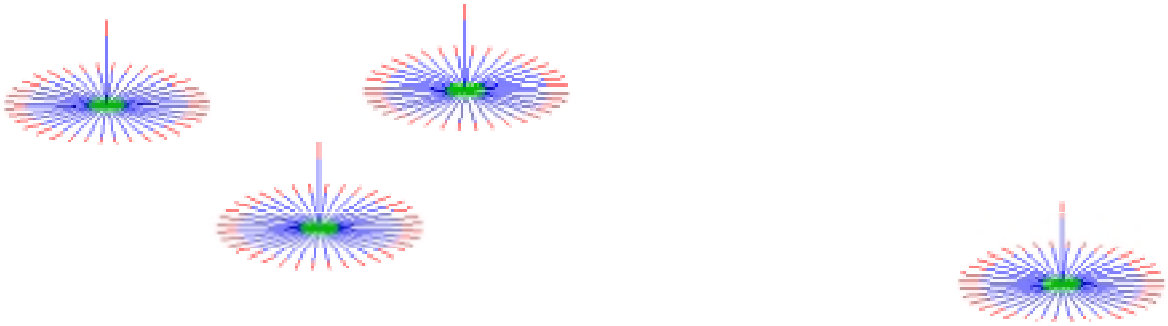


Figure 14 – NEC Antenna Array Model

Upon analysis of the antenna array and the effects of the larger antennas with gain, it was determined that the smaller antennas were the better choice of hardware. In addition to changing the electronic hardware, the decision was made to replace the dilapidated array (figures 2 and 16). A professional carpenter was contracted to build a more stable and exact antenna array frame, as seen in figure 17.

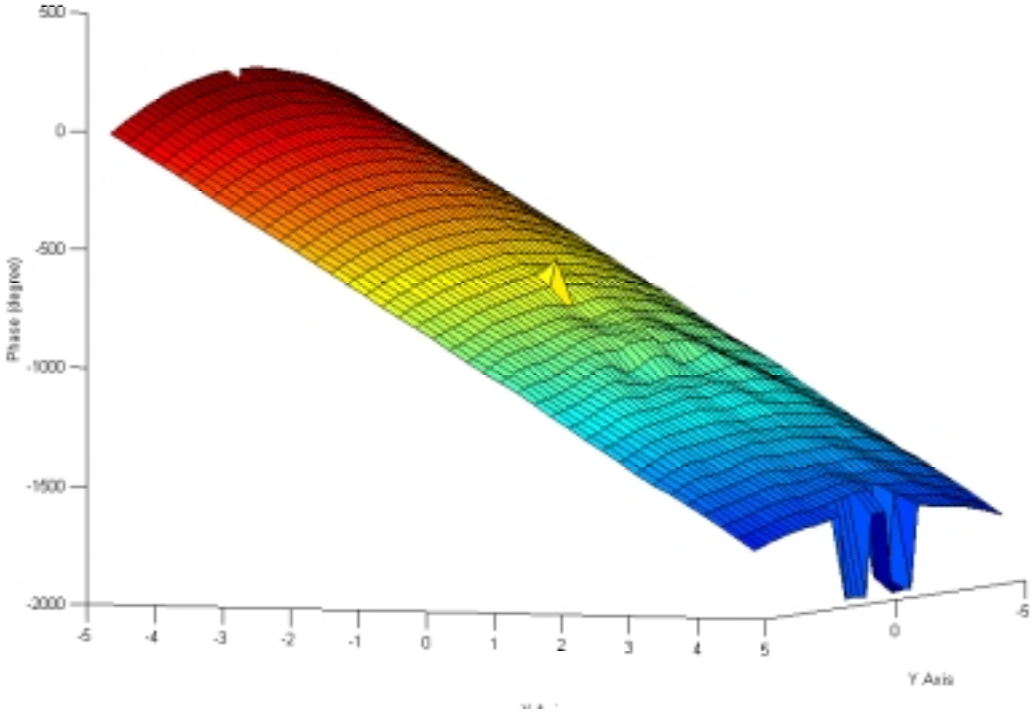


Figure 15 – Phase Response for 4 Monopole Antenna Array

Figure 16 – Old Array Frame

Figure 17 – New Array Frame

Currently during the data phase of matrix creation the bearing to target must be manually entered. A function to meet the final objective of the project, to automate the data collection, is currently being coded. It uses the DGPS position from the packet modem to calculate the actual bearing and save this information with the phase differences. This data can then be used in the automatic matrix creation function.

Results

Much progress has been made this semester in gaining a true and deep understanding of the Digital VHF Direction Finding System. These results support not only the project objectives, but the Coast Guard.

A diagnostic tool has been created to monitor the cross correlation function results, view the array of bearings that correspond to the given phase, and watch the composite bearings to determine the most likely bearing (see figure 1).

The mapping matrices were dissected from raw data to final product to understand the process of their creation. In so doing, it was confirmed that the theoretical values are very close to those measured, but with some distinct difference. Figure 18 highlights the differences between the theoretical matrices and ones built off of data collected on the 19th of March, 2001.

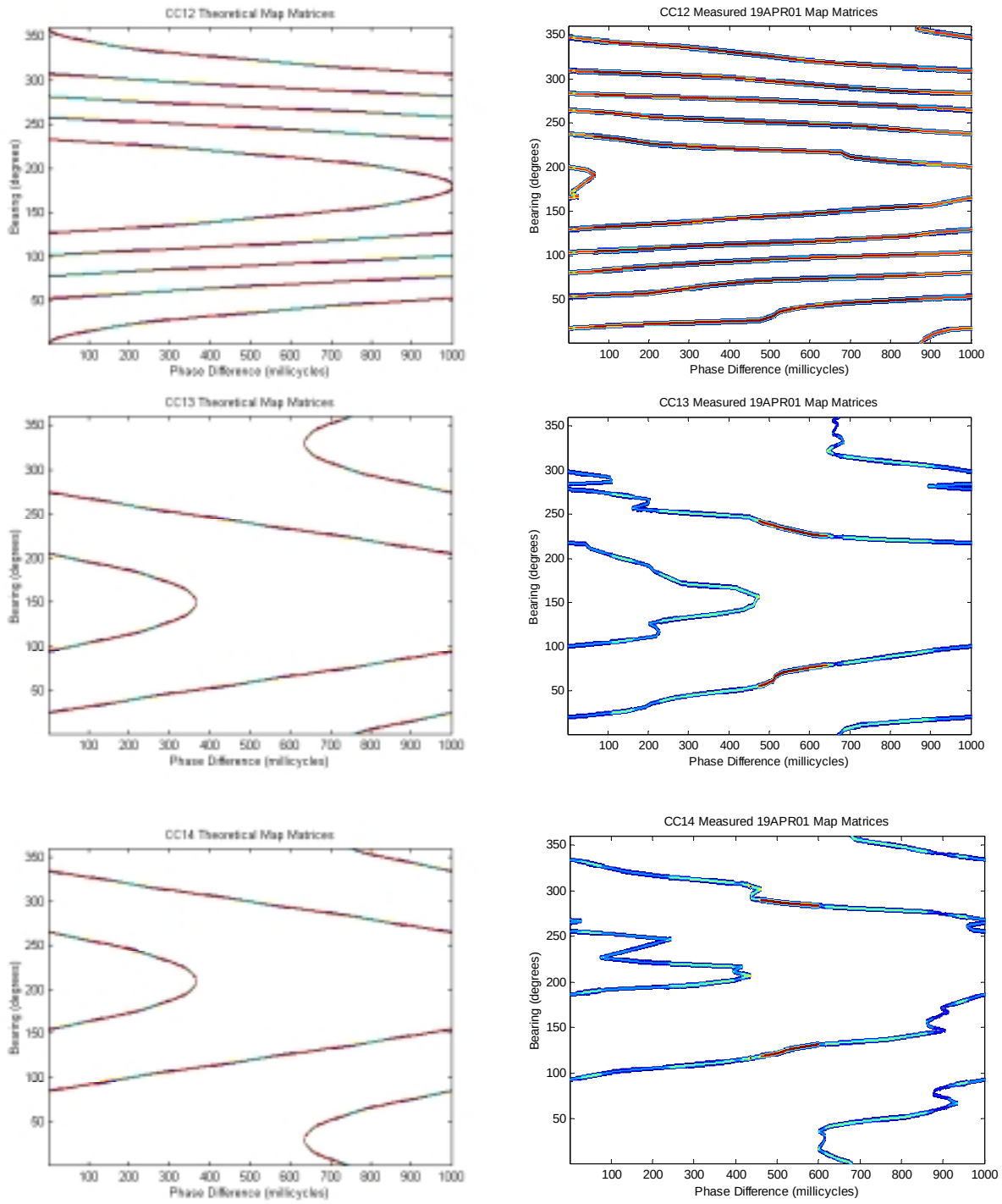


Figure 18 – Map Matrix Comparison. Left: Theoretical Matrix. Right: Mapping Matrix Created 19APR01

The knowledge of the mapping matrix was then used as the foundation to implement an automatic matrix creation function. This function accomplishes via computer what previously took days to do by hand.

Having a reliable tracking system is quintessential to testing not only this project now, but in the future as well as with other projects. The new system, using the 2W transmitter, eliminates the need for a control computer and greatly reduces the size, weight, and bulkiness of the unit.

In order to collect valid data, it is imperative that the system be constructed to specification. Bringing in a professional carpenter furthered this objective and provided for a rugged frame with adapters for the small-antennas.

The NEC antenna modeling and data analysis provided insight as to what was going on with the system. The old antennas were re-radiating and experiencing considerable interaction. This resulted in unusual behavior in the area of the antennas. Ultimately, it was decided that the smaller antennas were the better choice.

With the final system, a test was conducted to test the automatic matrix creation functions and analysis tools. Unfortunately, half a dozen "J" tubes (figure 19) were installed on the roof of McAllister Hall while the new frame was being built. Hence, the roof conditions to conduct DF exercises deteriorated considerably. In spite of this, the function proved to work correctly. The smoothness of the matrix, however, suffered and rather than a simple line, a sinusoidal appeared (figure 20).

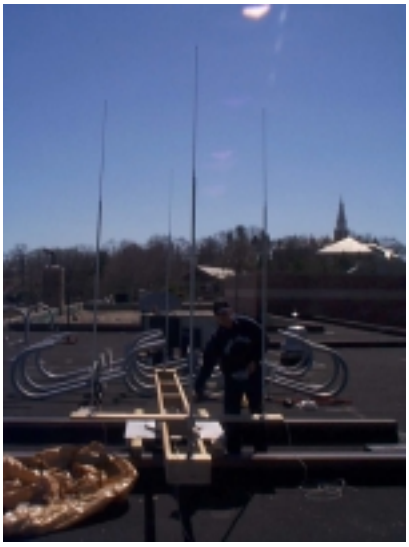


Figure 19 – Photo of "J" tubes

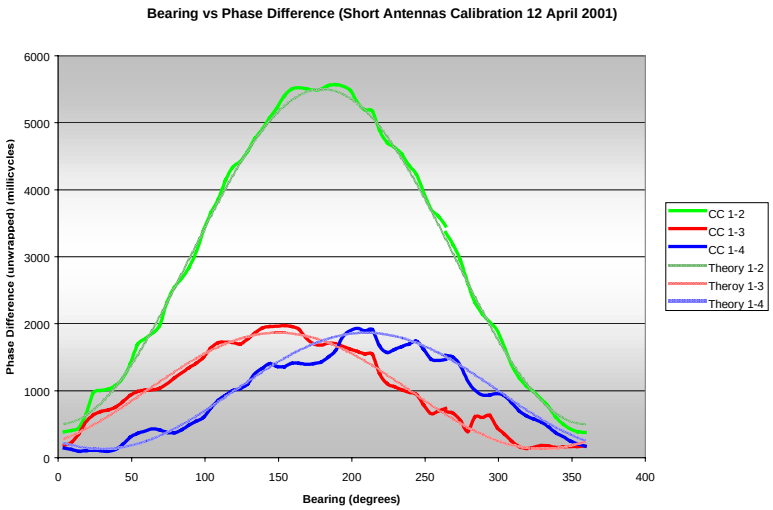


Figure 20 – 12APR01 Map Matrix; Note Sinusoidal Tendency

Conclusions

This Scholar's Project has been successful on many different layers: project objectives, larger Coast Guard significance, and personal development.

From the project's perspective, a series of deliverables have been produced that have furthered the understanding of digital direction finding. An in depth look of the mappings occurred and from that a greater level of confidence in the project and the system was achieved. To assist in this, a diagnostic GUI that runs off live or recorded data provides in depth information of the cross correlation function results, the associated bearings for the given maximum phase difference, and the composite bearing as calculated by a multiplication of bearing probabilities

(see figure 1). I am confident that the use of these functions in a more favorable environment will result in a fully calibrated system, only minutes from installation.

While it must be said that some of the original goals of the project were not met, there is no doubt that these goals would never have been met without the analysis and effort made to this point in learning how the DF system works. At each phase of the project, it seemed that there were obstacles to be overcome. Each of the hurdles was approached cautiously and a solution was engineered each time.

The Coast Guard is now smart on digital direction finding. Through research, analysis, and implementation, a considerable knowledge base has been accumulated to ensure that this tool that could serve our Service and Country so well will not be overlooked. With the shortage of technically-oriented individuals in the Government, the Coast Guard's support of meaningful and challenging projects like this one supports growth of "T" people within our Service and can pay huge dividends in the middle and long term.

This project has also taught me a great deal. In addition to the direct academic learning that occurred by performing the content of this paper, there is a considerable amount of indirect learning about the culture of the organization, project management, and career development. Through this project I had the opportunity to attend AFCEA WEST and learn about DF in the commercial sector. On this trip I was able to visit SPAWAR System Center San Diego. This allowed me to see the system they had built and increase my knowledge of direction finding principles. Throughout the semester I have been able to learn about product acquisition, the budget process, working with contractors, time line concepts and other areas of product management. Through meetings with Dr. Heiner, CAPT Hewitt, CAPT Abbott, CAPT Hartnett, and numerous other Coastguardsmen, I have gained a unique gleam into the inner workings of the engineering profession within the Coast Guard. In all of this, while labor and time intensive, this project has been fun and challenging. It was never difficult trying to be enthused about what I was working on, because I already was. I hope that my small contribution to the NDRSMP has been useful and I hope that some day in the future I have the opportunity to work with this project again.

This project is now ready to be installed in a completely new environment where it can then be calibrated and tested. Once this has been done, exploration of null forming, beam steering, and DDC can be accomplished.

The bottom line is that with this project's completion this semester, the Academy, as well as the Coast Guard, will have a viable, calibrated DVHF-DF System in operation with the tools to set up and demonstrate anywhere with minimal set-up.

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