Digital VHF Direction Finding

1/c Kevin Shmihluk

Project Advisors: Prof. Keith Gross, PhD and CAPT Richard Hartnett, PhD, PE

Abstract

Digital Very High Frequency (DVHF) 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 [1]. This year a new understanding of multipath environments was found and dealt with to generate more reliable and accurate data.

Introduction

This project will serve to assist the National Distress and Response System Modernization Project (NDRSMP) by providing them with a knowledge base from which to negotiate with three contractors on a Coast Guard-wide Direction Finding (DF) system. A Digital Very High Frequency (DVHF) DF system could be a critical asset to the Coast Guard in eliminating the "search" in Search and Rescue. A DVHF-DF system is able to determine the estimated bearing of a radio transmission, which would lead Coast Guardsmen directly to the source of a transmission, saving lives, time, resources, and money. Furthermore, keying in on signals sent from ashore could virtually eliminate the believability of hoax calls and possibly even bring these chaos-inducing perpetrators to justice. Finally, the use of a digital system provides many advantages, including the ability to "null-out" undesired audio content, focus on desired audio content, and save for processing the original, raw, and uncorrupted data indefinitely. The sponsors for this project are G-AND, which is an office of the Headquarters Acquisition Directorate (G-A), and the Research and Development (R&D) Center.

Background

Current commercial-off-the-shelf (COTS) direction finding (DF) products have various limitations that render them undesirable for installation aboard Coast Guard cutters. 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 short-comings of what COTS has to offer.

In 1998, Electronics Support Unit (ESU) Boston sponsored a study conducted at the United States Coast Guard Academy to evaluate a relatively low-cost, commercially available VHF-DF system. The system was found to produce accuracy within three degrees out to a range of eight to ten nautical miles (NM), which is reasonably good, but this system also had considerable limitations. It used suboptimal methods, could not discriminate/detect multiple targets at the same carrier frequency, did not improve the intelligibility of the demodulated audio by employing techniques such as beam forming or null steering, and the system employed hardware demodulation, hence weaker signals were 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 post-analysis. A digital system is also able to steer the antenna beam in software to null out 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 were tested and found to have a precision of ±4º. 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 computers with two analog to digital converters to read the signal from the antenna. Furthermore, beam forming and null steering techniques were researched and accomplished with limited success [2].

In FY01 most of the work involved building an extensive set of calibration and analysis tools using C++. The code also was improved to resolve a synchronization issue, and a lot of testing in the Thames River/I-95 in the nearby area was done to gather data on performance [1].

Objective

The goal of this project is to demonstrate the capability of optimal signal estimation and enhancement technology in the context of VHF-based direction finding and audio enhancement and the requirements of the NDRSMP. During the academic year of 2001-2002, the concentration of work was to perform tests of the river side of the Academy to determine if the system could generate repeatable data for a specific area. This involved an in depth learning process on how multipath environments affect systems and led us to look at ways to improve the system performance (i.e. reduce the variance/standard deviation of the results). Also, the array was rebuilt to ensure that the angles and antenna setup on the array was correct. Future aspects of this project will involve implementing the Digital Down Converter (DDC) into the system to replace the analog receiver.

Technical Approach

During this past academic year I performed many tests to see if the behavior of the current DVHF-DF system was accurate and repeatable. The types of tests conducted were:

- RHI test with tracking system
- Car test with tracking system
- Car test with hand held transmitter
- Plane test with tracking system

My goal was to perform each of these tests several times to see how each test correlated to the other. I also had planned on creating a new mapping matrix of the river side of the Academy using a plane, helicopter, or RHI to transmit a signal, but the learning curve on the system and further understanding of what affects the current system setup caused that step in my project to be moved down in the timeline. Creation of a new mapping matrix would show whether or not each location would need its own mapping matrix, and it would also prove if the system is repeatable.

Results

This year I spent most of my time testing the current system, troubleshooting problems and analyzing the data to see if the results from any test could be repeated (i.e. any transmitter at a specific bearing would produce the same/repeatable phase difference).

Many tests were performed, but only a handful of tests contain acceptable data. The other tests aided in troubleshooting in order to verify that the system was running properly. The following is a list of the noteworthy tests:

- Fall 2001 test
  - 12 NOV 2001 – car test (Ret/Naut/House)
- System setup/verification tests
  - 28 FEB 2002 – car test (Ret/Naut/House)
  - 04 MAR 2002 – RHI test
  - 19 MAR 2002 – RHI (loose connecter ant 2: 1-2 pair had bad data)
- Array on deck of Mac Hall roof:
  - 28 MAR 2002 – Flight test
  - 04 APR 2002 – RHI test
- Raised Array
  - 11 APR 2002 – Car test (Ret/Naut)
  - 15 APR 2002 – RHI test (with anchor to hold position more closely)
  - 18 APR 2002 – Car test with hand held transmitter (Ret)
  - 27 APR 2002 – Re-run RHI and car test with A/C on and off (Ret/House)

NOTE: The following are the details of the abbreviations used above:

Ret – Fairview Fellowship Manor (Retirement Home)

House – House along Thames River between Retirement Home and Navy Sub Base

Naut – Nautilus Submarine Museum at Groton Naval Submarine Base

On Monday, 12 NOV 2001, Prof. Gross, Christian Oates, and I conducted a test of the DVHF-DF system. This included transmitting with a packet modem (tracking system) in a car at Fairview Fellowship Manor Old Fellows Home of Connecticut (Fairview), which is located between the Groton submarine base and the Gold Star Bridge, in a stationary position. The vehicle was left there for the day with the packet modem transmitting data, while Prof. Gross and I ran tests on all of the different parts of the computer software in Mac Hall. The main purpose of this test was to get the system up and running and to further familiarize Prof. Gross and myself with the computer options.

One of the first issues looked at was the effect of a multipath environment on the antenna array. The environment that the array is located was further complicated with the addition of "J" tubes that were installed during summer 2001. The six or seven of these tubes in the local vicinity of the array, in addition to the air-conditioning units that already existed, considerably deteriorate the roof's condition for direction finding. We looked at the effects of the objects on the roof and the effects of antenna interactions with Dr. McKaughan's help using Numerical Electromagnetics Code (NEC) and with the tests identified above.

Dr. McKaughan produced several simulations of the antenna array in a field (Figure 1), which was then compared to a MATLAB model by Prof. Gross and me in MATLAB. The four simulations that we worked on involving the effect of the phase difference as a function of bearing were:

1. Antenna interactions of full antenna array (plots below for 1-3 pair only)

2. Multipath environment due to a box located near the array

3. Receiving a frequency different than antenna array constructed for

4. Development of simple antenna interaction model to explain antenna interaction observed in NEC, and comparison of results

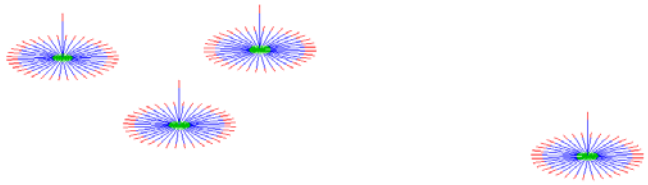

Figure 1 – Antenna Configuration in NEC (example)

The MATLAB model was a mathematically generated model that looked at the signal received by the antennas. For the 1-3 antenna pair analysis, we modeled the signal received on antenna 3 as the signal received on antenna 3 directly plus the signal received on antenna 1 reradiated (with some loss) to antenna 3 with the same interactions on antenna 1. Only one bounce of a reradiated signal between antenna pairs was calculated in this model.

Two main conclusions were found using the NEC simulations and MATLAB models. The first conclusion looked at the effect on phase difference between antennas due to antenna interactions. The left plot of Figure 2 shows the difference between the MATLAB model and the theoretical values, and the right plot shows the difference between the NEC simulation and the theoretical values. Figure 3 is the difference between the MATLAB and NEC plots in Figure 2.

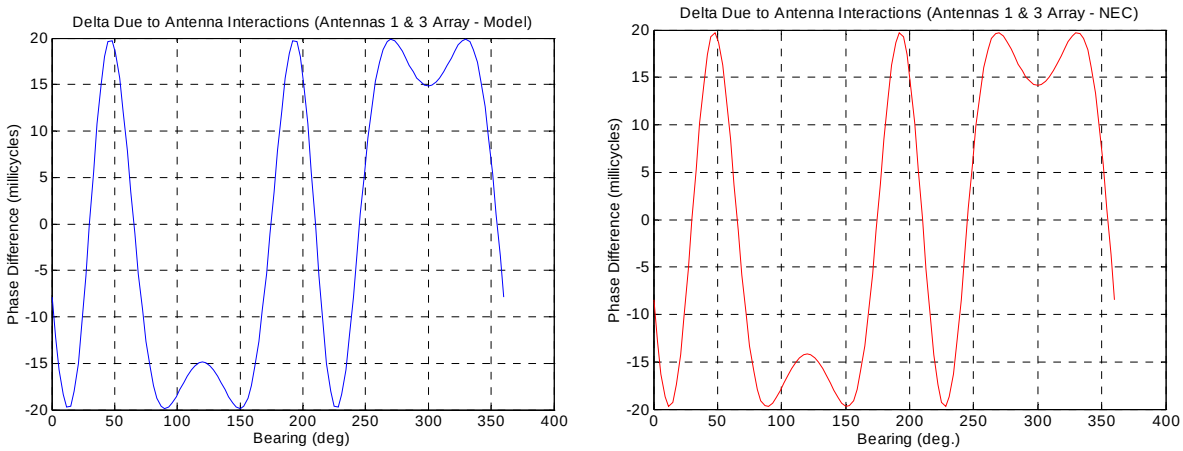

Figure 2 – MATLAB and NEC Phase Differences

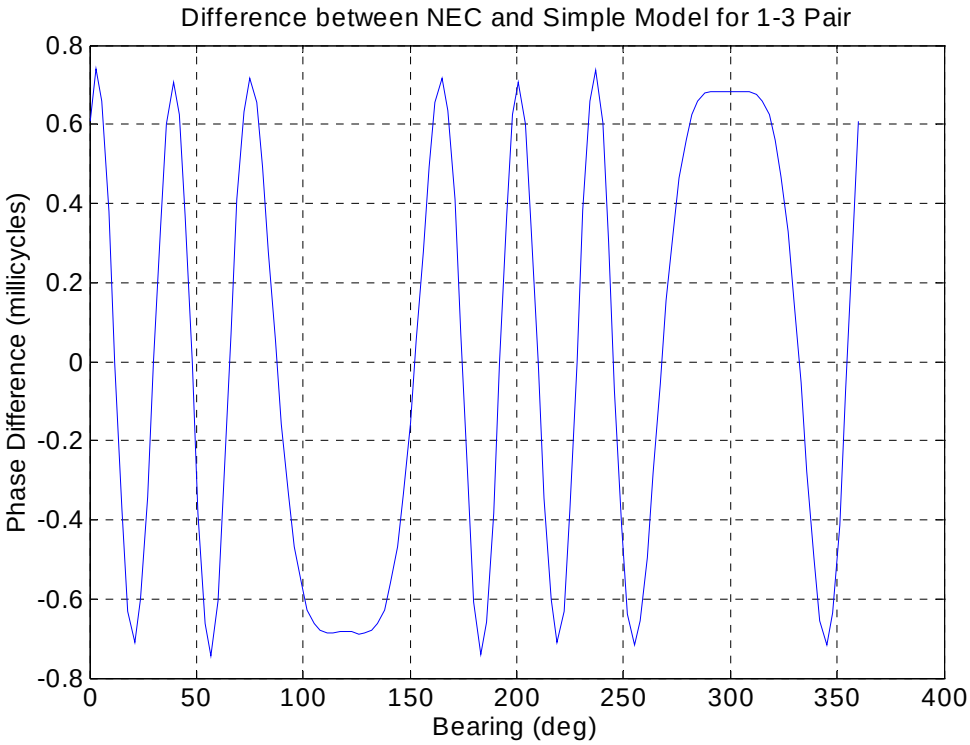

Figure 3 – MATLAB vs NEC Difference

Figure 3 shows that the MATLAB model and NEC simulations of the antenna interactions matched almost identically. The simple model accounts for all but 0.7 millicycles of difference, which equates to about 96% of the antenna interaction effect on phase difference being explained by the 1 bounce re-radiation model.

The other important conclusion found was when a reflective box was added to the NEC simulation (Figure 4). This box was meant to represent an air-conditioning unit, as the ones on the roof of McAllister Hall (Mac Hall). We found that the presence of the box above the ground plane of the antenna array caused noticeable changes in the phase measurements [3].

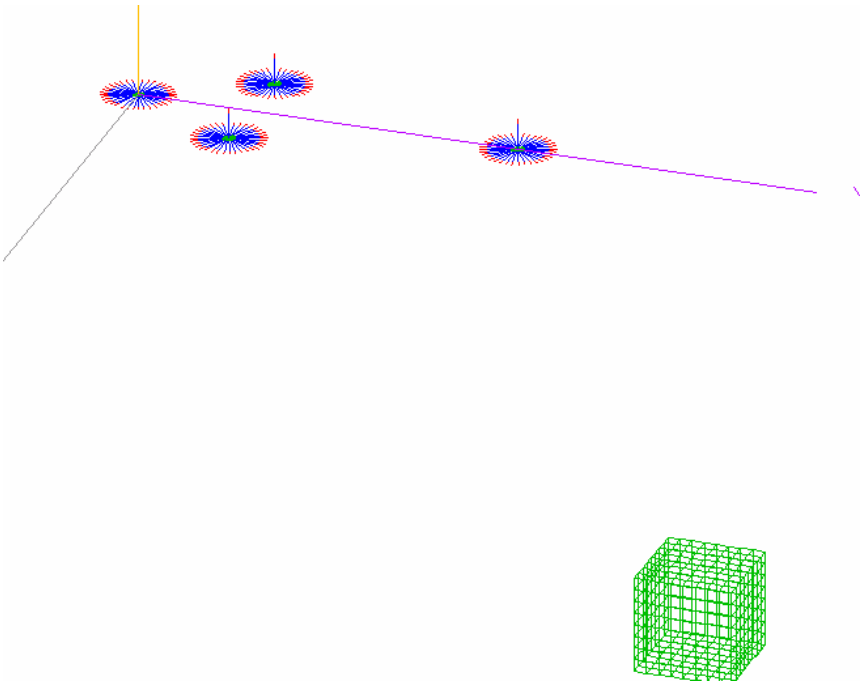

Figure 4 – NEC Array Simulation with Reflective Box

The next step involved testing to further observe the performance of the system. The first several tests, which included both RHI and car tests using the tracking system, returned data with large variations. This caused us to look more in depth at the system.

Christian Oates, George Sanders, Prof. Gross, and I went through almost every part of the system and made sure that it was working properly. The receiver was calibrated; the timing on the two A/D cards in the computer was examined; the cable connectors were tested; and the array was also looked into with more detail. It was determined that we should have the antenna array rebuilt. The fall 2001 stand for the antennas was made out of wood by a contractor during the spring of 2001, but it was left uncovered during that summer, which caused some warping in the wooden frame that holds the antennas (Figure 5).

Figure 5 – Fall 2001 Antenna Frame

Based on past data this warping of the frame will have an impact on the phase differences [2]. Therefore, the frame was rebuilt by a professional carpenter as shown in Figure 6.

Figure 6 – Spring 2002 Antenna Frame

We then continued to look at the effects of a multipath environment. During system verification testing, it was noted that there was a large change in phase difference when the car only moved a half a car length. An example of the large standard deviations received were 120, 105 and 82

millicycles for antenna pairs 1-2, 1-3 and 1-4 respectively, but for 089 degrees true the theoretical change in phase difference for a one degree change in bearing corresponds to 43.6, 13.2 and 12.9 for the 1-2, 1-3 and 1-4 antenna pairs respectively. This difference caused us to look more closely at the multipath environment. In reviewing the testing and performing the test several more times, it was concluded that a small movement in the presence of a multipath environment has a large change in phase difference (Figure 7).

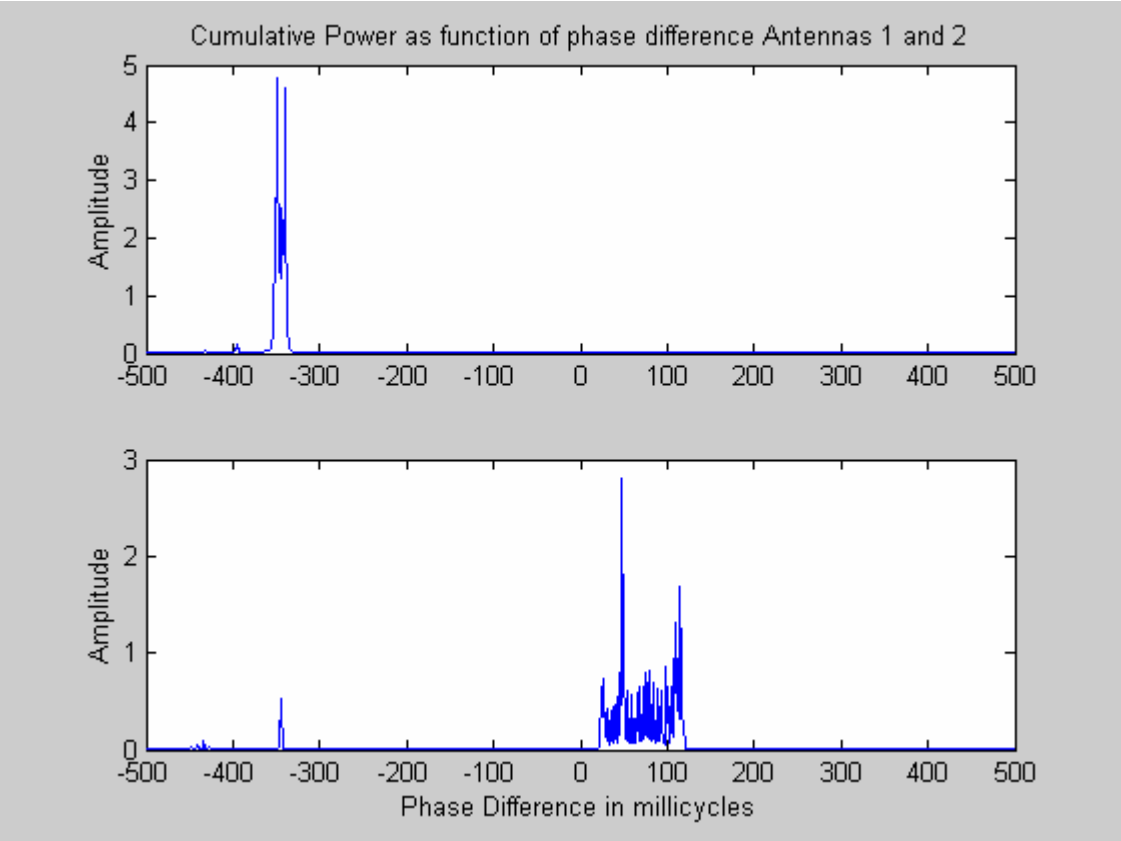

Figure 7 – Effects of Multipath on Estimate of Phase Difference between Antennas

The top plot in Figure 7 shows a fairly clear signal, while the bottom plot shows a signal from the same car, with the car moved ½ a car length in an environment of extensive multipath. The result of such a movement is a large amount of error. In conclusion, multipath environments extremely degrade the performance of a direction finding system, and all should be done to find a location for the array with as little environmental pollution as possible.

Next, we conducted an RHI test with the new antenna array. During this test the time stability of the phase difference was analyzed. The messages transmitted were approximately 1.35 seconds long and around 65 messages were received for each bearing. This test involved maneuvering the RHI to hold a bearing (89 +/- 0.5 degrees) for the message bursts. The results are represented below in Figure 8. The standard deviations of the observations were 22, 20 and 28 millicycles for antenna pairs 1-2, 1-3 and 1-4 respectively, which are fairly large.

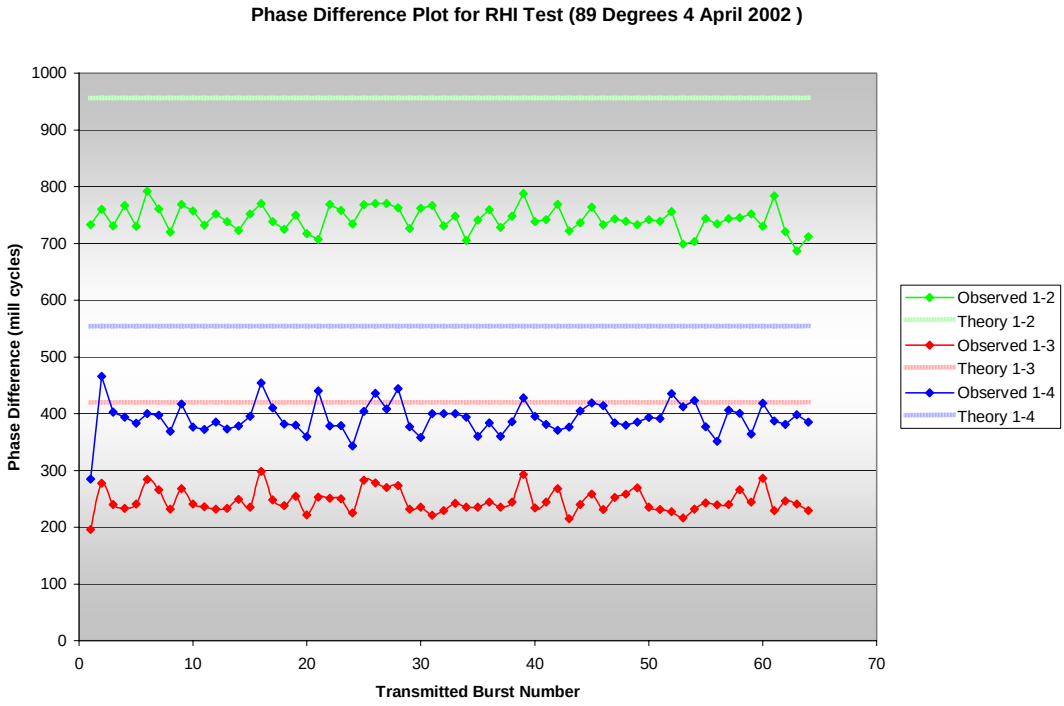

Figure 8 – Results from RHI Test (04 APR 2002)

One thought to the cause of the large standard deviations in the 04 APR 2002 RHI test was the presence of a multipath environment on the roof of Mac Hall. "J" tubes, air-conditioning units and other structures on the roof were thought to possibly be the root of the problem. Therefore, the next step was to get the antenna array out of the multipath environment. This was accomplished by raising the antenna array and placing it on saw horses about 87 inches off the deck of the roof, which put the array's ground plane above the objects that might cause interference on the roof. This is represented in Figure 9.

Figure 9 – Antenna Array Raised 87 inches above roof

Next, we conducted another car test to determine what effects raising the antenna array had on the standard deviations of the phase differences from a stationary target. This test involved having the transmitter fixed to a car, which we tested at several locations on the Groton side of the Thames River. The message bursts were again approximately 1.35 seconds, but the key difference with this test was that the transmitter did not move at all during the testing for one location. The results from a bearing of 089 degrees true from the Academy were outstanding and are presented in Figure 10. The standard deviations of the observations were 1.9, 2.5 and 3.1 millicycles for antenna pairs 1-2, 1-3 and 1-4 respectively.

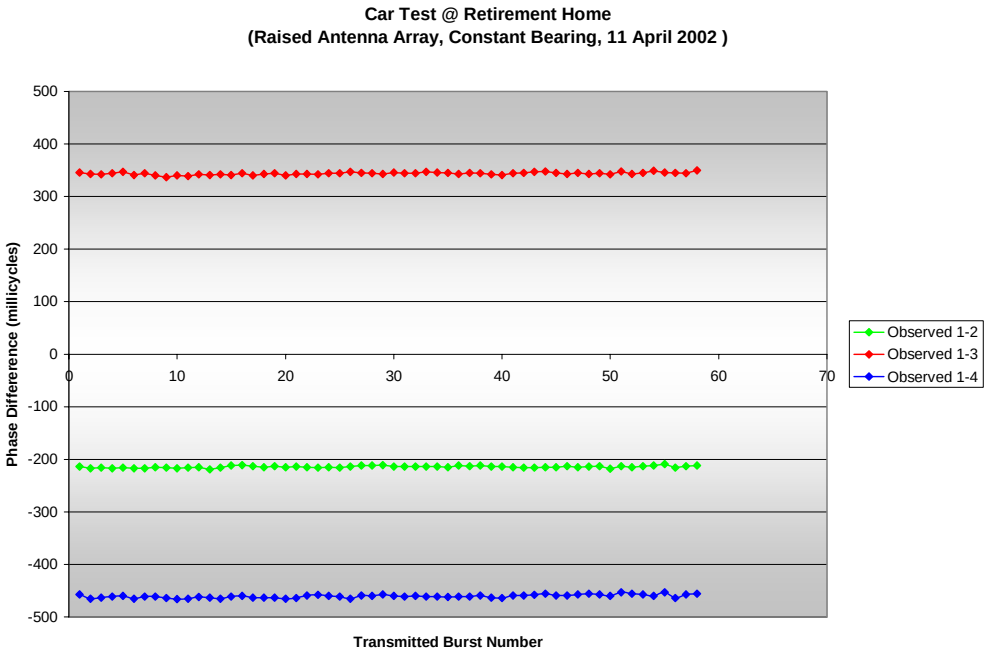

Figure 10 – Results of Raised Antenna Array Test (11 APR 2002)

Then we decided to conduct another RHI test on 15 APR 2002. This test was performed the same as the last RHI test, but this time I used an anchor to hold my position more accurately. The RHI still moved back and a forth a little on its swing circle, but it held one location much closer compared to the movement when the RHI had to be maneuvered. The results can be seen below in Figure 11.

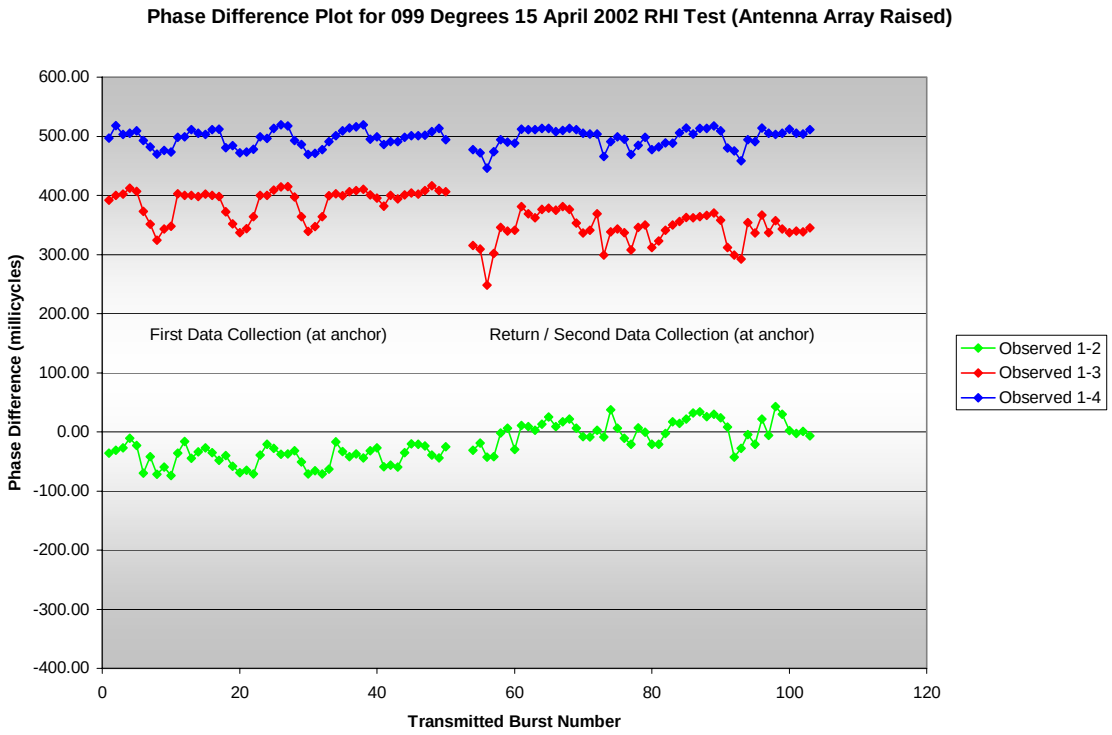

Figure 11 – Results of RHI Test with Array Raised (15 APR 2002)

At the time of the test, these results could not be fully explained. The standard deviations for the RHI anchored at 088 degrees true were 15.5, 4.79 and 11.8 for the antenna pairs 1-2, 1-3 and 1-4 respectively. These values were much larger than were found for the 11 APR 2002 car test. Also, we never saw periodic changes in the phase differences before, so we then looked for the cause. One idea that we had was that it could have been either the air-conditioning unit, which was turned on for the first time of the semester just before the test occurred, or it could have been the movement of movement of the RHI in the water along the swing circle from the anchor.

To see whether the air-conditioning unit was the cause we performed another car test on 27 APR 2002. We went to two different bearings, the Retirement Home and the House on the river, and turned on the air-conditioner on and off while transmitting. Although we did repeat the same performance as the other car test on 11 APR 2002 for the stationary antenna, the results did not explain the periodic movement of the phase differences, so we went one step further and looked at if the movement of the actual transmitting antenna on the RHI, the constant swinging around from waves, was causing the periodic phase differences. To do this I physically held the mounting magnet of the whip antenna through the sunroof of my car and moved the antenna in all directions with about a one foot diameter at the House and a two foot diameter at the Retirement Home. All results, shown in Figures 12 and 13, show that the air-conditioning unit being on and off did not cause any change in the phase difference, but physically moving the transmitting antenna did cause the phase difference to closely resemble past RHI data, while not specifically explaining the periodic changes.

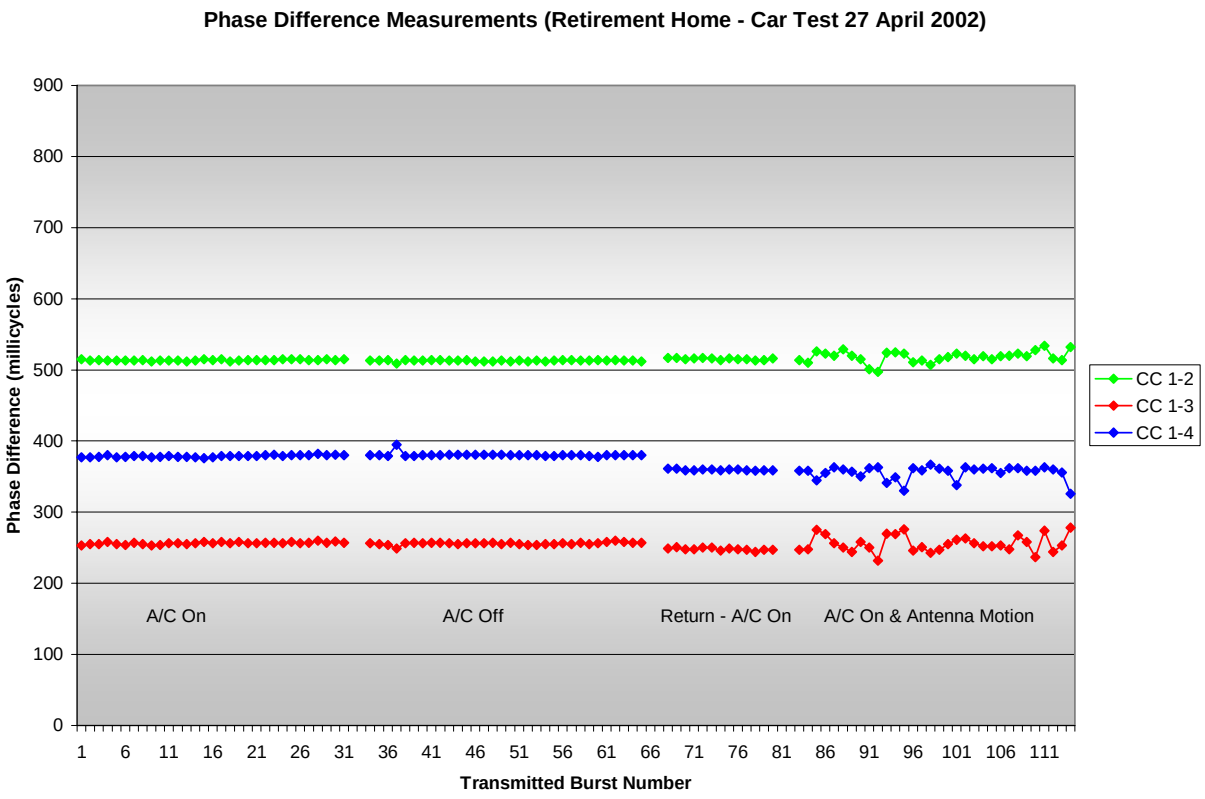

Figure 12 – Results of Car Test at Retirement Home with Array Raised (27 APR 2002)

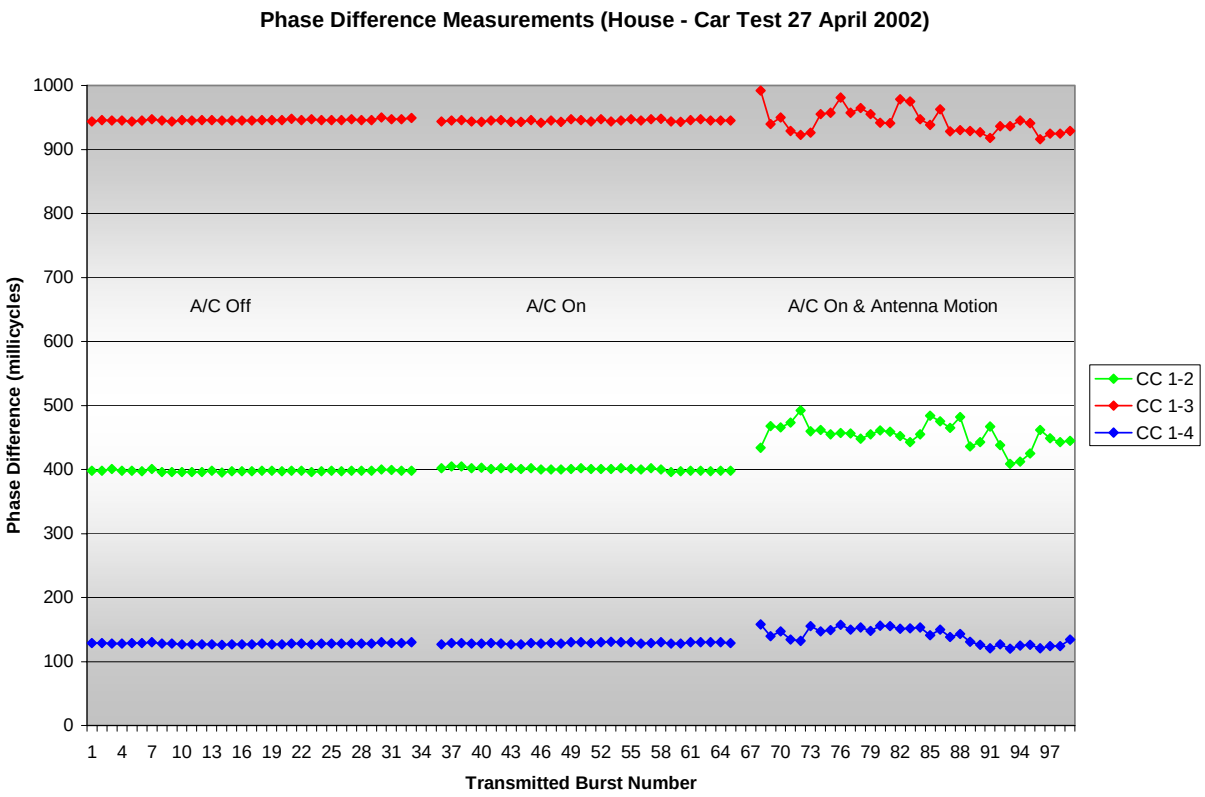

Figure 13 – Results of Car Test at House with Array Raised (27 APR 2002)

To further attempt to explain the periodic changes in phase difference, a final RHI test was also conducted on 27 APR 2002. The difference with this test was that we used two anchors for one test and one anchor for another test to determine if we could get the data from an RHI test to have the phase difference stability of the car tests with a stationary antenna and to also see if we could explain the periodic phase difference changes with the movement of the RHI on the swing circle of one anchor. In performing these tests, we also used two different antennas to see if a rigid (aircraft) antenna made a difference compared to use of a whip antenna on a constantly moving object such as an RHI. The results can be seen in Figures 14 and 15.

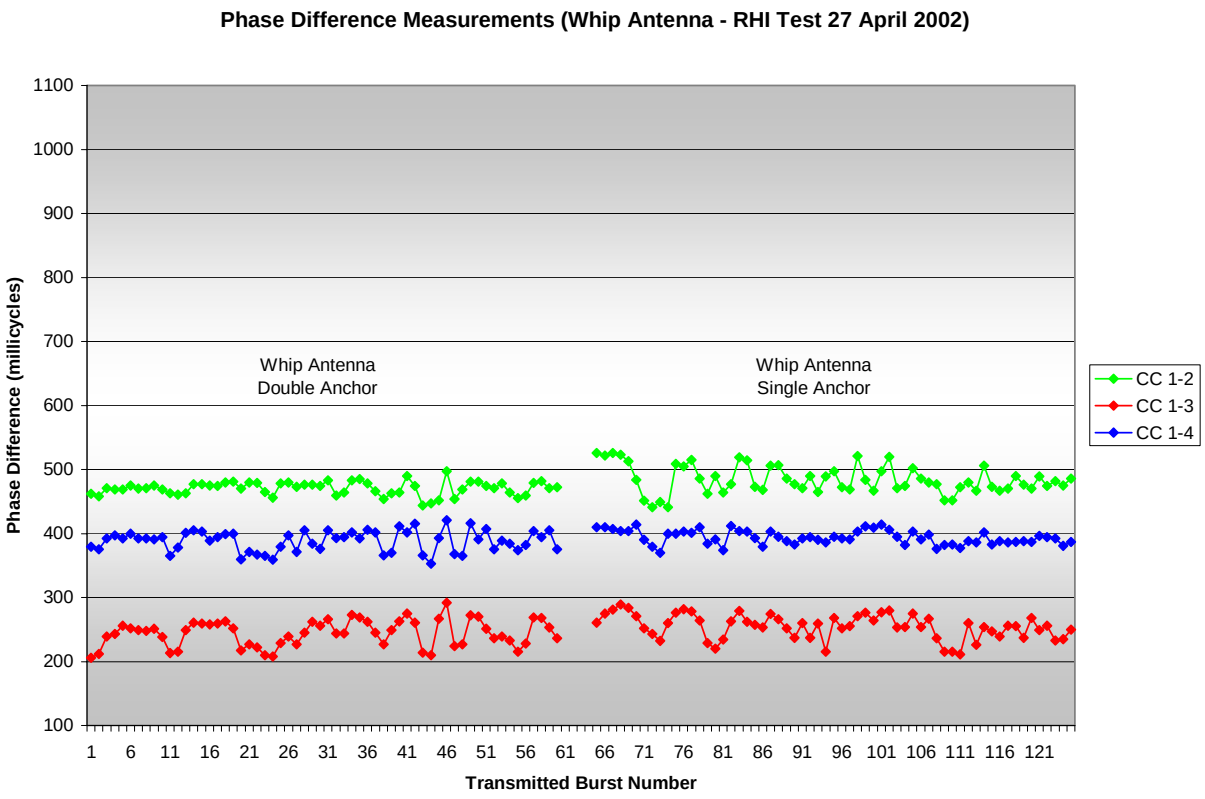

Figure 14 – Results of RHI Test with Array Raised – Whip Antenna (27 APR 2002)

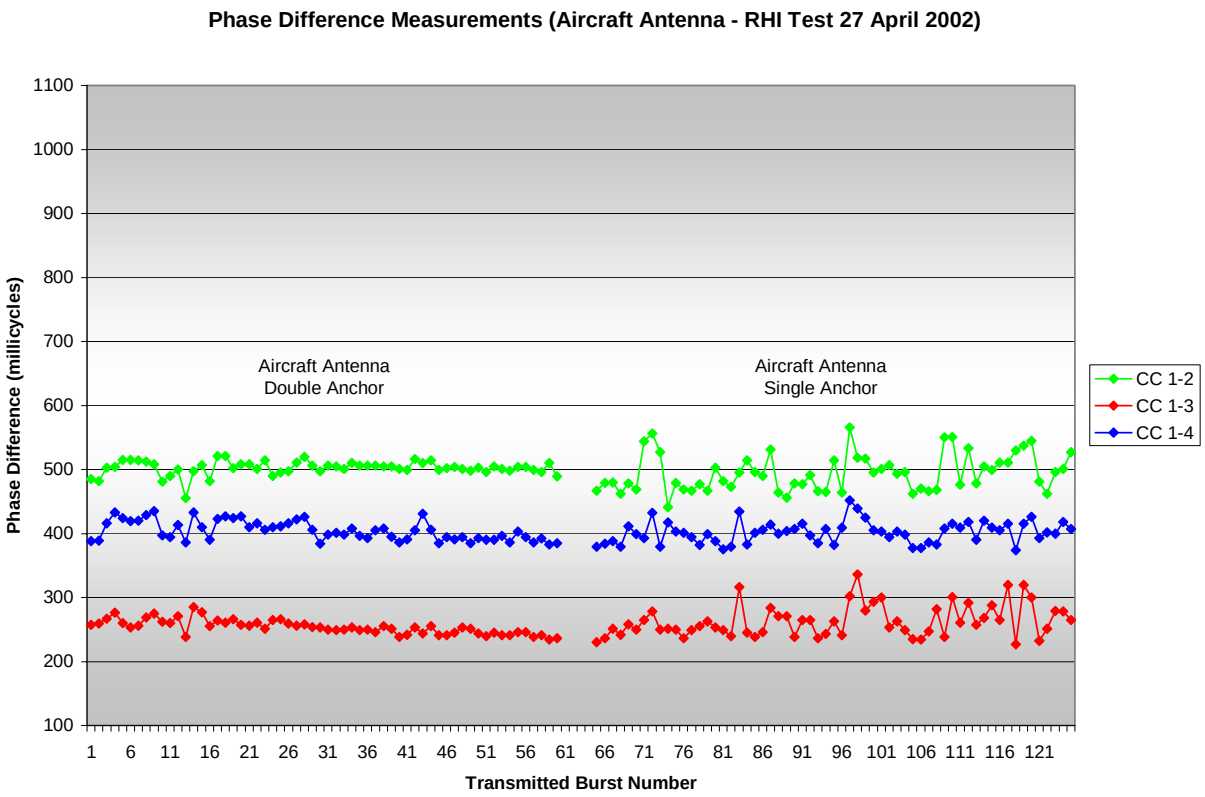

Figure 15 – Results of RHI Test with Array Raised – Aircraft Antenna (27 APR 2002)

The standard deviations (std dev) of the observations were as follows:

Whip antenna – double anchor:

Std dev: 10.45 20.55 16.15

Whip antenna – single anchor:

Std dev: 21.95 19.32 10.91

Aircraft antenna – double anchor:

Std dev: 10.97 11.12 15.39

Aircraft antenna – single anchor:

Std dev: 29.16 25.26 16.98

NOTE: Standard deviations arranged in this order: 1-2, 1-3 and 1-4

The results of the testing proved several important items of concern. First, both tests using the single anchor, the whip test especially, show that there is some sort of periodic movement of the

RHI along its swing circle, as expected. This is caused from the current and wind that forced the RHI to swing on one tack until the anchor line will not let it go any further, which then forces the RHI to then switch to its other tack until it cannot go any more in that direction. This cycle was also easily observed when it was looked for/expected during this test.

Second, the double anchor tests both show that the RHI data can much more closely represent the phase difference stability of a car test with a stationary antenna when it is held in position. One anchor was off the bow and the other was off the stern, with the goal of trying to hold the RHI in a single position as much as possible and stop the periodic movement of the RHI. The aircraft antenna clearly shows that when the position is held in check, the phase difference variance/standard deviation is largely decreased.

It is also believed that the whip antenna with the double anchor does not have the phase difference stability resembling that of the car test because although the RHI was held in check, it still rocked from left to right, which caused the whip antenna to swing back and forth and further amplify the rocking of the RHI rather than show that the RHI itself was holding position much more closely than prior tests. This rocking is thought to be the same as the moving of the whip antenna in my hand during the car test earlier that day on 27 APR 2002, which can be seen by comparing Figures 12 and 14.

Finally, the high standard deviations found are believed to be caused by the exaggeration of movements of the transmitter due to closeness to the receiver.

Conclusions

Two main conclusions were drawn from this year's work. First, the variance/standard deviation was looked at in great detail. After extensive research and numerous tests, it was determined that the main problem behind the high variance/standard deviation for our system was the multipath environment that was caused by the "J" tubes, air-conditioning units, and other items that can cause constructive/destructive interference on the roof of Mac Hall. Tests conducted this year showed that a small movement (small being considered moving only several feet), in the presence of multipath causes very large phase shifts. It was concluded that the antenna array had to be removed from this multipath environment to gather accurate data, which led us to the next important conclusion – raising the antenna array.

By raising the antenna array above the multipath environment on the roof of Mac Hall, we found that we could finally receive data with phase difference stability and with standard deviations in the single digit range. This conclusion gave us a good understanding of the impact of multipath environments and also gave us promise for future work with our current DVHF-DF system.

It is recommended that future tests be conducted at another site, where distances in the range of 5-10 NM can be tested. I believe this is the next step because the current distance of less than 1.0 NM (0.65 NM for the RHI tests and 0.8 NM for the car tests) between the array and transmitter causes the effects of slight movements in the transmitting antenna to be amplified, resulting in data with a large variance/standard deviation.

It is also recommended that the computers for the system be looked at for replacement next year. The current computers are outdated and cannot perform multiple tasks at the same time, which is needed for data analysis and will most likely be utilized to a higher capacity in the future.

References

[1] Benin, Joe. "Digital VHF Direction Finding System." http://webnt/d/de/dee/projects/VHF/2001/paper.pdf . U. S. Coast Guard Academy, May 2001.

[2] Corteville, Sarah and Stephen Walters. "21st Century VHF Direction Finding in the Coast Guard." U. S. Coast Guard Academy, May 2000.

[3] McKaughan, Michael E., Keith C. Gross, Richard J. Hartnett, and Kevin R. Shmihluk. "USCG Academy's Efforts in Digital VHF Direction Finding." U. S. Coast Guard Academy Center for Advanced Studies (CAS), to be published in May 2002.

"A User's Guide: How to Shop for a Radio Direction Finding System." AN-001. RF Products, 2000.

"A User's Guide to Radio Direction Finding Basics." WN-001. RF Products, 2000.

Burberry, R. A. "VHF and UHF antennas." P. Peregrinus on behalf of the Institution of Electrical Engineers: London, 1992.

Direction Finding Systems. http://www.cse-assoc.com/rf.html CSE Associates Inc., 04 OCT 2001.

Great Britain Department of Scientific and Industrial Research. "Radio direction-finding and navigational aids, Radio direction-finding and navigational aids." H. M. Stat. Off: London, 1951.

Hartnett, CAPT Richard J. http://www.rdc.uscg.mil/ VHF Direction Finding and Audio Enhancement Technology Assessment, 04 OCT 2001.

Lythall, Harry. Direction Finding System. http://hem.passagen.se/sm0vpo/rx/df-00.htm Updated 26 SEP 2001. 04 OCT 2001.

Mobile Adcock Radio Direction Finding Antennas. http://www.rfproducts-rdf.com/moblant.htm Updated 02 OCT 2001. 04 OCT 2001.

Radio Direction Finding Products. http://www.directionfinder.com/directionfinding.htm Direction Technology, Inc., 04 OCT 2001.

Radio Direction Finding Systems. http://www.dopsys.com/ Doppler Systems Inc., 04 OCT 2001.

Solt, Clyde T. "The development and application of marine radio direction finding equipment by the United States Coast Guard." Institute of Radio Engineers: New York, 1932.

Williams, Kathleen Broome. "Secret weapon: U.S. high-frequency direction finding in the Battle of the Atlantic." Naval Institute Press: Annapolis, MD, 1996.