NVIS Antenna Development and Testing for WPB-110 Class Cutters

Project Report

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Projects in Electrical & Computer Engineering
United States Coast Guard Academy
28 April 2006

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ABSTRACT

The purpose of this project is to test a Near Vertical Incident Skywave (NVIS) antenna design to determine if it is a viable solution to a major Coast Guard communications problem. The sponsor for this year's work involving NVIS was Coast Guard Telecommunication and Information Systems Command (TISCOM).

The current high frequency (HF) antenna configuration on a 110' Coast Guard Patrol Boat (WPB) class cutter has proven unreliable for mid-range communications reducing overall mission effectiveness [1]. Past Coast Guard Academy cadet design projects have used computer-modeling programs to determine that a potential solution is a "towel-bar" shaped NVIS antenna.

The work this year was focused on testing an actual prototype of the antenna. This testing had two stages: land based testing on the roof of McAllister Hall and testing on an operational 110' WPB cutter. The land based testing was completed to ensure that the actual antenna behaved as predicted by computer modeling and to ensure that the RT-9000, the radio transceiver currently employed by the Coast Guard, and antenna formed a functional communications system. Once the McAllister Hall tests confirmed that the system worked, another "towel-bar" antenna was installed and tested on the 110' USCGC TYBEE. The goal of the underway tests was to determine if the antenna improved communications in the range of 50-500 NM. Clear communications were observed during underway testing, but further testing in the range of 50-500 NM must be done to determine if NVIS is a solution to the mid-range communication problem. The data and knowledge developed throughout the testing process can be used to create NVIS antenna systems for the Coast Guard's other assets.

INTRODUCTION

110' WPB class cutters are an important asset to the Coast Guard. Unfortunately, their capabilities are hindered by a communications problem. Their primary missions of search and rescue (SAR) and law enforcement (LE) operations constantly take the cutters offshore, often between 50 and 500 nautical miles. Because the cutters are frequently offshore, reliable mid-range high frequency (HF) communications are vital to complete their mission.

110' cutters currently use a whip antenna for HF communications, which creates a low take-off angle for the signal. This produces a large skip zone, which is the distance from where the ground wave ends and where the sky wave returns to earth after bouncing off the ionosphere [2]. Figure 1 shows sky waves of different take off angles reflecting off the ionosphere, and the resulting skip zone.

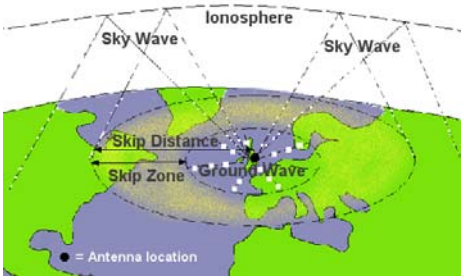

Figure 1: Skip zone created by Sky waves [2]

Due to these skip zones; the cutter's mid-range communication is unreliable. 110' cutters have other mid-range communication options such as Satellite

communications (SATCOMS), but the costs associated with operating SATCOMS is extremely high.

Near Vertical Incident Skywave (NVIS) antennas have recently been employed successfully by the Coast Guard to correct HF communications problems on larger platforms such as the 270 WMEC. NVIS antennas transmit HF waves at nearly vertical incident angles, almost 90 degree angles [3]. The signals reflect off the ionosphere and return to earth between 50-500 NM eliminating the skip zone [4]. Figure 2 shows the radiation pattern of NVIS and its elimination of the skip zone.

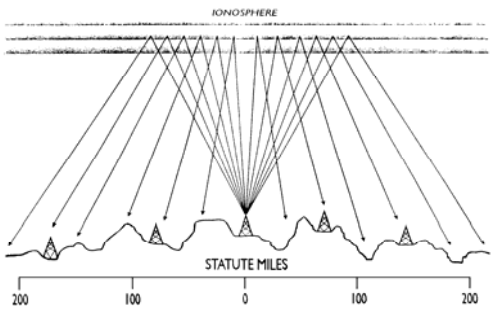

Figure 2: NVIS elimination of the skip zone [4]

The development of NVIS antennas for 110' WPB cutters began as a U.S. Coast Guard Academy senior design project three years ago. The project began with the work of cadet 1/C Sean Barnhill, who tested multiple NVIS antenna designs and determined that the best design was a "towel bar" NVIS antenna. Barnhill's work consisted mainly of computer modeling, using two antenna modeling programs called NEC4 (Numerical Electromagnetics Code version 4) and WIPL-D [5].

The project continued the next year with the work of cadet 1/C James Miller who compared antenna models using the computer modeling software NEC4 and WIPL-D, to determine if the predictions made by the two models were comparable. 1/c Miller determined that WIPL-D, which drastically simplified antenna modeling, produced results very close to those created using NEC4 [6].

Cadet 1/C Darla Mora and Cadet 1/C Chris Weiser did the most recent work involving the towel bar antenna for a 110' cutter. They initially used computer antenna modeling software, primarily WIPL-D, to develop various NVIS antenna models. 1/C Mora and 1/C Weiser confirmed that a towel bar shaped NVIS antenna was the most effective design. They modeled and compared characteristics such as the radiation pattern, driving point impedance, and signal strength of the NVIS antenna at various locations on a 110' WPB cutter's structure. Their work determined that the best location for the NVIS antenna was on the superstructure, in front of the bridge. In addition to computer modeling, 1/C Mora and 1/C Weiser built a prototype antenna [1]. Figure 3 is a model created using WIPL-D that shows the location of the towel bar antenna (red towel bar shaped line), and Whip antenna (vertical red line) on the 110' WPB.

Figure 3: Placement of Towel Bar Antenna and Whip Antenna on 110' WPBs [1]

The purpose of this year's project was to test the prototype towel bar NVIS antenna on a 110' WPB to determine if the NVIS antenna corrects the current mid-range communication problems. The first step in the project was to perform land-based tests with the existing towel bar antenna. The second part of the project was to install and test a towel bar antenna on the USCGC TYBEE out of Woods Hole, MA.

OBJECTIVES

The main objective of the project this year was to test the proposed NVIS towel bar antenna solution for 110' WPB cutters. In order for this objective to be met, there were several intermediate steps that had to be completed. A project plan was written that clearly outlined the objectives that had to be met during the course of the project. The project plan is included as Appendix 1.

The first step was to acquire the needed approval for testing a prototype system. An Engineering Change Proposal (ECP), composed of a prototype installation plan, a memorandum of agreement, and a prototype evaluation plan, was completed and sent to TISCOM. After approval by TISCOM it was passed on to Engineering Logistics Command (ELC) the final approving authority. Normally the ECP process

can take anywhere from months to an entire year, but the efforts of members of TISCOM and ELC who supported the NVIS project enabled us to receive approval in about one month. The ECP for the prototype testing of the towel bar antenna is enclosed as Appendix 2.

The second step was to thoroughly test the developed NVIS antenna on the roof of McAllister Hall with an RT-9000 transceiver, which is the standard HF radio for Coast Guard 110' WPB cutters. The results of the McAllister Hall tests were then used to correct any compatibility problems between the radio and the antenna. In addition, we wanted to ensure that the antenna functioned as predicted by computer models. These land based tests served as a baseline for knowledge about the function of the antenna and of the RT-9000 and its Automatic Link Establishment (ALE) capabilities.

ALE is a radio function that automatically runs through a pre-programmed set of frequencies and establishes a connection on the frequency with the strongest signal. Incorporating the ALE capabilities of the transceiver would make the NVIS antenna easier to use.

The third step and the most important objective was to actually test the towel bar antenna onboard a 110' WPB cutter. For our test we were able to schedule a day trip onboard USCGC TYBEE, as it transited from Provincetown, MA to Cape Cod, MA. The test analyzed the antenna's performance between 2 and 20 MHz, as well at the system's general ability to establish a connection.

During the test, the effectiveness of the antenna was evaluated both subjectively and objectively. One determination of effectiveness was the test teams' subjective measurements of the system's voice quality. The qualities of communications checks were described in accordance with the Radio Telephone Circuit Speaker PQS [7]. Appendix 3 shows the descriptors used to evaluate the voice quality of the signal. The objective results came from the RT-9000's Link Quality Analysis (LQA) measurement, which is a percentage ranging from 30 to 70 based on the radio's signal to noise ratio at a given frequency. The LQA values were taken directly from the RT-9000, which is an ALE capable transceiver. The transceiver linked up on the frequency with the strongest signal and therefore the highest LQA value. The test provided data regarding the quality of mid-range communications, and the results of the tests were analyzed to determine if the NVIS antenna concept really is an answer to the Coast Guard's mid-range HF issue.

Another component of the project that still needs to be addressed is an evaluation of the antenna's radiation hazards, and near field propagation characteristics. The antenna must be within the allowable radiation exposure limits to be safe and usable. According to the Occupational Safety and Health Administration (OSHA), personnel should not be exposed to more than 10 mW/cm^2 for periods of up to one hour [8]. Coast Guard personnel exposure limits are stricter, permitting exposure to only .4 mW/cm^2 for periods of one hour [9]. We installed the antenna immediately forward of the bridge; directly over the ET space. The ET space and bridge are high traffic areas, where crew members could stand duty for several hours. We need to ensure that the radiation penetrating the spaces does not exceed OSHA standards.

SYSTEM DESIGN

There were two phases of system design in this year's project. The initial phase of the system design was comprised of the McAllister Hall roof set-up. The roof test bed consisted of the NVIS antenna, the coupler, and the RT-9000 radio transceiver. The second phase of the system design was the installation and testing of the NVIS antenna on USCGC TYBEE. The installation of the antenna consisted of the NVIS antenna, the coupler, and the RT-9000 radio transceiver.

For the McAllister Hall system design, the original NVIS antenna prototype created by 1/C Mora and 1/C Weiser was used. The antenna was made of aluminum pipe that was 2.4 inches in diameter. The antenna was shaped like a towel bar only much larger. It was 24 inches tall and 10 ft long. The antenna was bolted to an aluminum "I" beam on the roof of McAllister Hall. TISCOM provided us with the RT-9000 and the coupler. The land based set up was made to mimic the configuration that was employed on the 110' WPB. Testing on land with the same equipment that was used on the cutter was done to allow troubleshooting and to run through an underway test plan in a controlled environment.

Another design challenge was the integration of the antenna and transceiver. This was also accomplished using the land based McAllister Hall antenna setup. We tested the impedance of the antenna at varying frequencies to determine if the impedance data was related to the computer modeling data. After an

unsuccessful communications test with group Woods Hole, and an afternoon spent with members of Coast Guard Electronics Support Detachment (ESD) Cape Cod troubleshooting the antenna, it was determined that poor grounding on the roof of McAllister Hall set up prevented the land-based antenna from radiating as predicted. ESD Cape Cod technicians took the prototype NVIS antenna and the RT-9000 back to Cape Cod and set up a test bed. ESD Cape Cod determined that the system worked as expected. This was enough assurance to begin installation on a 110' WPB class cutter.

The configuration on the 110' WPB was very similar to the land based system. It consisted of the NVIS antenna, the coupler, and the RT-9000 radio transceiver. The NVIS antenna was welded to the superstructure in front of the bridge on the TYBEE. The feed line from the starboard whip antenna was disconnected and reconnected to the towel bar antenna. This allowed the original Control and RF lines to remain connected between the cutter's RT-9000s and couplers. A block diagram of the system is shown in Figure 4. The antenna ran on shipboard power of 120 V,and 60 Hz.

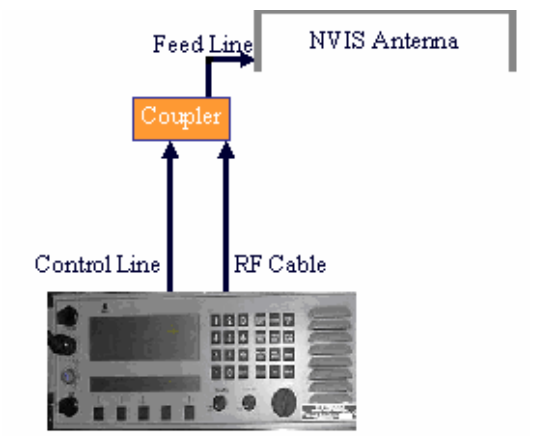

Figure 4: Block Diagram of the HF Communications System

To determine the effectiveness of the antenna a test plan was written for a transit from Provincetown, MA to Woods Hole, MA. Communication tests consisting of two subtests were completed approximately every 30 minutes. The first subtest recorded objective quantitative signal quality, and the second subtest recorded subjective, qualitative signal quality. The underway test plan is included in Appendix 4.

The first sub-test employed the Automatic Link Establishment (ALE) capabilities of the RT-9000. The TYBEE transmitted a signal and Group Woods Hole received, while frequencies in the range of 2-20 MHz were tested. Appendix 5 lists the HF frequencies that were tested. When a link was established the signal to noise ratio of the link was given a value by the RT-9000. This value was recorded on test sheets created specifically for underway testing. Appendix 6 shows the test sheets that were used. Unfortunately, the ALE capabilities only worked for the first three out of seven total tests. The transceiver faulted out of ALE during the four remaining tests. We were therefore unable to get quantitative measurements for the majority of the communications checks.

The second sub-test was a qualitative analysis of communications. USCGC TYBEE transmitted while Group Woods Hole received. A radio check was conducted and the quality of communications heard at the various frequencies were recorded in accordance with radio telephone PQS. Appendix 3 lists the terms used to describe the quality of the communications checks. All data from qualitative testing was also recorded on the test sheet.

Another item that must be addressed to determine if the towel bar antenna can be employed by the Coast Guard are measurements to determine if the radiation emitted by the antenna is within OSHA regulations for personnel exposure limits. The system requirements that had to be satisfied for this project are outlined in the Requirements Document shown in Appendix 7.

RESULTS

Testing thus far indicates that the NVIS antenna is a viable solution to the mid-range communication problem. Agreement between computer models and real world testing are encouraging and indicating the antenna functions as expected, however, further testing is necessary to fully support this claim.

We originally believed that the results of the land based impedance measurements suggested that the antenna worked as expected. A vector network analyzer was used to determine the reflection coefficients of the towel bar antenna at frequencies between 2-20 MHz. Then a MATLAB script file was written to calculate the driving point impedance of the antenna given the reflection coefficient at each frequency. This script file is given in Appendix 8. The values were plotted and compared to the previous year's modeled driving point impedance data. This is shown in Figure 5. The measurements that were taken to create the plot are given in Appendix 9.

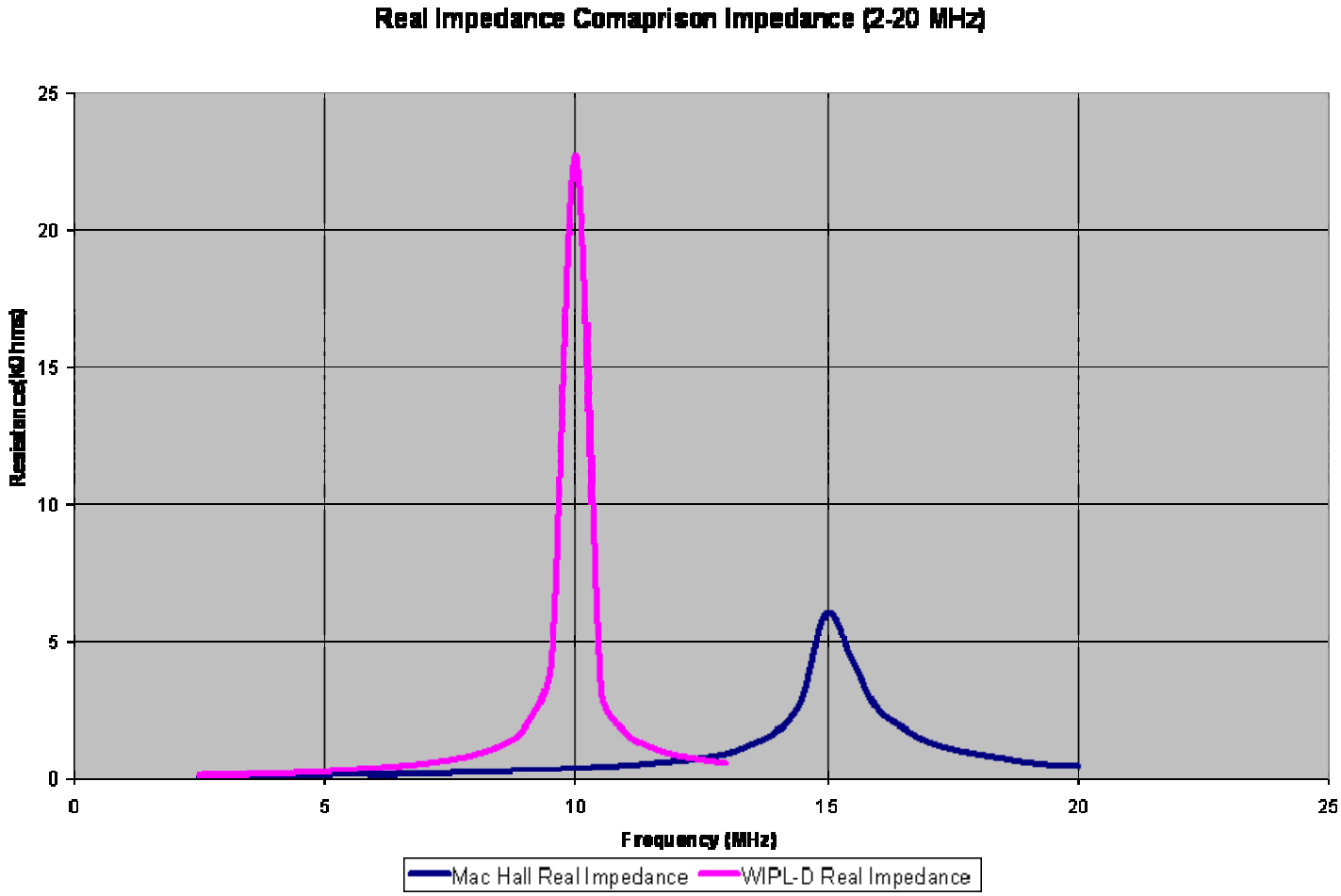

Figure 5: Real Impedance Comparison of McAllister Hall antenna and WIPL-D Model

Two major differences existed between the modeled and tested data. The first was that the magnitude of the driving point impedance at the resonant frequency in the observed data was substantially lower than that of the modeled antenna. The modeled data has a maximum impedance of approximately 22 kOhms, while the tested data has a maximum of only 6 kOhms. The second difference was that the resonant frequency for the modeled data occurs at 10 MHz; while the tested data's resonant frequency was 15 MHz. Initially we believed that these differences could be explained by comparing the differences between the WIPL-D model and the actual test antenna on the roof of the engineering building. The WIPL-D model assumed a perfect electrically conducting (PEC) structure for the ship and the antenna. The actual towel bar antenna on the roof of the building was made of aluminum. Additionally, the towel bar was bolted to an aluminum "I" beam that was not well grounded to the building's lightning arresting system. Thus, it seemed reasonable to expect the actual ground for the roof-top antenna to be much less efficient than the PEC hull of the patrol boat used in the WIPL-D model. We believed that if the WIPL-D model was adjusted to better reflect real conditions, it would match the results found from observing the land based NVIS, and we proceeded with land based testing.

We attempted to communicate with Group Woods Hole, but we were unable to transmit or receive using the roof set-up. We also attempted communications with local ham radio stations and operators, including Professor McKaughan on his personal radio. During the test we were able to successfully transmit, and on one frequency receive a transmission, but communication was not reliable, and we believe that successful attempts were due to the high power and close proximity of Professor McKaughan's station. We were also able to pick up transmissions on some HAM radio frequencies, and some powerful local transmission. Our inability to establish reliable communications with the land based antenna caused us to be concerned with the accuracy of the model and the impedance testing.

To try and resolve the antenna issues, we worked in conjunction with ESD Cape Cod to test the land based antenna with multiple different grounding and feed point configurations. Throughout the testing, the configuration used had little to no effect on the actual performance of the antenna. After the tests we determined that the most likely cause of the antenna's problems was its physical separation from true ground. Because it was mounted on top of a building over a solid rock formation, the antenna did not have a good ground plane to work with, no matter how the mounts are configured. To ensure that the issue was in fact with our antenna set up and not with our HF equipment, ESD Cape Cod took the RT-9000 back with them and tested it on their proven NVIS antenna network. Using their setup they were able to establish comms with other NVIS stations, proving that there was a problem with the land based antenna platform. Although the fact that our McAllister Hall based test had not been as successful as hoped, we believed that the antenna would perform as predicted when attached to the aluminum hull of a 110' WPB, as the large conductive surface along with the much shorter distance to the water would resolve the ground plain issue. ESD Cape Cod therefore took the second NVIS prototype with them, and had it installed onboard USCGC TYBEE.

After the antenna was installed onboard the USCGC TYBEE, the vector network analyzer was used to determine the reflection coefficients of the towel bar antenna at frequencies between 2-20 MHz. Then the MATLAB script file given in Appendix 8 was used to calculate the driving point impedance of the antenna given the reflection coefficient at each frequency. The values were plotted and compared to the driving point impedance data of a NEC4 model from previous years. This is shown in Figure 6.

Once the antenna was installed on the TYBEE we were able to conduct an underway test of the NVIS antenna. The testing lasted seven hours and consisted of a test round approximately every hour. Each round of testing consisted of two steps, an attempt at establishing an ALE connection, and a manual test of cycling through each of the ten test frequencies, and recording a sound quality analysis. The first portion of the tests suffered many technical difficulties throughout the day. During the first three tests, the

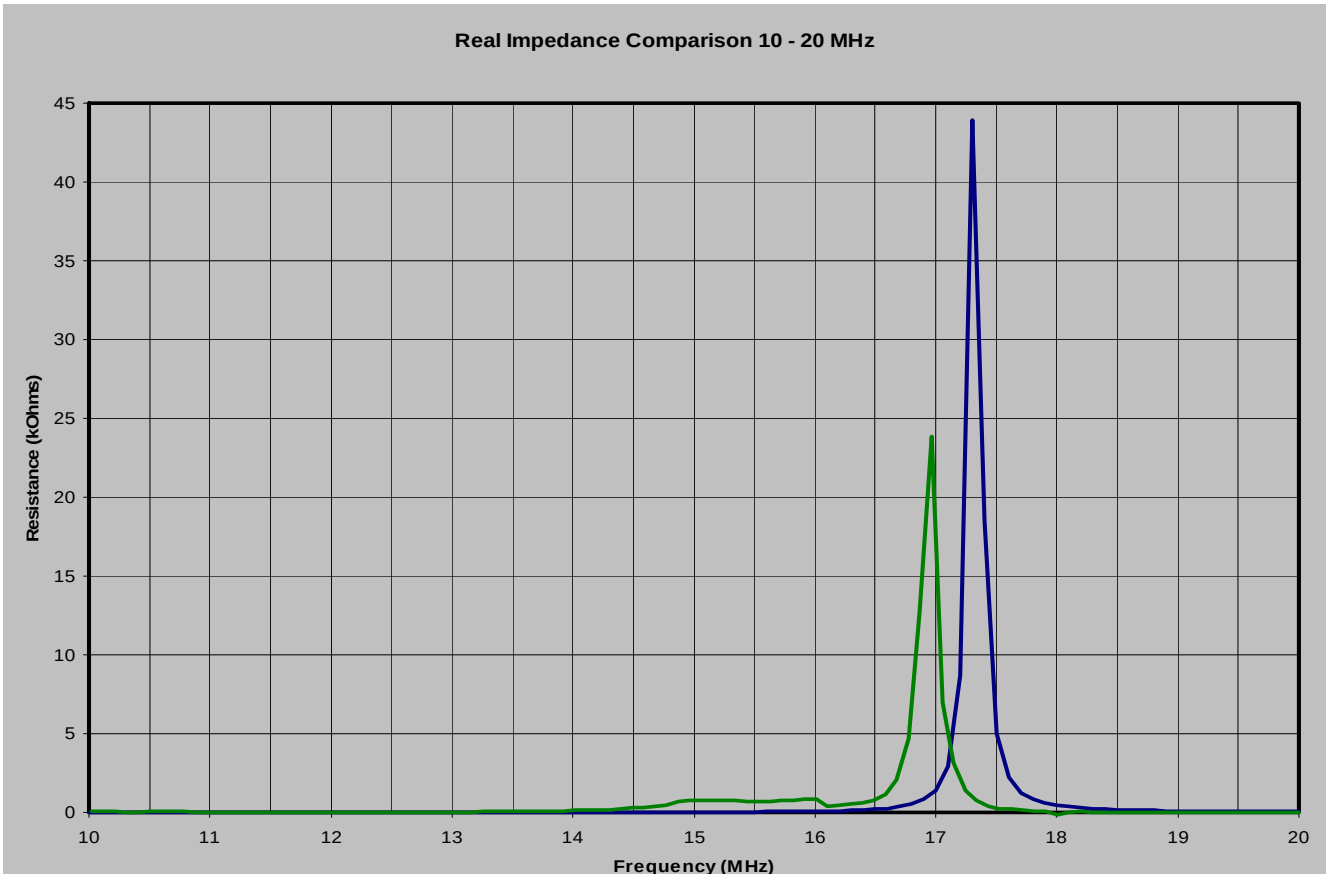

Figure 6: Real Impedance Comparison of TYBEE antenna and NEC4 Model

self ID for the Group Woods Hole transceiver was set incorrectly. This meant that the TYBEE transceiver as trying to find an ALE station that did not exist, making it impossible for a link to be established. Once the proper self ID was programmed, TYBEE and the Woods Hole transceiver were able to establish two strong ALE link ups. The linking process was both short and effective, requiring only one cycle through the test frequencies before establishing a link. Unfortunately, after the second successful connection the transceivers lost the ability to link up to one another. We have not yet determined the exact cause of the problem, but we believe that it was a matter of transceiver or system failure, not a problem with the antenna.

The manual frequency testing was much more consistently successful then the ALE portion. During the initial test attempt there was an error with the equipment onboard TYBEE that prevented their radio from transmitting at all. The error was quickly found and corrected, and from the second test through the seventh there were always at least two frequencies with readable and understandable communications. The results of the manual checks were recorded on scores sheets designed to allow for quick and simple recording of sound quality descriptions. The quality of a transmission was based on strength and readability. They could range from "Loud" to "Weak" and from "Clear" to "Unreadable; along with any combinations of the descriptors described in Appendix 3. Sound quality was recorded independently for both the TYBEE and shore side transceivers. When the data was being analyzed, the subjective descriptions were arranged and given numerical scores, with loud and clear or loud and readable signals scoring a four, and weak and broken or intermittent and unreadable transmissions scoring a one. The values for the 10 frequencies across the seven tests were then graphed using Excel. The graphs, cone based displays where the height of the cone is proportional to the magnitude of the score, for both sites are shown in figures 7 and 8. The results show that 4900 kHz, 6700 kHz and 13000 kHz all had consistently readable communications, and that at some point every frequency was readable. We do believe that the final test was in fact with range of the antenna's ground range, which is its values for every frequency are so high, but we still believe that the test as a whole shows that the antenna is capable is reliable mid- range communications.

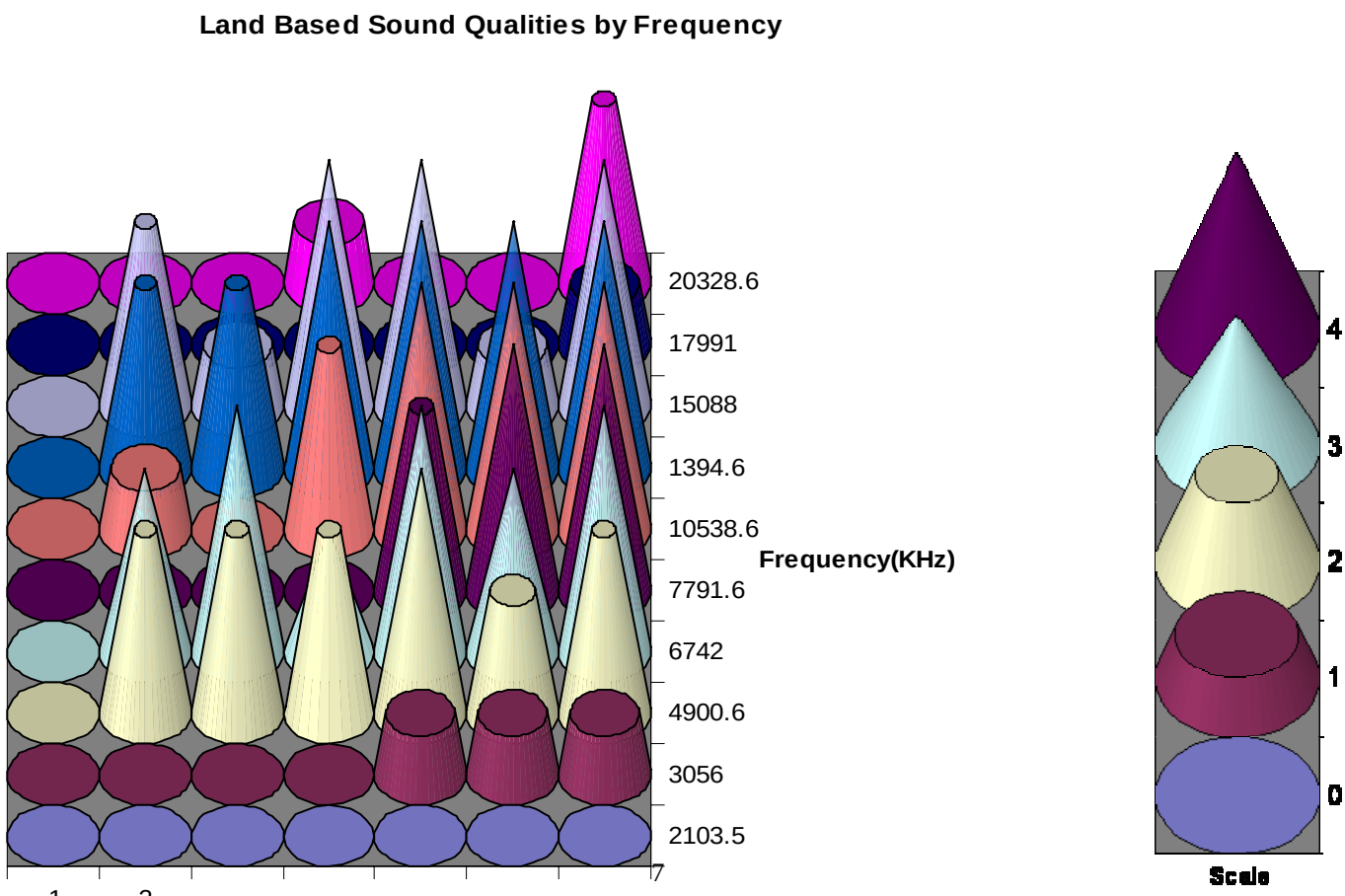

Figure 7: Shore Side Results

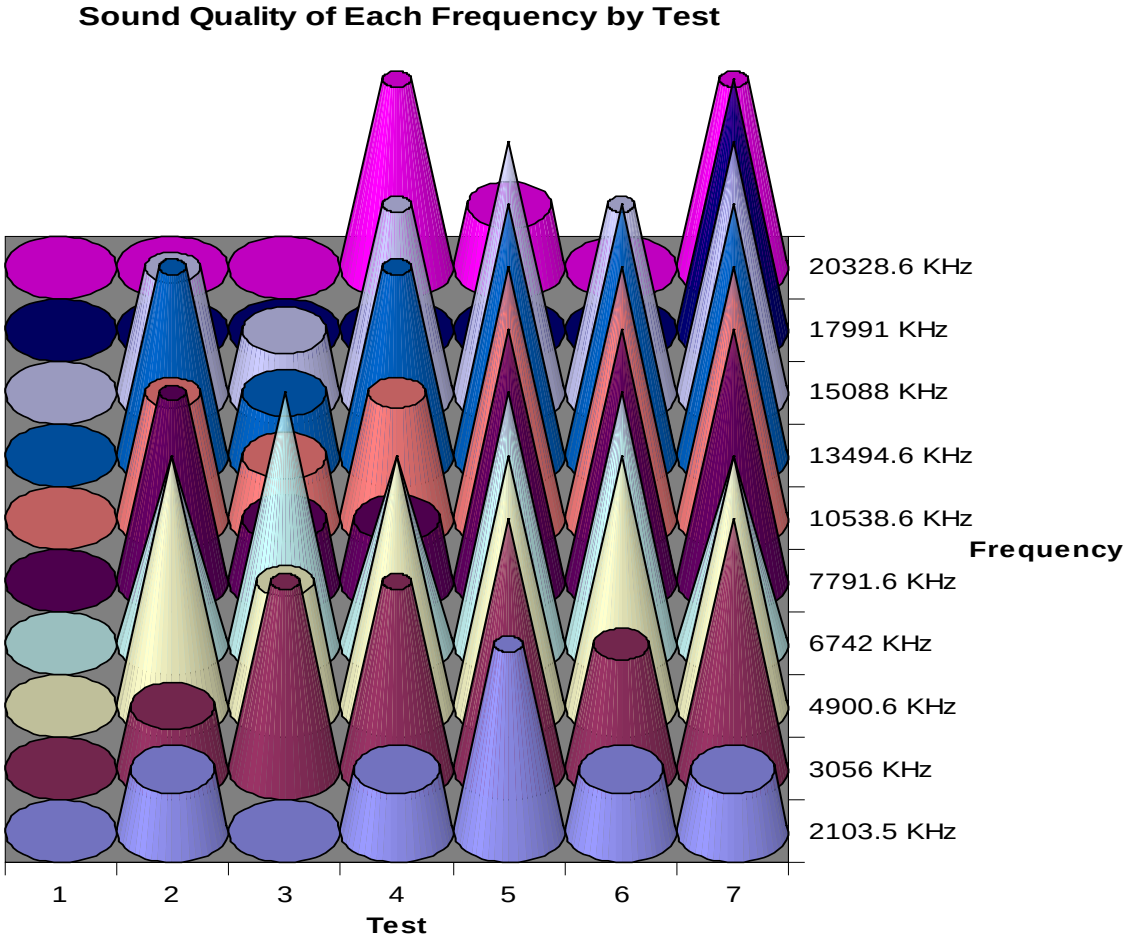

Figure 8: TYBEE Results

CONCLUSION

The ultimate goal of the project was to test a NVIS antenna on a Coast Guard 110' WPB cutter and determine if it is a solution to the mid-range communication problem. Underway testing was accomplished in late February 2006. Analysis of tests indicates that a towel bar NVIS antenna will correct the mid-range communications problem. Antenna characteristic measurements matched computer modeled data. In addition, underway tests were successful, and clear communication was possible. Agreement between modeled data and real world testing, in conjunction with clear communications using the NVIS antenna suggests that the NVIS antenna will provide coverage in the range of 50-500 NM. Unfortunately, the limited availability of 110' cutters, for prototype testing, prohibited testing over 50 NM. The test furthest from Woods Hole, MA was just under 50 NM. Further, tests are necessary to determine if the towel bar antenna truly improves mid-range communication. Similar tests, to those that we conducted on our transit from Provincetown to Woods Hole, at distance greater than 50 NM are necessary to make a definitive statement on the capabilities of the antenna.

Another test that would demonstrate the capabilities of the antenna would be to run a communication check with the whip antenna, and then a communication check with the NVIS antenna at varying distances from a land based communication site. A comparison between communication quality using the whip antenna and the NVIS antenna would demonstrate whether the NVIS antenna provided communication coverate in the areas that the Whip antenna does not.

More computer modeling would increase confidence in our real world results. Currently, computer modeling done in WIPL-D does not match modeling using NEC4 and real world measurements. If the 110' WIPL-D model was redone using a non-perfectly conducting medium for the boat hull, if sea water were accounted for, and if items such as couplers and the mast were included we believe that the WIPL-D model would be much closer to NEC4 and real world data.

Overall, the goal for this semester was met. Underway testing was completed, and analysis of results is encouraging. With more mid-range testing and modeling the Coast Guard may have a lower cost, effective solution to the mid-range communication problem effecting 110' WPB class cutters.

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APPENDICES

1. Project Plan
2. Engineering change Proposal
3. Qualitative Communications Check Descriptors
4. Test Plan
5. HF Test Frequencies
6. Test Sheet
7. Requirements Document
8. Script File
9. McAllister Hall Impedance Measurements