



Vivaldi Wire Antennas with Direct Write Technology

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*Program Information:*

National Science Foundation

Grant NSF #EEC-1359476

Research Experience for Undergraduates

Summer 2015

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## Abstract

The Vivaldi antenna was designed in 1979 by PJ Gibson (Gibson, 1979). Our focus is to take this design and adapt a single wire to the profile designed by Gibson. Our antennas were designed, simulated, tested and compared to a vee dipole of a  $45^{\circ}$  angle using various software and devices. For this comparison, the Vivaldi and vee are the same wire length. Some Vivaldi antenna designs have resistive loading added to improve frequency bandwidth performance. The values derived from the simulations and testing are compared to measure the success of the project.

## 1. Introduction

In this Project, direct write technology was used to “print” Vivaldi wire antennas on flexible polyimide substrates. The Vivaldi antenna was designed by P.J Gibson in 1979 (Gibson, 1979), it is an exponentially expanding slot antenna (see fig 1). For this project, a single trace or wire will be fabricated using the Vivaldi profile. This approach to the design will save material and time in the fabrication process. In addition, resistive loading will be used on some antennas. Resistive loading reduces the signal reflecting back down the trace from the open end of the antennas. Before fabricating antennas, the Numerical Electromagnetics Code (NEC) modeling program is used to simulate the antennas. The input resistances and reactances of the Vivaldi antennas are compared to vee dipole antenna of the same wire length.

Our goal is see how the antennas perform when compared to each other with and without resistive loading. As a secondary goal, we will demonstrate how easy it is to fabricate these antennas with direct write technology. The results of the NEC simulations decide which antennas to fabricate and test. The input resistance and reactance values are used to see how the actual antennas perform when compared with the simulations.



Figure 1 Vivaldi UWB antenna Image courtesy of <http://www.uwbs.ru>

## 2. Broader Impact

This project will have a very broad impact. For example, the ability to rapidly prototype antennas will quicken research efforts and allow for replacement of antennas rapidly. With the

advancement of printing technology, we can rapidly replace designs that would have taken weeks to design and construct using traditional fabrication techniques. With the use of flexible substrates, the antenna can be used in many design applications which require antennas that are flexible such as aviation, wireless communication (Greenberg, Virga, & Hammond, 2003), and various imaging applications (Yang, Wang, & Fathy, 2008).

### **3. Procedure**

#### **3.1 Materials**

The following materials were required to achieve the goals:

Polyimide substrate sheet

Method Developments 6130F conductive ink

Method Developments Goldstone 3100 resistive ink

Low temperature solder paste (138<sup>0</sup>C)

SMA connector

#### **3.2 Equipment**

Specific equipment was needed to gather the measurements, create the antennas, and analyze the results. This equipment is as follows:

nScript Micro Dispense Direct Write (MDDW) printer (Figure 2)

MATLAB software

AutoCAD software

Numerical Electromagnetics Code (NEC) version 2.0

Laptop PC

Convection curing oven

Soldering station

Agilent 4396B Vector Network Analyzer 50 MHz to 1.8 GHz

Agilent 85046A S Parameter Test Set

Agilent 85033E Calibration Kit 3.5 mm



Figure 2. nScript direct write device used to print the antennas

### 3.3 NEC analysis of antenna

Various antenna designs were simulated to see if they warranted construction. In this case, the Numerical Electromagnetics Code (NEC), a Method of Moments based software package, was used. To utilize NEC, an input text file that describes the antenna geometry and desired results must be written. MATLAB was used to generate many of the lines of code that form the portion of the input text file describing the geometry of the antennas. Additional comments and test parameter (e.g., frequency range, gain, impedance) lines were entered manually. The input text files were then ready to be read into the NEC program.

The resistance, reactance, and gain values produced by NEC were entered into Microsoft Excel for cataloging. MATLAB presents, in graphs, the collected resistance, reactance, and gain values over the range of frequencies simulated. These simulations were performed for all antenna designs. For the simulations, the antennas were initially assumed to be in free space, made of perfect conductors for the conductive portions, and dipoles. Later, conductance and/or resistance per meter values for the conductive portions antenna arms are inserted into the coding of the NEC input text file to better match the actual antennas. This information was not available until the antennas were fabricated. Based on the simulation results, the decision on which antennas to fabricate was made. The decision was made to fabricate a vee 100% conductive (Figure 3), Vivaldi 100% conductive (Figure 4), Vivaldi 50% resistive (Figure 5), Vivaldi 25% resistive (Figure 6), and Vivaldi 12.5% resistive (Figure 7) monopole antennas. All the antennas had wire lengths of about 250 mm. The DC resistances of the resistive portions of the arms of the antennas with resistive loading were measured. The resistances were 3181  $\Omega$  for the 50% resistive antenna, 1848  $\Omega$  for the 25% resistive antenna, 1131  $\Omega$  for the 12.5% resistive antenna.

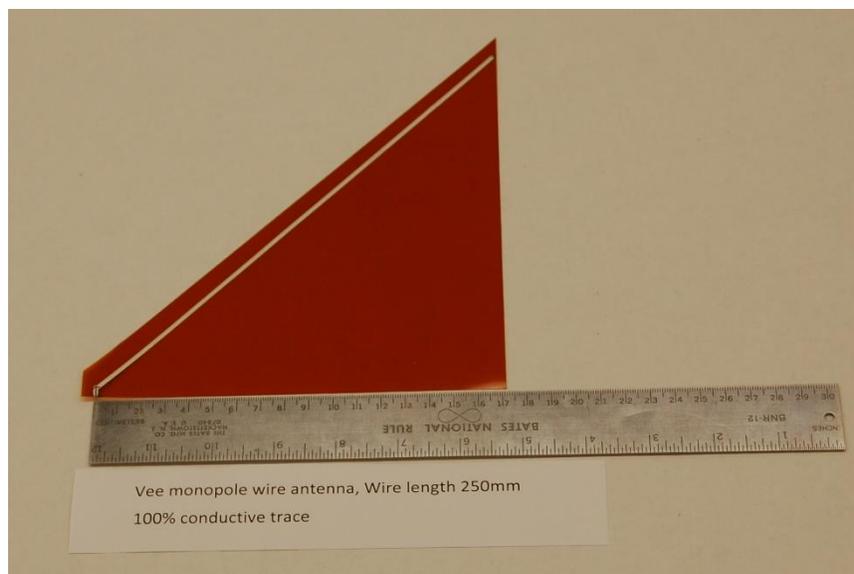


Figure 3. 100% conductive vee antenna

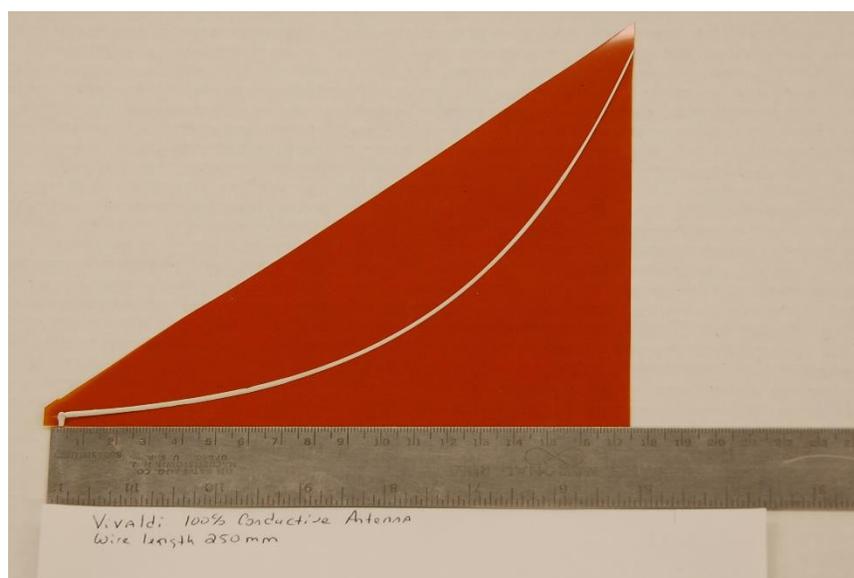


Figure 4. 100% conductive Vivaldi

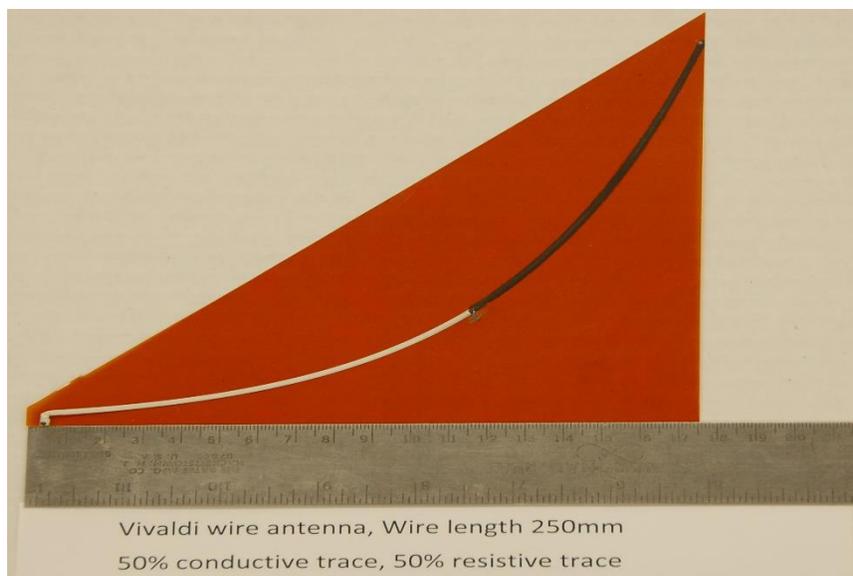


Figure 5. 50% resistive Vivaldi antenna

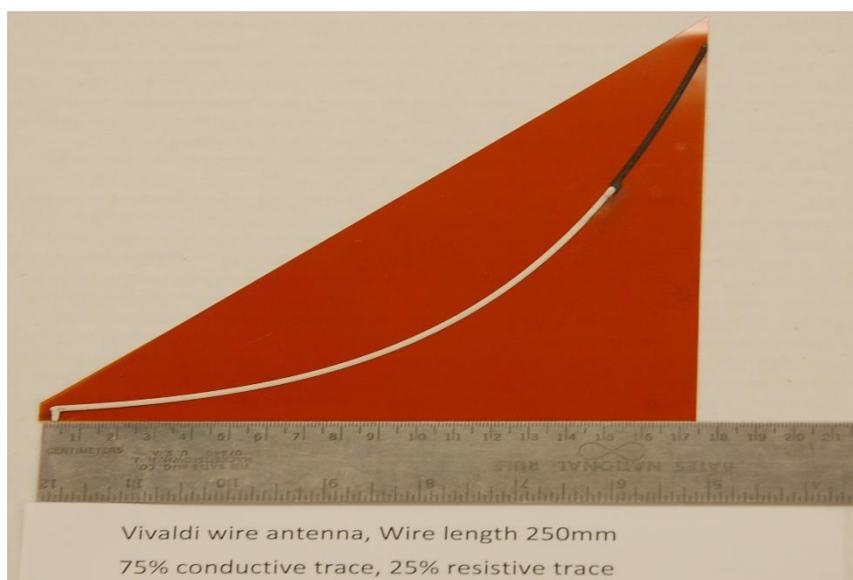


Figure 6. 25% resistive Vivaldi antenna

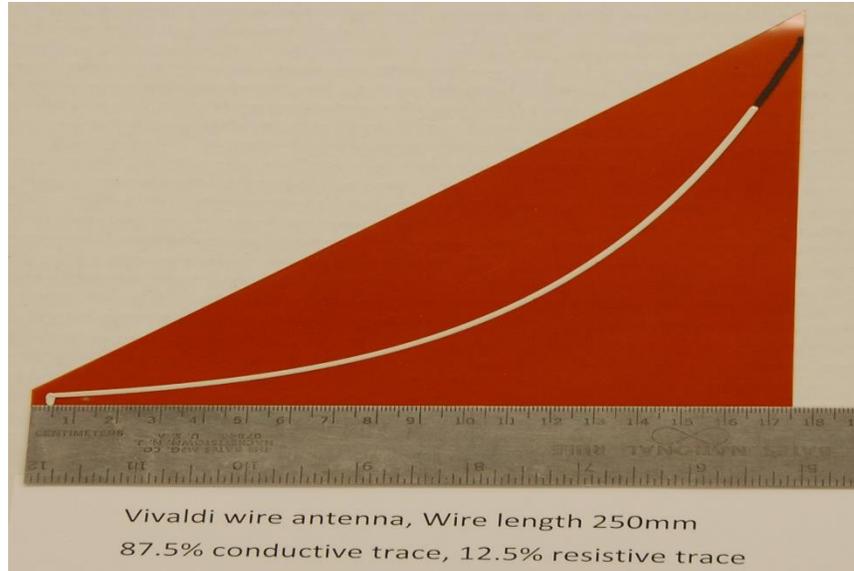


Figure 7. 12.5% resistive Vivaldi antenna

### 3.4 2D model antenna

The process making a 2D model of the antennas required a lot of attention to detail. This process required MATLAB to calculate the shape, output lines for the simulation text files, and output the text for the script file to be used in AutoCAD. This script file consists of  $x$  and  $y$  coordinates of the endpoints of the segments along the antenna arms calculated by MATLAB. The PLINE command is used to formulate the line that is drawn by AutoCAD. Our equation for calculating the Vivaldi profile is

$$y=A*\exp(p*x) \text{ (Gibson, 1979) (see Figure 8)}$$

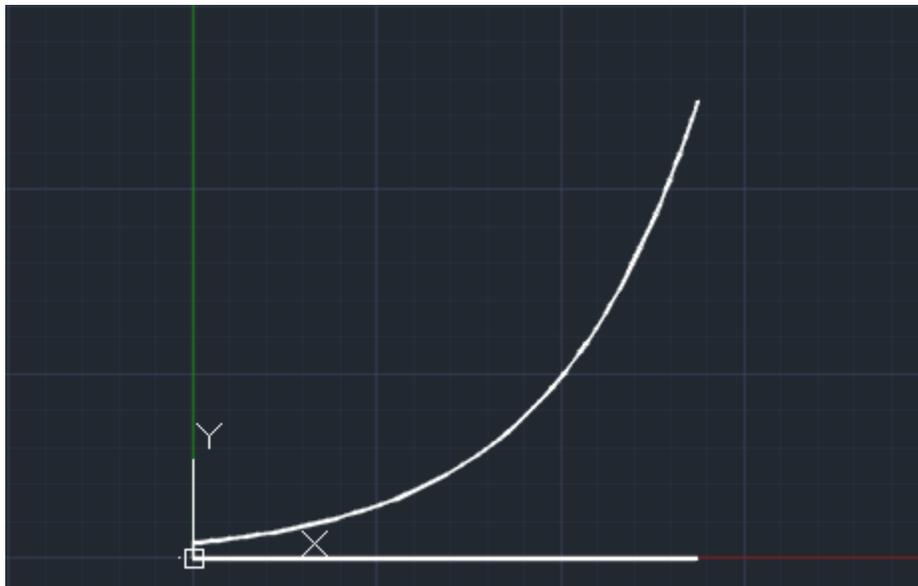


Figure 8 Vivaldi curve from equation

Here,  $x$  and  $y$  are the Cartesian coordinates of the Vivaldi profile.  $A$ , in this case, is the measurement of the  $y$  distance from the end of the center conductor of the SMA connector to the ground plane. For this case, it is 5.08 mm. This distance  $A$  is the opening for the antenna at its smallest point and allows the antenna to be soldered to the SMA connector. The value  $p$  is the expansion rate of the exponential curve. This was calculated as 0.019924, this value has no units, in order to achieve a wire length of 250 mm. Using MATLAB, the spacing of  $x$  values was selected to break the Vivaldi profile into roughly eighty equal length linear segments for the sake of the NEC simulations.

### 3.5 Constructed antennas

The 2D drawing from AutoCAD is imported into the PathCAD software. This PathCAD software outputs the file format used by the nScript printing device. This device uses air pressure to dispense material through a syringe directly onto the polyimide (Figure 9). The traces measured roughly 2 mm in width. The width of the printed trace is controlled by the amount of air pressure that is set in the path file. For the conductive ink 6130F, a pressure setting of 8.75 psi was used. For the resistive ink Goldstone 3100, a setting of 26.25 psi was used. The traces were compared to ensure that the pressures would create a trace width that was similar. It is important to note that the height of the syringe above the substrate is set by the nScript device and recommendations are that it be left at 250 microns. The process of creating the traces was to print the conductive portion of the trace first. The next step was to cure the conductive portion of the trace before printing the resistive portion of the trace. The last steps were to print and cure the resistive trace.

The most difficult part of the process was the printing of the resistive ink traces. The two traces, conductive and resistive, were printed at different steps to avoid mixing the conductive and resistive inks. This process requires special attention. In order to match the ends of the resistive and conductive traces to each other, you must follow an exact procedure. The portions of the traces that are resistive are the continuation of the Vivaldi profile. The same profile would need to be followed had they been printed at the same time. First, the nScript device must be calibrated. These procedures are available in the publication provided by Mr. James Randle of the Direct Write Laboratory (DWL). Once the calibration is complete, a camera mounted on the nScript needs to be calibrated to the syringe. This is done by setting the tip of the syringe on a black dot on a photocopy paper square located in the back left corner of the printing plate. Additionally, in the software, you must load, or switch to, the camera and set its cross hairs over the dot on the paper. Once both of these are calibrated to the dot, the beginning of the trace that was printed previously can be located. Due to the fact that the substrate is no longer oriented in the same direction as when the conductive trace was printed, set the dry run variable to *true*, in the software. This option is on the run controls of the nScript device. After you have completed several dry runs to ensure that the trace will continue as it should, change the dry run variable to *false*. The ink will now dispense along the path that the dry run completed. It was found useful to teach the points of the start of the trace for the conductive ink as well as the resistive ink.

The curing process was done in stages. After the conductive portions of the antenna were printed, they were placed in the oven to cure at 138°C. The curing time was approximately five

and a half hours. This time was the least amount of time a trace could cure given the oven needed two hours to heat and two hours to cool. The time spent at  $138^{\circ}\text{C}$  was one and a half hours. The cure time was taken from Andrew Downs's thesis (Downs, 2010). The resistive traces were cured in the same manner.

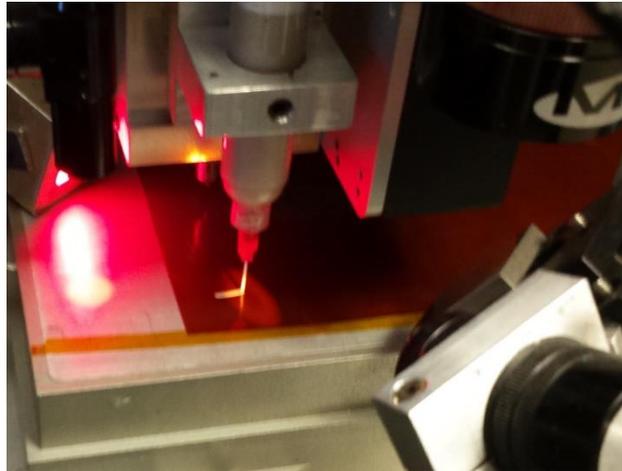


Figure 9. nScript device printing the Vivaldi conductive trace

### 3.6 Testing the antenna

Coaxial transmission line feeds are preferred for experimental testing, chief among which is that Vector Network Analyzer (VNA) uses coaxial transmission lines. Therefore, the tested antennas were monopoles fed by a coaxial cable through a ground plane. By image theory, the monopoles produce radiation patterns above the ground plane equivalent to full dipole antennas while having an input impedance half that of dipoles. To reduce reflections, carbon loaded foam was placed around the edges of the ground plane to absorb radiated energy.

Figure 10 shows an antenna setup for testing in the lab. In order to test antennas, they need to be soldered to the SMA bulkhead connector located in the middle of the roughly 48" square ground plane. This was done using a solder paste ordered based on a low setting temperature of  $138^{\circ}\text{C}$ . The solder paste is applied to the 5.08 mm section of the antennas (see lower left portion of Figures 3-7). To solder the connection, a soldering iron set at  $450^{\circ}\text{C}$  was used. This process had to be done very carefully because polyimide will melt at  $250^{\circ}\text{C}$ . The soldering of the connection took only a few seconds and the polyimide substrate was unaffected. The SMA to antenna connection was tested with a Tenma True RMS DMM 72-410A digital multi meter to ensure continuity.

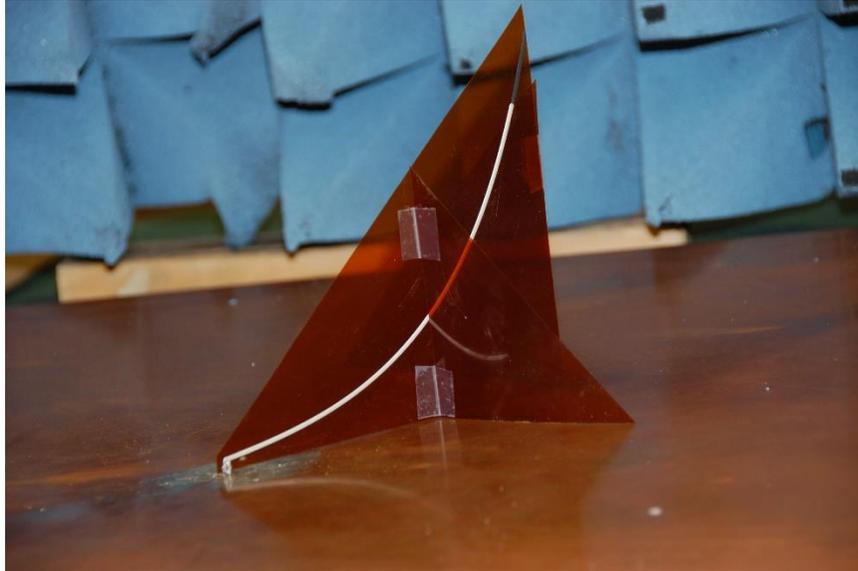


Figure 10. Vivaldi 1/8 resistive loading in the testing lab

Our last step with the antennas is to test the finished antennas with a VNA that has a range of 50 MHz to 1.8 GHz. The VNA was calibrated to remove the effects of the coaxial lines and SMA connectors which connect it to the antenna. Once the calibration is completed, the antenna was tested. The range of frequencies tested was from 50 MHz to 1.8 GHz at 50MHz intervals. The measured values of  $S_{11}$ , or reflection coefficients, versus frequency from the VNA were saved and then input into Microsoft Excel for cataloging.

In order to make comparisons with the input impedances found using the NEC software during the simulations, the  $S_{11}$  test data had to be processed. To process the data, the  $S_{11}$  values were input into the equation below:

$$Z_{ant} = Z_0 * (1 + S_{11}) / (1 - S_{11})$$

In this equation,  $Z_{ant}$  is the input impedance value of the tested monopole antennas, a complex number.  $Z_0$  is the characteristic resistance value of the cable used to connect the VNA to the antenna, here it is 50  $\Omega$ . The resistance is the real portion of the impedance and the reactance is the imaginary portion of the impedance. MATLAB was used to plot the values of resistance and reactance versus frequency.

Additionally, the resistance, reactance and frequencies of the simulated values must be adjusted for true comparison. The resistance and reactance values from the simulated dipoles must be divided in half to allow comparison to the experimental monopoles. Also, the frequencies from the simulations must be divided by the square root of the effective permittivity constant of the experimental antennas on a polyimide substrate surrounded by air to allow comparison. The effective permittivity constant was observed to be 1.3. With these calculations, the input resistance and reactances of the experimental antennas were examined to see how the antennas performed with respect to the simulation data.

## 4. Results

### 4.1 Resistance

The input resistance of the antennas was graphed for the simulated data (see figure 11) and the measured data (see figure 12). At first, these two graphs were similar in pattern, but greatly different in magnitude. This difference is explained by the way the antennas were initially simulated. In the simulations, the software assumed that the conductive portions of the antennas were perfect electrical conductors. However, the silver-based 6130F conductive ink is not a perfect conductor. Using NEC to vary conductance values for the conductive portions of the simulated antennas, the conductance value of the tested antennas was found to be approximately  $3.0 \times 10^3$  S/m. By simulating the antennas with this conductance value, we have reasonable agreement between the simulated and measured data. Note that increased resistive loading (e.g., from 1/8 resistive to 1/2 resistive) on the antennas reduced the variations in the input resistance values.

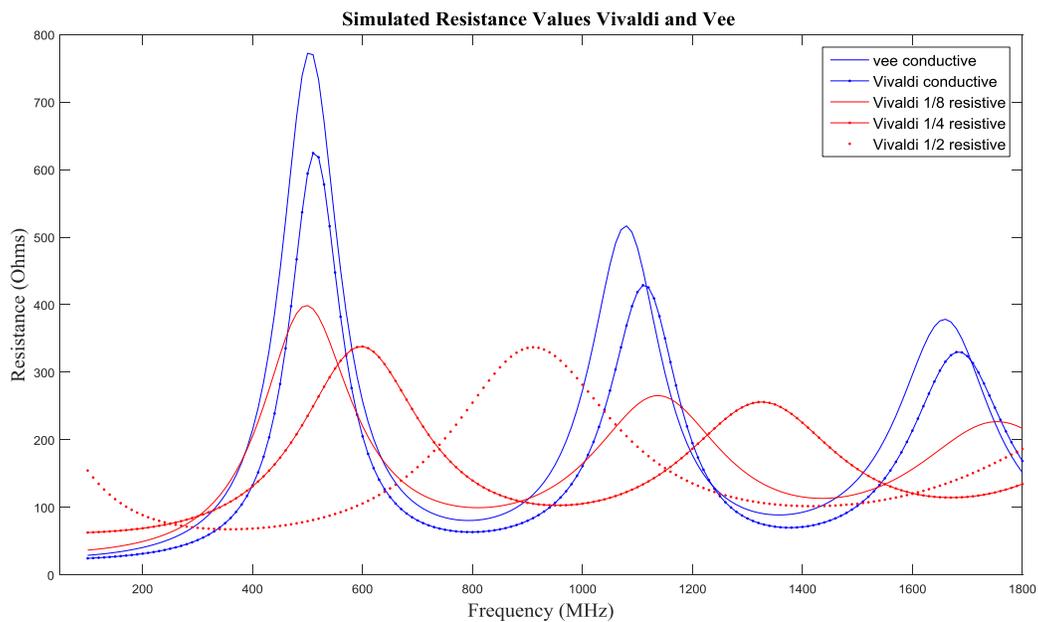


Figure 11. Simulated values for the resistance of the antennas after conductance corrections

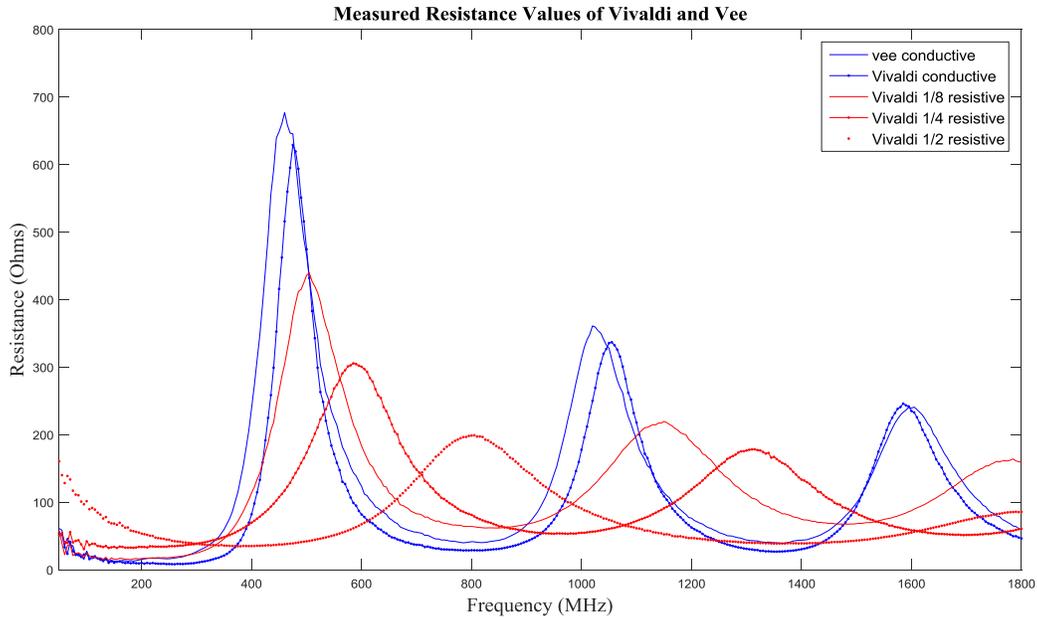


Figure 12. Measured values for the resistance of the antennas

#### 4.2 Reactance

The input reactance was also graphed for the simulated (see figure 13) and measured (see figure 14) antennas. As with the resistance values, initially the simulation assumed that the conductive portions of the antennas were perfect electrical conductors. Again, the simulated antenna models were adjusted for true comparison.

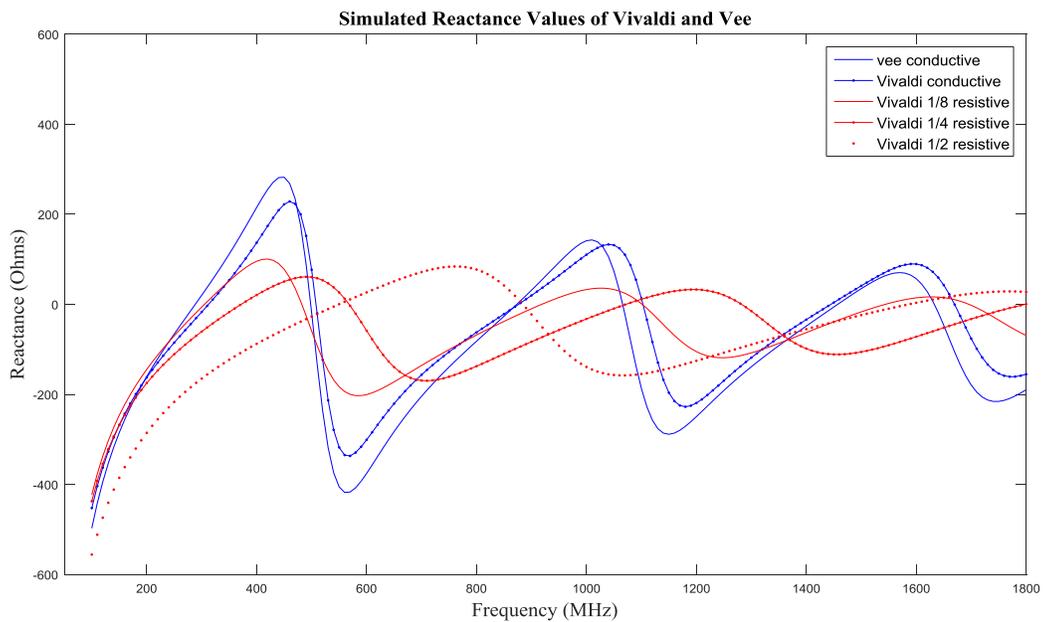


Figure 13. Simulated reactance values for the antennas after conductance corrections

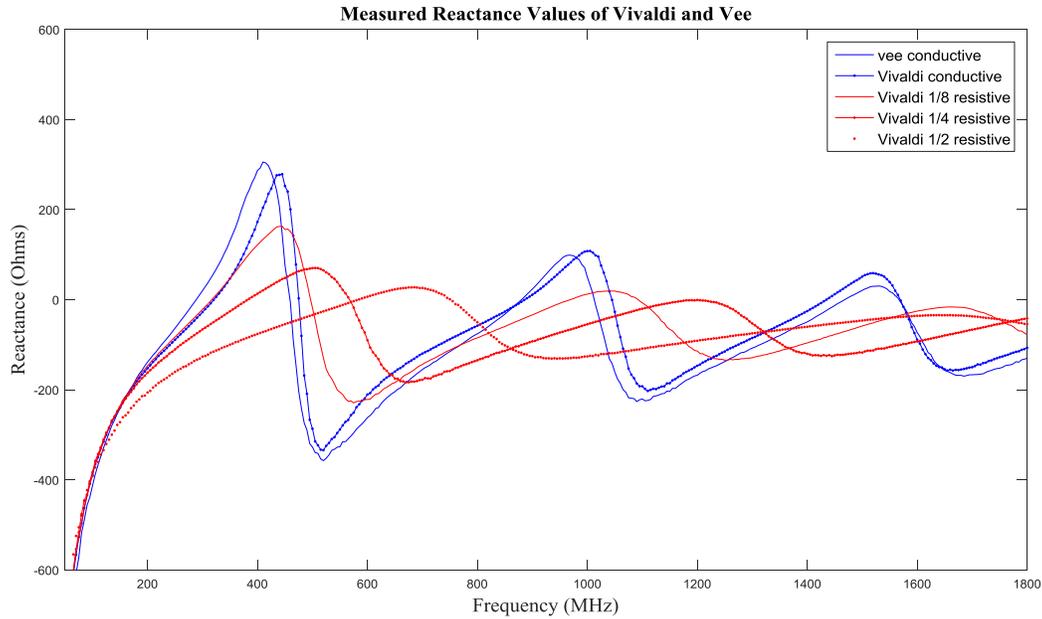


Figure 14. Measured reactance values for the antennas

### 4.3 Gain

Gain is one of the most important characteristics associated with an antenna. Gain is a measure of how much input power the antenna radiates in a particular direction. In Figure 15, the boresight gain of the simulated antennas is shown versus frequency. The tested antennas were not measured for gain, therefore we do not display that data. As expected, increasing amounts of resistive loading decreased the gain of the antennas

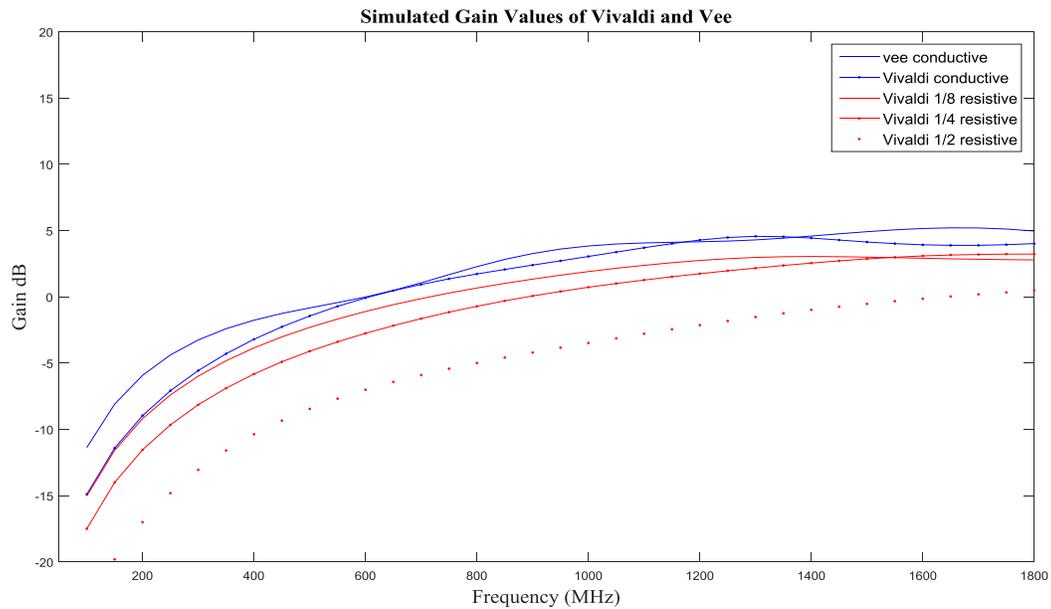


Figure 15. Simulated Gain values for the antennas

## 5. Conclusion

The Vivaldi profile wire antennas have been simulated, manufactured, and tested throughout this project. The process of manufacturing antennas, by direct write technology has been reasserted in this project. Overall, five antennas were successfully prototyped, tested, and compared with simulated data. The data shows that given the process is sound and the fabricated antennas perform as expected from simulations using the NEC software.

In addition, it is expected that the Vivaldi wire antenna will perform well at higher frequencies than tested. In the future, the antennas should be tested at these higher frequencies to validate this expectation. The process overall was very daunting. The coordination of several departments went very well and the equipment performed equally as well. In retrospect, an attempt to print the conductive and resistive portions of the traces at the same time should have been made. This would allow for less time spent in the curing process. In addition, a protective coating might be applied to the antennas as they became very brittle after a few days. Also, testing antennas with lighter resistive loading might be beneficial.

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### Acknowledgments

The National Science Foundation funded this research under the provided grant. Many Thanks to Faculty Advisors Dr. Thomas Montoya, REU Site Director, Electrical Engineering and Physics Department and Dr. Alfred Boysen, Professor, Department of Humanities for their constant guidance and direction. A special thank you to my colleagues and fellow students in the research undergraduates program.