Developments in the Teaching of Engineering Electromagnetics for Improvement in Student Interest and Understanding

Ms. Lauren E. Donohoe, Department of Electrical Engineering at The Pennsylvania State University

Lauren Donohoe received B.S. Degrees in both Electrical Engineering and Physics from the Pennsylvania State University in 2014. She is currently a M.S. student in Electrical Engineering at the Pennsylvania State University.

During her graduate studies in electrical engineering, she researched and implemented teaching methods to stimulate interest in students. She chose to perform education and learning research in the STEM academic discipline of engineering education, specifically targeting the development of better teaching methods for engaging students in the applications of electromagnetic theory. This research has been culminated in the development of a laboratory component for the undergraduate engineering electromagnetics course at Penn State. The laboratory activities were designed to give students as many chances as possible to gain hands-on experience with real-life tools, measurement devices and analysis techniques.

Dr. Julio Urbina, The Pennsylvania State University - University Park

JULIO V. URBINA, Ph.D is an Associate Professor in the School of Electrical Engineering and Computer Science at Penn State. His educational research interests include effective teaching techniques for enhancing engineering education, global engineering and international perspectives, thinking and working in multi-, inter-, and transdisciplinary ways, cyberlearning and cyber-environments, service and experiential learning, teaming and collaborative learning.

Dr. Tim Kane, The Pennsylvania State University - University Park

TMOTHY J. KANE, Ph.D is Professor of Electrical Engineering and Meteorology at Penn State who teaches the undergraduate engineering electromagnetics course, EE 330. His educational research interests include developing course materials for enhancing engineering education, collaborative learning, and increasing student involvement.

Dr. Sven G. Bilen P.E., The Pennsylvania State University - University Park

SVEN G. BILÉN, Ph.D., P.E. is Professor of Engineering Design, Electrical Engineering, and Aerospace Engineering at Penn State and Head of the School of Engineering Design, Technology, and Professional Programs. His educational research interests include developing techniques for enhancing engineering design education, innovation in design, teaching technological entrepreneurship, global product design, and systems design.

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Abstract

This paper discusses the motivation for, procedure behind, and results of revamping the laboratory component for the introductory engineering electromagnetics course at The Pennsylvania State University. In this course students spend two hours every week complementing what they have learned in lecture and practiced in homework problems with hands-on experience using modern tools and technology to solve real-world problems. Measured using pre- and post-lab surveys, the student responses to these new laboratory activities demonstrate a significant increase in both interest and understanding of topics in electromagnetics.

I. Motivation

Electrical engineering is a broad field with many specializations. Of the many specializations — electrical circuit design, power systems, communications, computer hardware and software, signal and image processing, control systems, optics and lasers, and electromagnetics, among others — some are more commonly chosen by students than others.[1]

Electromagnetics is often perceived by students as being too highly mathematical, conceptual, and theoretical in nature.[2] With a reputation of being difficult and demanding, electromagnetics has become one of the least popular undergraduate specializations within electrical engineering programs.[3] Introductory classes in electromagnetics focus on the study of Maxwell's equations, the fundamental equations governing electromagnetism.[1] The broader field of electromagnetics also encompasses antenna theory, radar systems, and the relations between electric and magnetic fields.[4] The applications of electromagnetics allow us to listen to music on the radio, to receive satellite television via a dish antenna on the roof of our house, to determine our location through GPS signals broadcast from satellites, and to converse via cell phone with someone on the other side of the country or the world. In addition to their highly theoretical nature, textbooks on the subject often lack connection to real-world engineering issues.[5] While some sparse analogies can be drawn between electromagnetic waves and real waves on a string, electromagnetic theory is extremely challenging to visualize and, therefore, has historically been both difficult to teach and difficult to learn.[3]

At The Pennsylvania State University, the introductory engineering electromagnetics course for undergraduates (EE 330) is taught by a different instructor each semester with five to six instructors in the rotation. Concepts such as transmission lines, static and time-varying electric and magnetic fields, antennas, electromagnetic radiation and wave propagation have historically been taught through lectures and textbook problem-solving sessions. About a decade ago, a set of eight MATLAB-based computer "labs" were added to the course to begin to address the need for more exploration into real-world problems. At the time, however a physical laboratory component was not possible due to limited resources. Since then, some instructors have included a subset of four of the labs, whereas others have skipped the laboratory component of the course altogether. These labs, largely unchanged over time, each include a well-defined problem with

simulation data and skeletal MATLAB code provided. The students report to a computer lab to complete the lab activities, following a set of pre-defined steps to fill in the skeleton code and answer questions along the way.

The problem is that this teaching structure lacks a concrete connection to applicable, hands-on examples, a primary factor in developing students' interest in electromagnetics.[5] Without this connection, many students develop the impression that these mathematically-based theories are not of practical use and subsequently avoid more advanced courses in electromagnetics. As modern wireless technology advances, engineers with a strong understanding of electromagnetics become more and more valuable. Low undergraduate interest and high demand for graduates specializing in electromagnetics poses a problem[3] and is an example of the system of education in America devised for a world that increasingly does not exist.[6] The need for better alignment between engineering curricula and the nature of academic experience, with the challenges and opportunities graduates will face in both research and the workplace, is one of the primary reasons behind the National Academy of Engineering Committee on Engineering Education's report *Educating the Engineer of 2020*. This book summarizes the issue by stating "as time progressed, a disconnect between engineers in practice and engineers in academe has developed and grown. The great majority of engineering faculty, for example, has no industry experience. Industry representatives point to this disconnect as the reason that engineering students are not adequately prepared, in their view, to enter today's workforce."[7]

II. General Approach

Just as the world is continually transforming due to the advance and growth of communication technologies, the methods by which we teach engineers must adapt and evolve.[5] While teaching procedures and practices that have been used for decades have considerable strengths will endure into the future, there are also many weaknesses that require new teaching methods to adequately address. As engineering educators, we not only need to convey information, but must also provide students with different learning styles and diverse backgrounds the means to develop the skills required for a broad range of career paths, from teaching and research to design, industry and production.[8]

Three of the most important abilities for engineers — logical reasoning, critical thinking, and problem solving — are some of the toughest to teach. In addition to these abilities, developing a command of electromagnetics requires the ability to visualize and manipulate fields and vectors in three dimensions, making this subject one of the most difficult to teach within the field of engineering.[9] Usually, individuals who are highly educated in the subject, such as instructors, have spent many years developing intuition and visualization methods that aid them immensely in solving electromagnetics problems. Many of these same instructors resultantly ask questions in which the students need to rely on an intuition they have not yet formed.[1] As electromagnetics instructors, we need to develop methods that enable these students to develop the intuition necessary to understand electromagnetics. One of the reasons that many students perceive introductory electromagnetics as the most difficult class they have ever taken is that we, as instructors, fall short of our responsibility in helping them to build this intuition.

Throughout the ages, from philosophers like Aristotle to present-day engineering and science education researchers, there is general agreement that students learn by doing. This is reflected in the aphorism "Tell me and I forget, teach me and I may remember, involve me and I learn"[10] [which is often misappropriated to Benjamin Franklin, but likely derived from writing of the Chinese Confucian philosopher Xunzi (312–230 BC)]. While it is true that information and equations can be learned by reading, memorization, or listening to someone else speak, these are not the best methods to build intuition. Intuition is built through experience, learned by doing, and reinforced through practice. The processes of learning and doing are inseparable.[6] The complexity of topics taught limits the ability for students to "learn by doing" within the time-restricted classroom setting.[5] In addition, the cost of testing and measurement equipment used in the electromagnetics field often limits what can be done. While it is possible to develop simplistic analogies and demonstrations that convey some of the basic topics in electromagnetics in a more elucidating manner, the need for hands-on work by the student is apparent.[1] With a goal of attracting students to the field of electromagnetics and motivating them to learn, researchers have found a heavy emphasis on lab activities to be indispensible.[11] In addition to the concept of learning by doing, the ideal learning environment in which students take the most away from a class is only present when the students *want* to learn. These learning environments exploit teaming, active learning, and problem solving experiences and can be enriched using hands-on project-based learning.[10] Even the best students often do just enough to pass an exam, after which they forget everything they learned. The material taught in a course quickly fades unless the student has applied the knowledge in some way. There are two things that stay with students after a class ends: the interactive and stimulating hands-on experience they gained practicing the use of some instrument or software package, and any material that was of particular interest to them. This is why it is as important to spark interest, building motivation for students to learn the desired material, as well as to provide relevant hands-on activities.

Excitement is contagious. One of the most important characteristics of a good teacher is the ability to make the material exciting. Just as a topic can be presented in an exciting manner in order to draw in students and keep them curious, the same topic can be presented in a manner such that the students would rather "watch paint dry". Teachers do more than just aid in the learning process as a source of information. Enthusiasm is a primary determining factor in sparking interest, which can not only affect absorption of the course material, but also influence the students' future learning and career choices.[7] We must also provide better resources for graduate students who work closely with the students as teaching assistants and who will also be the instructors of the future.[7]

We must teach students how to use the language of mathematics to describe and solve a physical problem as well as how to efficiently use computer simulations and perform numerical analysis. As teachers of electrical engineers, we must also give them the opportunity to become familiar with the tools and equipment they will use in their jobs after graduation.[12] This, in the time constraints of a semester-long course taught three times a week, is one of the hardest jobs in the world. Teachers can contribute to a lasting education using the combination of the three priceless ingredients: clear explanations, hands-on experiences, and most importantly the excitement that generates involvement, curiosity, and fascination.

III. Experimental Design

In some fields more than others, hands-on experience is an essential element of learning. In engineering, many concepts simply cannot be fully taught in a lecture hall or out of a textbook. The teaching of these concepts requires the development of a supplement to the textbook, which demonstrates the interplay between basic electromagnetic theory and engineering practice.[5] In the long term, the plan is to create a laboratory component for EE 330 in which the students will spend two hours every week complementing what they have learned in lecture and practiced in homework problems with hands-on experience using current tools and technology to solve real-world problems. In the short term, two new hands-on laboratory activities have been created to compliment the four existing MATLAB-based activities. In addition, an Introduction to MATLAB laboratory activity has been created to introduce students to concepts and commands needed throughout the semester. In order to better prepare the graduate student teaching assistants (TAs) who run these laboratories, TA preparatory documents have also been generated for each activity, including for the pre-existing four computer labs.

As suggested by industry representatives who have hired Penn State electrical engineers, these two new labs introduce the students to test and measurement equipment such as network analyzers and anechoic chambers. In addition, these two new labs expand on the use of MATLAB, a technical computing language, beyond programming simple equations into a pre-existing skeleton code. These labs provide practice with reading information from a real-time measured data file and include the use of MATLAB as a tool to create a visual representation of a complex concept, transforming the students' understanding from mathematical equations into some they can readily visualize. As a result, the students gain first-hand experience in taking measurements and performing analysis with the same equipment and software used in advanced research and industry.

Measurement Procedure

While encouraging educators to consider ways to re-engineer engineering education, MIT President Charles Vest stated "As we think about the plethora of challenges, it is important to remember that students are driven by passion, curiosity, engagement, and dreams."[7] The aspects of teaching that cause students to retain the material they have learned often pertain less to the material being taught and more to the method by which the material is presented to the students. Motivating students to learn can be accomplished by sparking students' interest. When students are interested, they are more motivated to learn and, therefore, have a greater chance at understanding and retaining the course material. At the same time, this sparked interest provides the instructors the opportunity to get students involved in research projects. Sparking interest and creating curiosity in students are, therefore, among most important elements necessary for students to truly learn.[13]

During the Fall 2015 semester, these two new labs were implemented in combination with the four existing laboratory activities. The formatting of the existing labs was updated to match the formatting of the new labs without changing the procedure of the activity. The students were told that there was going to be a new laboratory component to the class and were unaware of which labs were new versus old. In a focus group session toward the end of the semester, the

students were asked whether they knew some of the labs were new and some were old. Less than 10% of the students — only those who had previously taken the class and either late dropped or failed — were aware that new and old labs were being compared and were under the impression that all the labs were new. Pre- and post-laboratory surveys approved by the Institutional Review Board were used to measure changes in interest and understanding before and after each laboratory activity. The pre-lab survey was provided to the students with the pre-lab activity a few days prior to the lab. The post-lab surveys were provided to the students immediately after the closing of the lab and were collected before the students left the room. The pre-lab surveys included questions to gauge the interest and understanding of the topic at hand in each individual lab, measured on a scale of 1–10. The format of these questions is presented in Table 1. The blanks show where the questions change based on the objectives for each lab. These objectives are included in Table 2. The post-lab surveys included the exact same questions as the pre-lab survey as well as three additional open-answer questions asking what the students liked and disliked about the lab and for any additional comments. The students who agreed to be a part of the study and signed the informed consent form were presented with the option to complete the surveys for a small amount of extra credit.

Table 1 - Survey Question Structure Examples

	Strongly Disagree				Neutral			Strongly Agree		
I have a solid understanding of _____	1	2	3	4	5	6	7	8	9	10
I am able to correctly solve textbook problems involving _____	1	2	3	4	5	6	7	8	9	10
I would be able to apply my knowledge of _____ in a real-life situation.	1	2	3	4	5	6	7	8	9	10
I would be comfortable being asked to _____ during an internship/job.	1	2	3	4	5	6	7	8	9	10
_____ is interesting to me.	1	2	3	4	5	6	7	8	9	10
I would like to take a higher-level class that further discusses _____	1	2	3	4	5	6	7	8	9	10
I will pursue further understanding of _____ on my own time.	1	2	3	4	5	6	7	8	9	10

Table 2 - Learning Objectives

Lab Activity Number	Objectives/Student Outcomes
1 (Old Lab)	− Students will be able to correctly apply textbook equations describing the cylindrical capacitor − Students will understand the differences between concepts of voltage rating, breakdown voltage, and dielectric strength − Students will apply programming concepts complete a provided MATLAB script
2 (New Lab)	− The students will explore frequency considerations necessary to correctly take device measurements − The students will solder components onto SMA connectors. − The students will learn how to calibrate the network analyzer − The students will measure the characteristic impedance of components the network analyzer − The students will interpret impedance measurements using the Smith chart
3 (Old Lab)	− Students will be able to correctly apply the textbook equations describing transmission lines − Students will understand the process for measuring the impedance of a device without the use of a Network Analyzer − Students will continue to apply previously learned concepts to complete a provided MATLAB script
4 (Old Lab)	− Students will be able to correctly apply the textbook equations describing electromagnetic wave reflections and transmissions at the boundary between two different materials − Students will be able to correctly apply the textbook equations describing the decay of an electromagnetic wave in a lossy medium − Students will continue to apply previously learned concepts to create a MATLAB script
5 (New Lab)	− The students will learn the basics of how anechoic chambers work − The students will understand how to predict the radiation pattern for dipole antennas and antenna arrays − The students will generate their own MALAB code to read and plot data from the anechoic chamber antenna measurement file − The students will investigate three-dimensional images of the radiation pattern from antenna arrays
6 (Old Lab)	− The students will use supplied MATLAB code to plot the radiation pattern of an antenna − The students will understand how to use multiple antennas in a linear array pattern to achieve concentration of a signal in certain directions by producing nulls at appropriate angles and maximums at others

The Labs

The 120 students in the class are organized into four 30-student sections by the campus registrar. Each student attends three 50-minute lecture sessions and one 120-minute laboratory/recitation session per week. In the first of the new labs, Lab 2, the students learn how to use network analyzers to measure the impedance of a component. Due to space and equipment limitations, the two-hour sections of 30 students are split into halves for this lab. Therefore, the entire lab consisted of a one-hour session for 15 students at a time, followed by another one-hour session the following week for 15 students at a time. In the future, Penn State hopes to expand the laboratory facility for this class allowing for 30 students to complete the lab in one two-hour session. Over the two-week span in which this lab takes place, the students learn transmission line concepts and how to use the Smith Chart in the lecture portion of the class.

Before participating in the lab, the students complete a pre-lab activity. In this activity, the students must read a portion of Agilent Technologies' Network Analyzer Basics document.[14] The sections of this document chosen for the reading assignment include the "Lightwave Analogy to RF Energy," "Transmission Line Basics," "Transmission Line Characteristic Impedance," "Transmission Line Terminated with Z_0, Short, Open, 25 Ω," and "Smith Chart Review." The students must answer questions based on the reading and hand in the answers when they arrive to lab.

In the first half of this two-week lab, students worked in groups of three to familiarize themselves with the network analyzer at their particular workstation and to prepare the hardware needed to take measurements during the second part of the lab. In order to familiarize themselves with the network analyzers, the students investigate the brand and model of the analyzer on their bench as well as the frequency range over which it can operate. In addition, the students explored the other network analyzers in the room to determine the similarities and differences from the one on their own workbench. Through research and group discussion, the students determined some of the properties of the variety of available RF connectors. They answered questions about the input/output characteristics of the ports on their network analyzer and provided examples of applications for SMA, BNC, and N-type connectors.

Following the investigation of the network analyzers, the students prepared the hardware needed to take measurements in the second half of the lab. This hardware preparation for each group included using a digital multimeter (DMM) to measure the resistance of three resistors, then cutting the leads of the resistors to three different lengths leaving one at full length, cutting one set of leads as short as possible so that it could still be soldered onto a SMA connector, and cutting the leads of the last resistor to a length about halfway between the previous two, as shown in Figure 1. As a result of this process, each group of students will have a set of three resistors, each of which will have leads of different length. The students then worked as a team, employing good soldering techniques to attach each of these resistors to a SMA connector, as shown in Figure 2. An example of the three resulting SMA connector-resistor pairs that are used in the second half of the lab is shown in Figure 3.
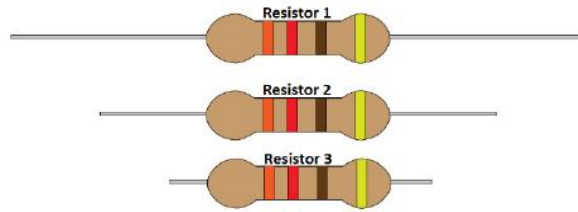
Figure 1 - Diagram from Lab Handout for Cutting Resistor Leads

Figure 2 - Teams of Students Soldering the Resistors to SMA connectors

Figure 3 - Example SMA Connector-Resistor Pairs

After the soldering was checked and the TA signed off on the laboratory handout, the students measured the resistance of the SMA connector–resistor pair to make sure the resistance has not changed significantly, as a significant change in the resistance would indicate an inadequate solder connection. Following the first week of the lab, the students were provided two more documents, one on the Short, Open, Load, Thru (SOLT) calibration procedure and one about electrostatic discharge (ESD) safety. The students were instructed to read this information and answer questions before returning for the second half of the lab the following week.

In the second week of this lab, the students learn from the TA about the process of calibration on the network analyzers and its importance. The calibration procedure is done with a measurement cable attached to "calibrate it out" and so that the measurements include only the device under test. The students take turns following the procedure they read about and using the calibration tool to perform a SOLT calibration on the network analyzer at their workbench. Questions in the handout push the students to think and discuss the calibration procedure further. For example, one question asks how the process of a two-port calibration would be different from a single-port calibration. Another set of questions gives examples of situations such as the cable attached to the analyzer being changed or the frequency range being changed and asks if re-calibration would be required.

Next, the students change the viewing mode of the analyzer to real/imaginary impedance on the Smith Chart and connect each of the SMA connector–resistor pairs soldered during the first half of the lab to the network analyzer one at a time. Questions ask the students to explain the expression "$R + jX$", which in this case represents the measured complex impedance of the connected load at each specific point in frequency, with R representing the resistance or real part and X representing the reactance or imaginary part of the complex impedance. Figure 4 shows an example of a set of screen captures taken when measuring the impedance of the SMA connector–resistor pairs. The students are also instructed to place markers at specific frequencies.
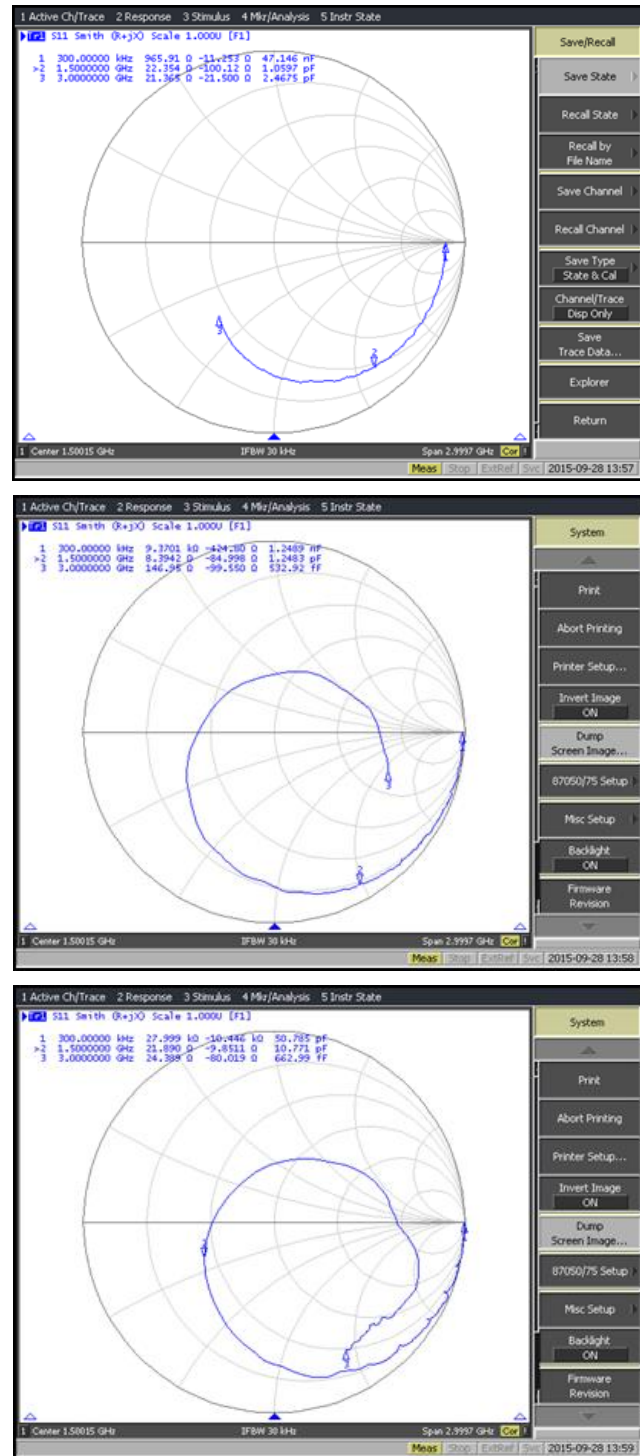

Figure 4 - Network Analyzer Measurements (for the resistor with the shortest leads, *top*, the resistor with mid-length leads, *middle*, and resistor with full length leads, *bottom*)

When viewing the measurements the students must first make observations then attempt to interpret the meaning of these observations. The questions are phrased specifically to push the students through these interpretations. The questions and answers include:

Q: You should see a curve appear on the Smith Chart. What is this curve? Why aren't you seeing only a single point?

A: *There is a single point representing the impedance of the connected load at each specific frequency. The analyzer takes the point at each frequency and connects them with a line. The curve is therefore a plot of the complex impedance versus frequency, over the range of frequencies from 300 kHz to 3 GHz.*

Q: At what frequency (which of the three markers) is the impedance measured by the network analyzer most similar to the resistance measured by the DMM? Does this make sense? Explain your reasoning.

A: *The network analyzer measurements should agree most closely with the measurement taken by the DMM at the lowest frequency within the range of measurement frequencies, in this case at 300 kHz. This does make sense because the DMM measures at the lowest possible frequency, 0 Hz or DC.*

Figure 5 – The Penn State EECS Anechoic Chamber

Q: Compare all three network analyzer measurements. What are the difference(s) between the measurement results from the three different resistor lead lengths? Attempt to interpret the measurements – what is the reason for these differences?

A: *A comparison of all three measurements shows two main differences. The first is that the longer the leads, the farther the curve wraps around the Smith Chart. This is because there are more wavelengths fitting within the longer leads (once around the Smith Chart represents a half-wavelength). The second observation is that the longer the leads, the less smooth the curve. This is a result of coupling and environmental effects of the un-insulated wires.*

Q: There is a third measurement value provided along with the measured resistance and reactance at each marker. What does this value represent? If you move one of the markers around, you will notice that the values take on a different form based on whether the measurement point is on the top or bottom half of the Smith Chart. Why? Does this make sense? Explain your reasoning.

A: *These values represent the capacitive or inductive nature of the load. If you move the marker over the center line of the Smith Chart, you can see two things change. The first is the sign on*
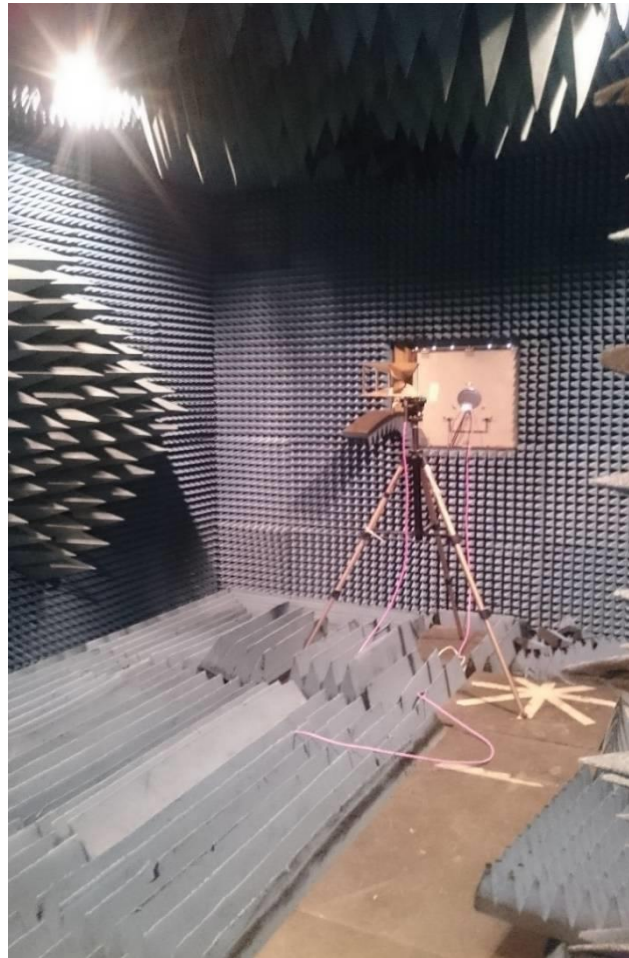
the reactance value and the second is the units on this third value. If the marker is in the
bottom half of the Smith Chart, the reactance is negative and units appear to be F for
Farads, the unit of capacitance. If the marker is in the top half of the Smith Chart, the
reactance is positive and the units appear to be H for Henrys, the unit of inductance. This

makes sense because the impedance of a capacitor, $Z_C = \dfrac{1}{jwC} = -j\left(\dfrac{1}{wC}\right)$*, is negative,*
while the impedance of an inductor, $Z_L = jwL,$ *is positive.*

In the second of the new labs, Lab 5, the students learn about anechoic chambers, dipole antennas, radiation pattern measurement techniques, and antenna arrays. An anechoic chamber is a room with walls designed to both completely absorb reflections of electromagnetic waves and to insulate the area from exterior noise sources. With minimal reflections and exterior noise, accurate antenna measurements can be taken. In the pre-lab activity, the students read about the purpose and uses of anechoic chambers, along with basics on how these chambers work. Figure 5 shows the anechoic chamber on Penn State's University Park campus.

As a part of the description of how the anechoic chamber works, the radiation absorbent material (RAM) is described in detail. A close-up of this radiation absorbent material is shown in Figure 6. The size and shape of the pyramidal RAM, as shown in Figure 7, controls the frequency characteristic of the chamber. In order to minimize reflections, the pyramid height must approximately equal $\dfrac{\lambda}{4}$, where λ is the free-space wavelength. With a limited amount of space in the chamber, the pyramids can only be so large. For this reason, it is more difficult to minimize reflections at lower frequencies than it is at higher frequencies. Increasing the pyramid height of the RAM (for the same base size) improves the low frequency characteristics of the chamber, but comes with a tradeoff of increased cost and reduced area for working inside the chamber. The equation governing the relationship between wavelength and frequency along with the measurements is provided. The dimensions of the pyramids in the specific chamber on Penn State's University Park campus is also provided and the students are asked to determine whether the larger or smaller pyramids determine the low frequency characteristic of the chamber, and to explain why. They are also asked to calculate the lowest frequency at which this specific chamber can be used. Lastly, in a deeper thinking question, the students are asked why there are differently sized sets of pyramids in the chamber, and why are they located as shown in Figure 8.
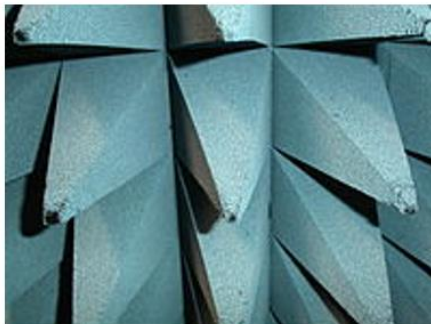

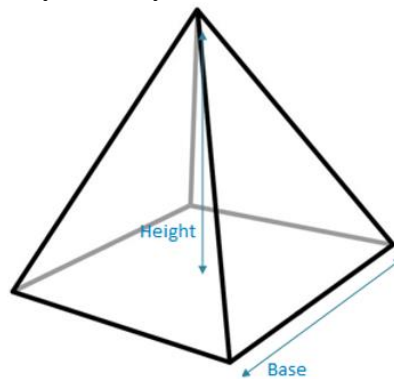Figure 6 - Radiation Absorbent Material   Figure 7 - Shape of the Pyramidal RAM
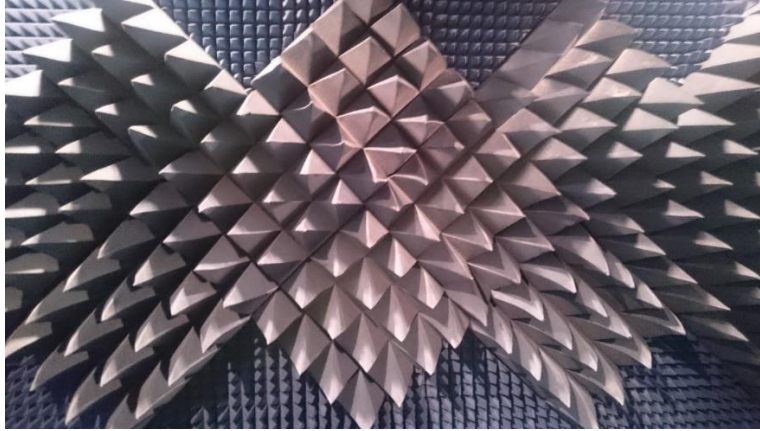
Figure 8 - Side Wall of Anechoic Chamber

     This lab, similarly to the other, is broken up into two weeks because of size limitations in Penn State's microwave laboratory facility. During the week that this lab takes place, the students are being introduced to antennas in lecture, specifically dipole antennas and arrays of dipole antennas. For the first half of this lab the students break up into groups of three and research the radiation pattern of the dipole antenna. When the students are confident that they understand what the radiation pattern of the dipole antenna looks like, the teaching assistant escorts them into the anechoic chamber. The students investigate the inside of the chamber and the control room with the computer and network analyzer that are used to take measurements. The teaching assistant shows the students how the mechanical table pivots and rotates and how the measurement software works. The students attach the dipole antenna to the mechanical table and run the system through the movements of a 360° azimuth cut with 10° increments. As the students watch the mechanical table rotate, they must determine, with help from the teaching assistant, what they expect to see in the measurement data. Based on their understanding of how the anechoic chamber takes measurements and the general shape of the radiation pattern of a dipole antenna, the students are asked to sketch the general shape that they expect to see from a plot of the measured data on a set of polar axes.

     In the second half of this lab, the students confirm their prediction using the actual measurement data from the antenna pattern mapping system in the anechoic chamber. Given general direction with a few hints, the students are asked to generate the MATLAB code on their own:

Reading data from files and writing data to files are important aspects of programming. In order to practice, you will write a MATLAB code to read the data from a text file. The text file on ANGEL (The Pennsylvania State University's course management system) called "AntennaChamberMeasurement.txt" contains the data from the antenna chamber measurement. Using MATLAB, plot the measured data from this text file on polar axes. Print the MATLAB code and the plot that you create and hand them in at the end of this lab.

Figure 9 - One-dimensional Cuts of Dipole Radiation Pattern

Next, a series of three MATLAB figures provide the students with a visual of antenna radiation patterns. The first, shown in Figure 9, shows the one-dimensional cuts of a three-dimensional radiation pattern. Using the same concept, the students are asked to plot the azimuth and elevation cuts of a dipole on their handout, which is oriented in a different direction than the one shown in Figure 9. In the second of these MATLAB figures, the dipole radiation pattern is shown in three-dimensions. A capture of this window is shown in Figure 10. When the students open this figure in MATLAB, each of the six sets of axes can be moved and rotated in three-dimensions using the mouse. The students must match the orientation of the dipole antenna with the corresponding orientation of the radiation pattern.
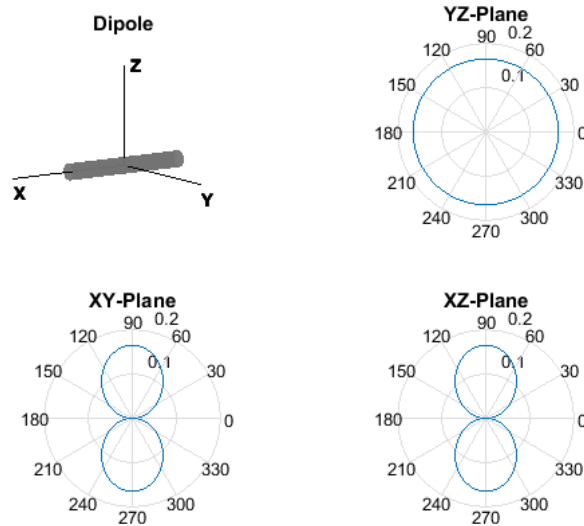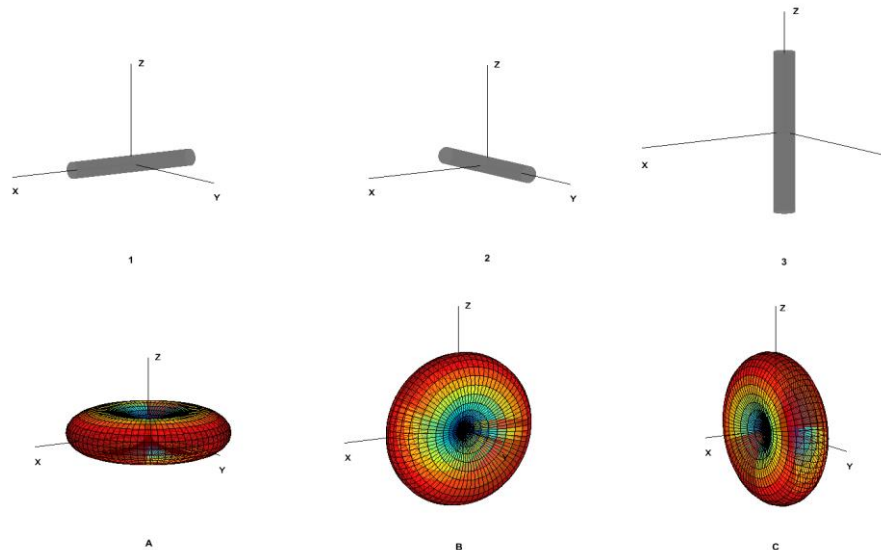

Figure 10 - Three-dimensional Dipole Radiation Patterns

The last of these MATLAB figures shows three-dimensional radiation patterns, but this time for a phased array of two dipole antennas with different separations and phasing. A capture of this three-dimensionally movable figure is shown in Figure 11. Provided three sets of parameters including the separation between the antennas and the phasing used to feed the antennas, the

students are asked to determine which parameters would result in each of the radiation patterns shown.
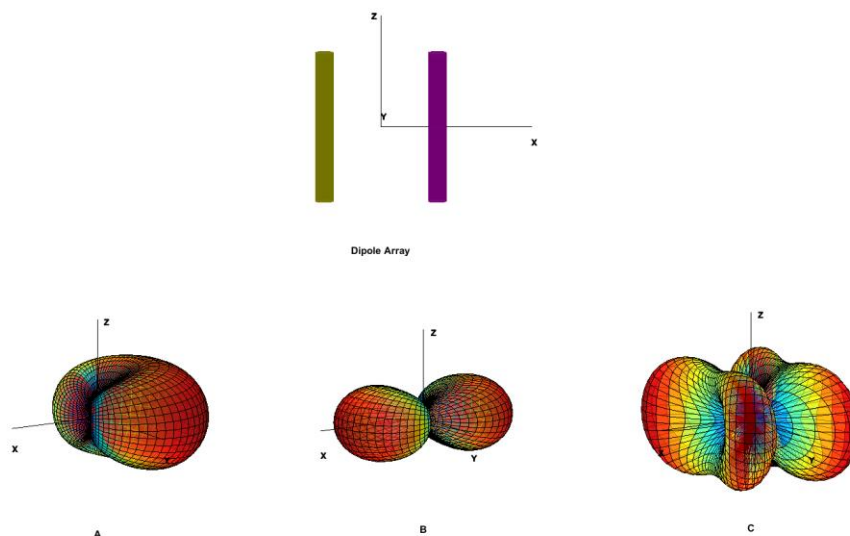

Figure 11 - Three-dimensional Radiation Pattern of Two Dipole Array

IV. Results

After entering all survey responses into a database, a few methods were used for error correction. First, each of the surveys had a repeated question built in to catch students randomly circling answers without reading the survey. When a collected survey had answers for this repeated question that were not within three points of each other, all responses of this survey were discarded. Next, survey answers from students who completed only one of the two surveys were discarded. This way, only the surveys from students who completed both the pre-lab and post-lab survey for a specific lab were included. The course had 120 students enrolled. There were a few students who did not participate in the surveys, and others who dropped the class along the way. After the two error correction methods described above, the number of individual student responses for each survey kept in the database and used for the results of this study ranged between 86 and 108 with an average of 96, as shown in Table 3. This means that over 70% of the students taking the class participated in full.

Table 3 – Number of Surveys Used to Measure Results of this Study

Survey	Number	Survey	Number
Pre-Lab 1	108	Post-Lab 1	108
Pre-Lab 2	100	Post -Lab 2	100
Pre-Lab 3	97	Post -Lab 3	97
Pre-Lab 4	95	Post -Lab 4	95
Pre-Lab 5	86	Post -Lab 5	86
Pre-Lab 6	90	Post -Lab 6	90

From these remaining surveys, all answers to each individual question within each survey were averaged. The average value of the student answers in the pre-lab survey were compared to the average value in the corresponding post-lab survey. For example, Figure 12 shows the comparison between the average pre- and post-lab survey responses for the statement "I am confident solving problems involving _____." Similarly, Figure 13 shows the comparison between the average pre- and post-lab survey responses to the statement "I know how to _____." Lastly, Figure 14 shows the comparison between the pre- and post-lab survey responses to the assertion "I will pursue further understanding of _____ on my own time."

Figure 12 - Comparison of Student Responses on Pre- and Post-Lab Surveys for the Statement "I am Confident Solving Problems Involving ___."
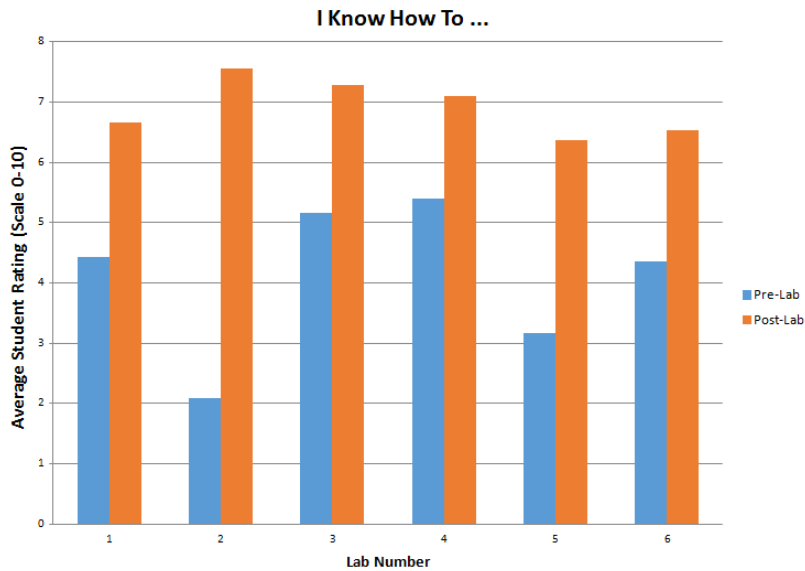

Figure 13 - Comparison of Student Responses on Pre- and Post-Lab Surveys for the Statement "I know how to __."
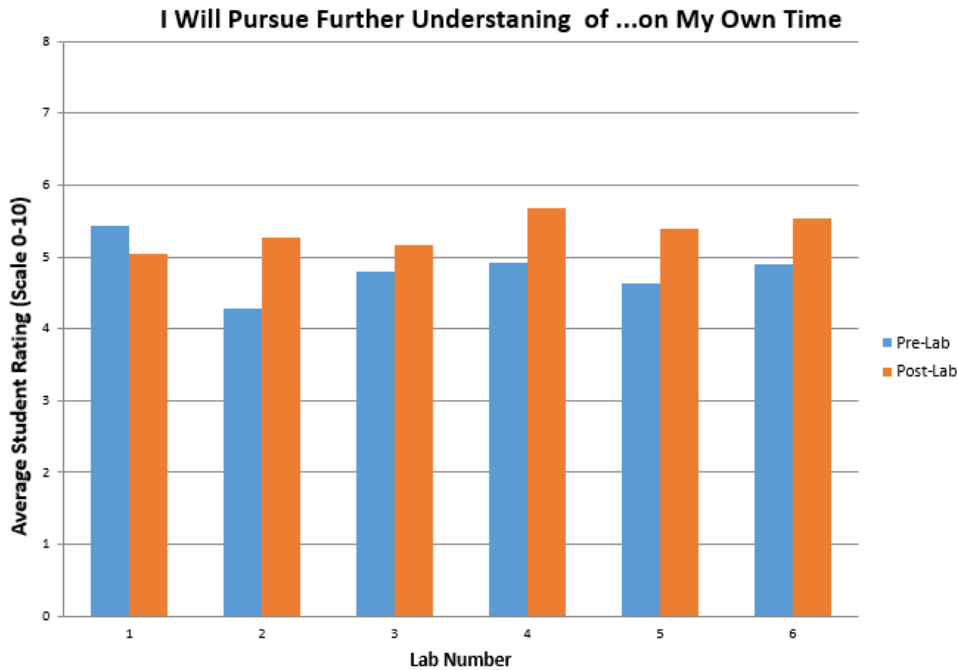
Figure 14 - Comparison of Student Responses on Pre- and Post-Lab Surveys for the Assertion "I Will Pursue Further Understanding of ___ on My Own Time."

Next, the increase in the average student rating from the pre-lab to the post-lab response was determined for each question on each survey. The questions from the survey were separated into two groups, one representing measurements of student interest and one representing measurements of student understanding. Figure 15 shows the responses to each of the statements in the student interest category while Figure 16 shows the responses to the statements in the student understanding category. The specific questions can be found in the legend of each figure.
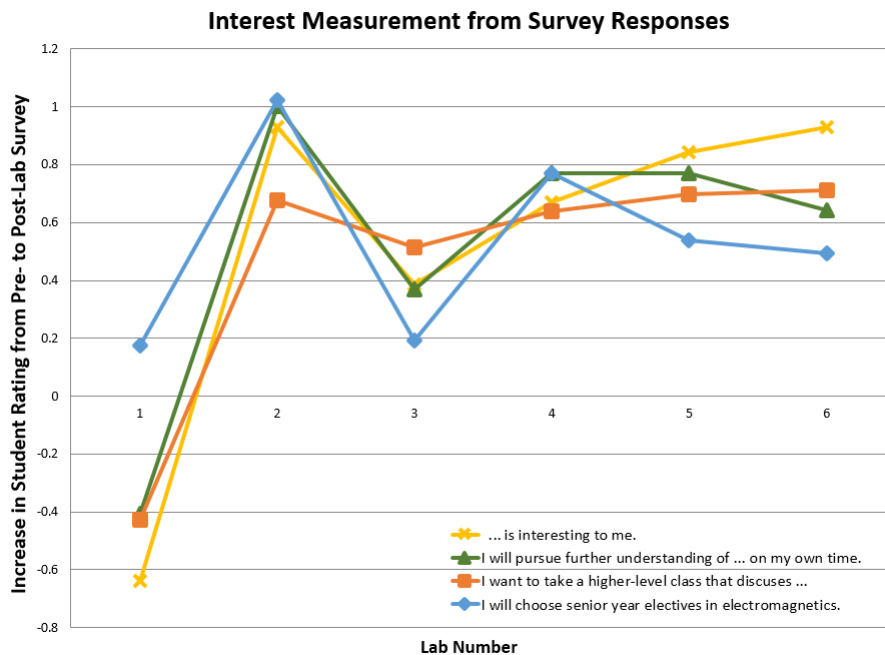
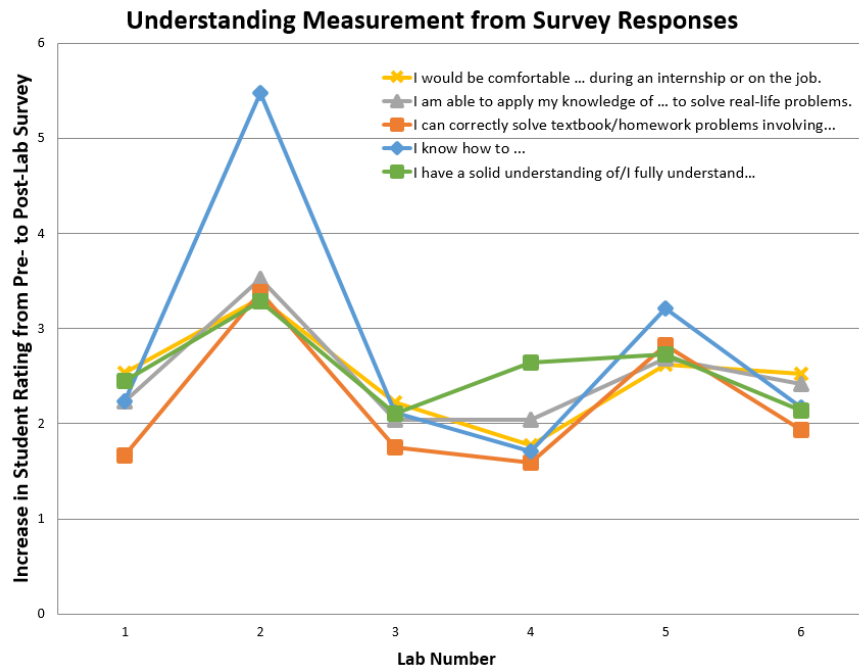Figure 15 - Measure of Student Interest Based on Survey Responses

Figure 16 - Measure of Student Understanding Based on Survey Responses

Using the increase in the average student rating from the pre-lab to the post-lab response, the two new labs, Lab 2 and Lab 5, were also compared to the four existing labs, Labs 1, 3, 4, and 6. The percent increase of the averages for the two new labs based on the four old labs for each survey question is presented in Table 4.

Table 4 – Average Percent Increase from Old to New Labs

Survey Question	Percent Increase
… is interesting to me.	163.3 %
I will pursue a further understanding of … on my own time.	158.0 %
I want to take a higher-level class that discusses …	91.3 %
I will choose senior year electives in electromagnetics.	91.7 %
Overall Increase in Interest	*124.0 %*
I have a solid understanding of/I fully understand…	28.8 %
I know how to …	111.1 %
I can correctly solve textbook/homework problems involving…	79.0 %
I am able to apply my knowledge of … to solve real-life problems.	42.4 %
I would be comfortable … during an internship or on the job.	31.0%
Overall Increase in Understanding	*50.6 %*

The free-response section of the student surveys also provided insight into the student perception of the new labs. The surveys asked students to list both the things they liked and disliked about the lab. In response to Lab 2, the students liked

- *"being able to look at some of the functions to reference some projects I saw a coworker do at my internship"*
- *"learning how to calibrate the NA (network analyzer) because I know I will need it in the future"*
- *"the hands on experience and putting the class material into reality"*
- *"the hands on experience using the NA as it will help in the future with jobs"*
- *"using actual lab equipment and learning about real world applications"*
- *"the hands on aspect, it's good to see a real world application"*
- *"helpful in actually using equipment in the lab and is actually relevant to lecture"*
- *"using the NA and applying what we learn in lecture to something real"*
- *"using the NA to see how frequency affects components"*
- *"understanding the application and what all of this stuff actually means"*

In contrast, the students disliked a few things about the lab. The majority of comments about disliking the lab had to do with equipment freezing and malfunctioning in other aspects causing the students to have to wait for the analyzer to restart. Other comments involved the small size of the room where this lab is hosted, the need to share the calibration tool, and being forced to wear a grounding wrist strap. A few of the students' comments in the dislike section even included sentiments such as, "wish we could take more time to explore more real-world applications" and "want to dig deeper into the NA." In response to Lab 5, the students liked

- *"visual learning actually being inside the chamber"*
- *"less coding and more conceptual and more hands on stuff"*
- *"seeing plots of radiation patterns which helped me understand it better"*
- *"the real-life application"*
- *"the visual representation in MATLAB"*
- *"seeing the data from the anechoic chamber, plotted, take the same shape that we learned it was supposed to be"*
- *"applying knowledge of dipole antennas to simple problems that solidified the material for me"*
- *"that it made us think and browse the internet as if it were a real life task"*
- *"actually learning the material for class"*

Again, there were also aspects the students disliked. These aspects included "having to figure it out ourselves," "it taking forever to generate a few lines of code correctly," "not enough direction," and "having to tell MATLAB to skip the first three title lines in the file." While a few of the students were dissatisfied with not having step-by-step directions, others recognized that this lab was "challenging and makes you experience similar to real-life situations," and "very much independent work which made me search for information myself to complete the task."

V. Conclusion

As indicated by the overwhelmingly positive responses from the students, it is clear that the objectives of this effort and these two new laboratory activities have been satisfied. The increase in understanding of these topics gave the students more confidence in working with these topics both in the remainder of their education and in their future jobs. The overall increase in interest from the students tells us that we have sparked their curiosity. As a result of these new labs, Penn State hopes to measure an increased enrollment in higher-level electromagnetics classes in future

semesters. There are eight specific cases of the responses measured for Lab 2 alone in which the student response to the statement "I will choose my senior year electives in the electromagnetics area" increased by five or more points. Electromagnetics isn't for everyone, but this means that there are eight more students who may go on to take higher-level courses in electromagnetics and to possibly become the microwave and RF engineers that the world desperately needs.

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