Homemade-Antenna Project for an Undergraduate Wave-Propagation Course

Gregory J. Mazzaro
Department of Electrical & Computer Engineering
The Citadel, The Military College of South Carolina
171 Moultrie St, Charleston, SC 29409

Abstract

A commonly-offered senior elective for electrical-engineering majors is Antennas & Propagation. The course exposes students to antenna design and radio-frequency (RF) circuit analysis; unfortunately, opportunities to engage in hands-on laboratory work are limited, as equipment required to prototype RF circuits is often prohibitively expensive.

Presented in this paper is a hands-on project which introduces undergraduates to RF fabrication and testing; this activity is affordable to an undergraduate institution. The project requires construction of two antennas. The instruments required for signal generation and capture (at MHz frequencies) are typically available at an educational laboratory. Students submit a report containing a picture of their antennas, data demonstrating successful transmission of at least one radio frequency, and a discussion of how their antenna design can be improved. This paper presents guidance for a professor to expose his students to RF prototyping at the undergraduate level and samples of student work.

Keywords

homemade, antenna, radio frequency, laboratory

I. Introduction

Undergraduate programs in electrical engineering (EE) comprise general-theory courses paired with educational laboratories, such as a sophomore-year Circuit Analysis lecture and its associated Electrical Circuit Laboratory. Courses become more narrowly-focused in the senior year, which may include one or more electives which follow on from junior-year Electromagnetic Fields. One such elective which offers a light specialization in radio frequencies (RF) and waves is Antennas & Propagation. Typical objectives include the analysis of high-frequency circuits, determination of fields and waves transmitted through and reflected from material media, and evaluation of antenna structures using metrics such as standing-wave-ratio and gain.

An elective such as Antennas & Propagation is not often paired with a laboratory course, nor does it usually contain an integrated laboratory component. Compared to the equipment required to prototype digital-logic or baseband-analog designs, equipment required to prototype RF circuits (e.g. signal generator, vector network analyzer, power meter) is orders-of-magnitude more expensive. Thus, such hardware is typically not found in an undergraduate laboratory. Studies of high-frequency circuits and electromagnetic (EM) waves are generally confined to analyzing simple canonical structures using highly-idealized theory. RF design (largely by simulation) becomes accessible at the early-graduate level, while fabrication of EM structures is generally reserved for advanced graduate studies.

Nevertheless, within the budget of a typical undergraduate EE department, students can be given opportunities to complete hands-on activities to reinforce RF analysis and design concepts. One such activity is a controlled indoor experiment during which each student is provided a pair of antennas, a support structure to hold those antennas, a low-frequency signal generator, and a data-acquisition interface to capture signal strength vs. antenna position [1]. Another activity is the outdoor "fox hunt," during which students detect and locate an errant RF emitter using an antenna and spectrum analyzer provided to them [2]. A variation of this activity permits the students to design and construct their own antennas such as the 4-element Yagi-Uda or 2-element phased array using copper wire [3].

Departments with machines available to fabricate printed-circuit-boards permit students to create microstrip-patch antennas on FR4 or Duroid 5880 [4]. Even if these designs cannot be tested in an appropriate anechoic-chamber or at an open-area test site, a spectrum analyzer (not necessarily a top-of-the-line model) may be used to measure standing-wave-ratio to evaluate antenna performance.

A contest to receive a broadcast UHF television channel spawned creativity amongst students to build folded-dipole, bow-tie, parabolic dish, and quad-array antennas, out of wire and copper tubing [5]. Elements of Ham Radio have been incorporated into freshman-orientation projects such as high-altitude balloons and senior-capstone projects such as solar cars [6]. A "quick and dirty" antenna for amplitude-modulation (AM) radio may be constructed by coiling a thin-gauge insulated wire around an insulated core [7, 8]. AM transmission and reception may be substantially improved by implementing a slightly more sophisticated structure such as a square-loop wire antenna held in its form by a cardboard box [9].

This paper incorporates an amateur-antenna-build project into a senior-year Antennas & Propagation course, as an additional outside-of-class homework assignment, completed by the student on his own time but with materials provided by his undergraduate institution. Section II describes the assignment itself and guidance for the teacher who offers it. Section III presents pictures of antennas constructed by students when this project was recently offered as part of an Antennas elective at the author's institution. Section IV concludes with a sample grading rubric, results of the exercise, and suggestions for improving the assignment during future offerings of the Antennas & Propagation course.

II. Outside-of-Class Project: Antenna Build

The primary objective of the antenna-build project is for the student to engage in a laboratory-style activity to reinforce the fundamentals of analyzing high-frequency circuits, measuring fields and waves transmitted over-the-air, and evaluating antennas. As part of their coursework before evaluating antennas, students learn to treat coaxial-line feeds to antennas as transmission lines. They understand that all current-carrying conductors emit radiation; in essence, any piece of metal fed by a current acts as an antenna. They understand that higher frequencies correspond to shorter wavelengths; thus, physically longer antennas correspond to larger fractions of wavelength and higher antenna efficiency. Students also learn about “sniffer” antennas used as basic detectors of fields and waves; those signals must be captured by an oscilloscope or a spectrum analyzer to be observable and measurable.

Assembling these ideas, for the assigned activity, the students are instructed to fabricate a pair of antennas from materials of their choice. The instructor provides

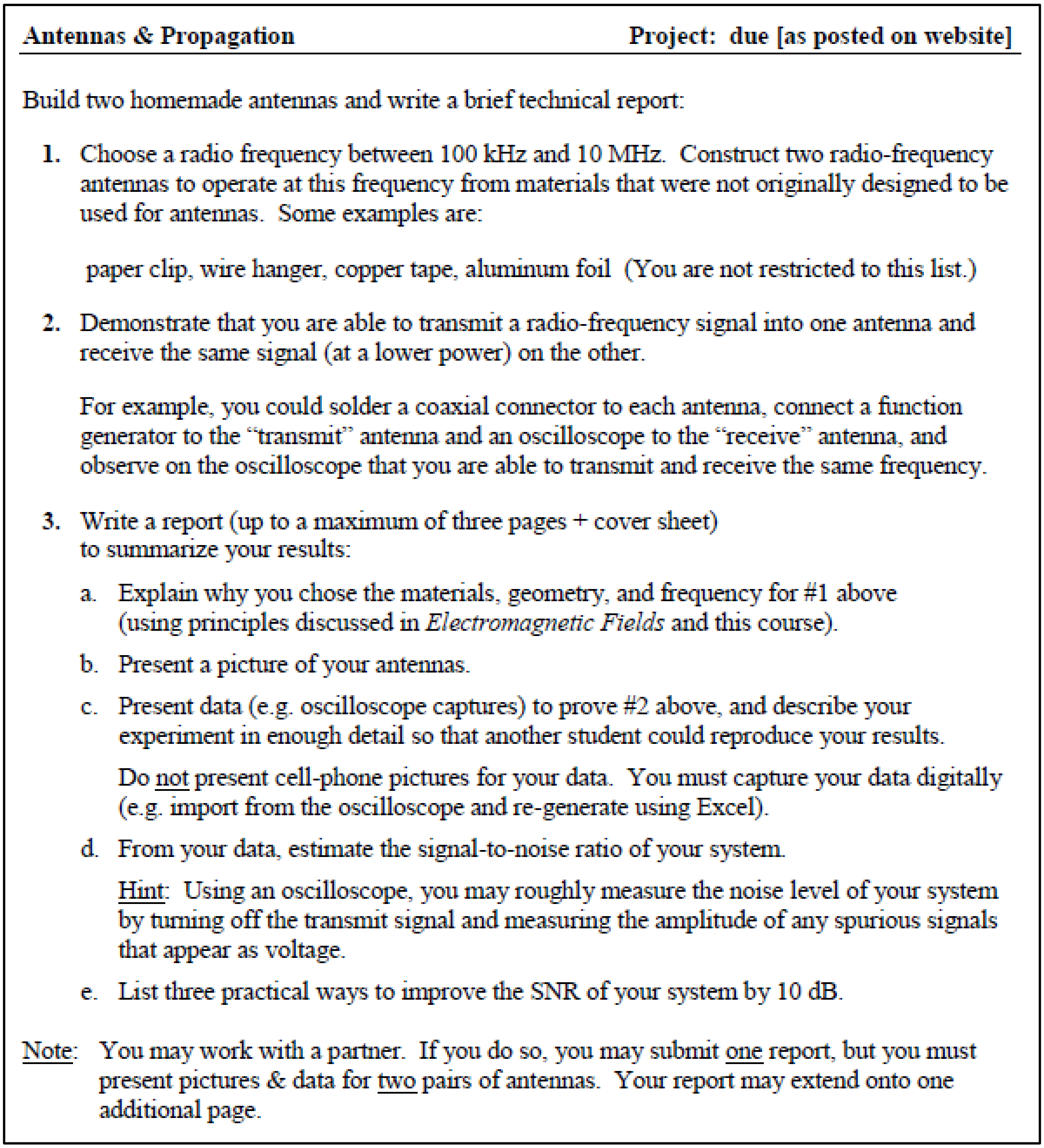
- 50-Ω BNC coaxial cables (with at least one BNC connector at one end of each cable),
- a soldering station (soldering iron, solder, tip cleaners),
- miscellaneous tools: wire cutter, wire stripper, vice grip,
- readily-available metals: aluminum foil, coat hangers, paper clips, insulated wire,
- at least one laboratory bench, one function generator, and one oscilloscope.

The intention of the exercise is for the students to solder or clip a pair of metal objects (either selected from items provided by the instructor, or brought to the laboratory by the student) to a pair of coaxial cables used as feedlines. The students are provided access to a laboratory bench with a function generator which can generate sinusoidal voltages up to at least 10 MHz (such as the Keysight 33210A) and a digitizing oscilloscope (such as the Keysight DSO-X 2022A). The instructor may need to remind students how to operate this equipment, but it is fair to expect that the students are familiar with the equipment from having used a function generator and an oscilloscope during at least one sophomore- or junior-year electrical laboratory course.

The goal of the assignment is for the student to demonstrate functionality of the “hack” pair of antennas by feeding one of the antennas with a signal of a particular frequency from the function generator, spacing the antennas apart from each other on the lab bench, and capturing the same frequency on the oscilloscope. Figure 1 is a sample of the text of the project, as assigned during the Antennas & Propagation course taught by the author during Summer 2021.

Each student is required to construct two antennas: one for transmit and one for receive. They may be the same design. It is understood that the student will select the highest frequency that may be output by the function generator. The free-space wavelength corresponding to 10 MHz is 30 meters; therefore any antenna which fits atop the laboratory bench will behave as a short/Hertzian dipole and transmitted/received signal strength will be proportional to the dimensions of the antenna (e.g. linearly proportional, for thin/long antennas).

The student connects one of his antennas to the function generator. He tunes the function generator to its highest frequency and its maximum voltage output (e.g. 10 Volts peak-to-peak). He places the receive antenna a few feet apart from the transmit antenna. He attaches the receive antenna to the oscilloscope. The student adjusts the horizontal and vertical scales of the oscilloscope so that he observes (at least two full cycles of) the transmitted frequency and he captures this waveform so that he may reproduce the data in the project report. The student turns off the function generator and records another data trace so that he may capture electronic noise present in the laboratory environment.



Antennas & Propagation **Project: due [as posted on website]**

Build two homemade antennas and write a brief technical report:

1. Choose a radio frequency between 100 kHz and 10 MHz. Construct two radio-frequency antennas to operate at this frequency from materials that were not originally designed to be used for antennas. Some examples are:

   paper clip, wire hanger, copper tape, aluminum foil (You are not restricted to this list.)

2. Demonstrate that you are able to transmit a radio-frequency signal into one antenna and receive the same signal (at a lower power) on the other.

   For example, you could solder a coaxial connector to each antenna, connect a function generator to the "transmit" antenna and an oscilloscope to the "receive" antenna, and observe on the oscilloscope that you are able to transmit and receive the same frequency.

3. Write a report (up to a maximum of three pages + cover sheet) to summarize your results:

   a. Explain why you chose the materials, geometry, and frequency for #1 above (using principles discussed in *Electromagnetic Fields* and this course).

   b. Present a picture of your antennas.

   c. Present data (e.g. oscilloscope captures) to prove #2 above, and describe your experiment in enough detail so that another student could reproduce your results.

   Do not present cell-phone pictures for your data. You must capture your data digitally (e.g. import from the oscilloscope and re-generate using Excel).

   d. From your data, estimate the signal-to-noise ratio of your system.

   Hint: Using an oscilloscope, you may roughly measure the noise level of your system by turning off the transmit signal and measuring the amplitude of any spurious signals that appear as voltage.

   e. List three practical ways to improve the SNR of your system by 10 dB.

Note: You may work with a partner. If you do so, you may submit one report, but you must present pictures & data for two pairs of antennas. Your report may extend onto one additional page.

Figure 1. Antenna-build project, as assigned during the Summer 2021 offering of Antennas & Propagation.

Along with this single-frequency time-domain data, the student explains why his antennas are functional, he presents a picture of his antennas, and he estimates the signal-to-noise ratio (SNR) of his signal-generator-to-oscilloscope system. SNR may be estimated by calculating the ratio of the peak-to-peak voltage received when the transmitter is on/active to the peak-to-peak voltage received when the transmitter is off/inactive. The student then lists three practical ways to improve the SNR of the system, such as (a) increasing the length of the transmit antenna, (b) increasing the length of the receive antenna, (c) using a higher frequency, (d) bandpass filtering to pass the transmit signal and attenuate noise, and (e) bringing the antennas closer together.

The students are allowed to work with a partner, although if they do, they must construct an additional pair of antennas and present data which demonstrates functionality of all four antennas.

III. Examples of Student-Constructed Antennas

Figures 2–6 are pictures of antennas that students constructed. In Figure 2 are a pair of antennas in a fractal pattern and held flat by tape to pieces of cardboard. (The cardboard is electromagnetically transparent.) In Figure 3 are two cut-open empty beer-cans; each antenna is connected to its respective coaxial feed using an alligator clip and a BNC-to-terminal-post adapter.

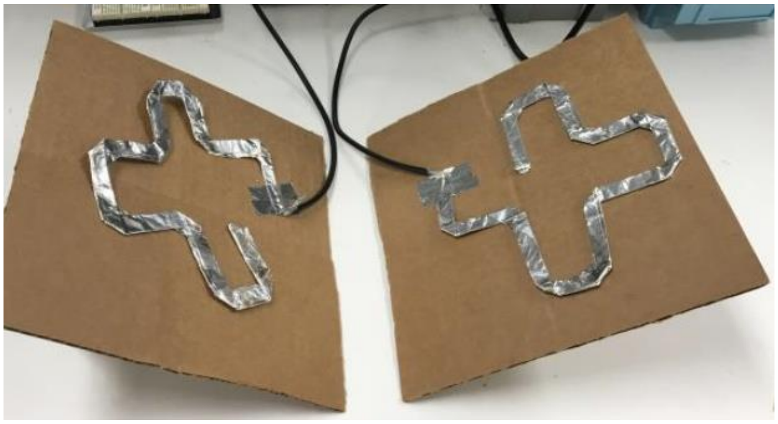


Figure 2. Aluminum-foil “fractal” antennas
(courtesy of Clinton Snider, Summer 2016)

Figure 3. Beer-can antennas
(courtesy of William Kelly & Brandi Vanover, Summer 2019)

In Figure 4 is a drill-bit used as a transmit antenna and a turkey-baster-and-wire-brush used as a receive antenna, arranged as a "diorama": a truck near a cell-phone tower disguised as a tree. In Figure 5 is a pair of metal shafts removed from ceiling fans; the ground wire from each shaft is attached to the center-pin of each coaxial feedline.

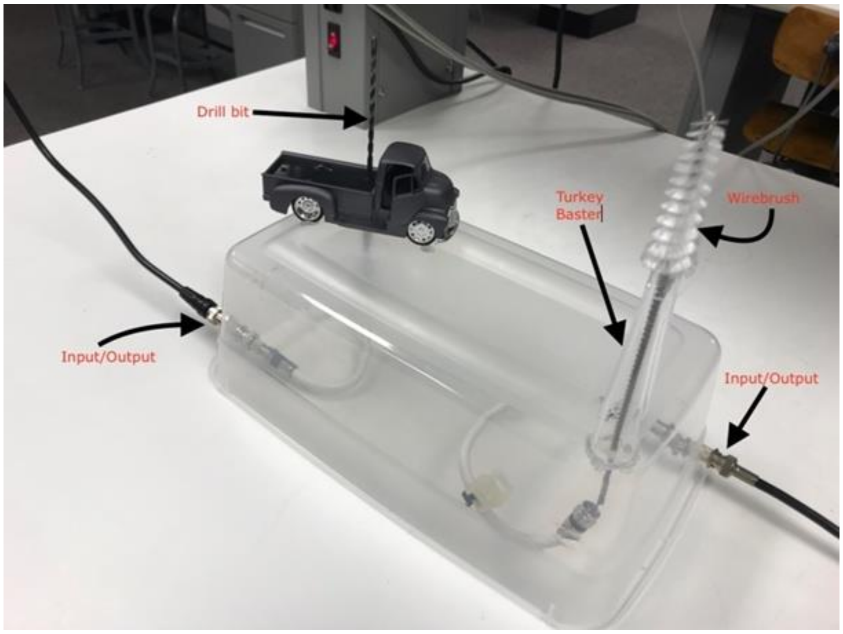


Figure 4. "Diorama" antennas: drill bit, turkey baster, wire brush (courtesy of Robert Brown & Hunter Hess, Summer 2018).

Figure 5. Ceiling-fan shafts as antennas (courtesy of Jonathan Dobson-Lewis, Summer 2021).

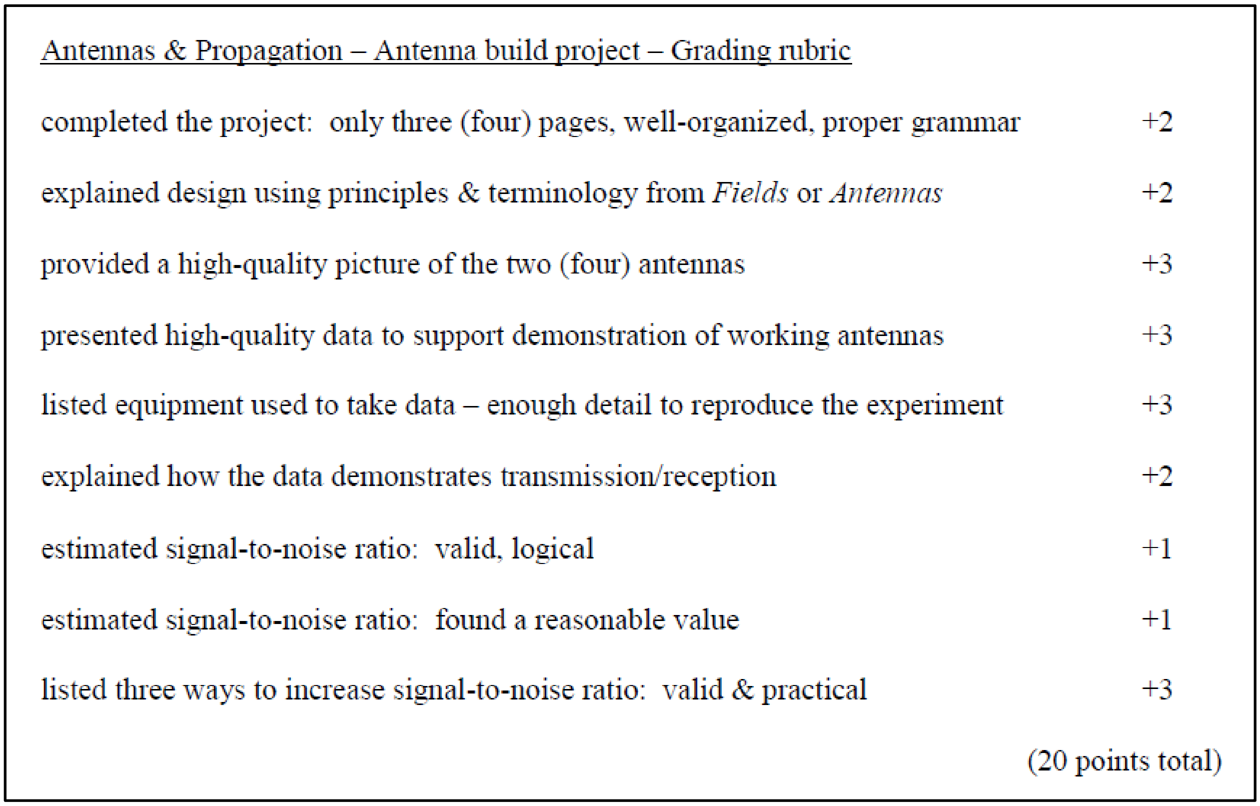
In Figure 6, one golf club is attached to the function generator (not shown) using a single red insulated wire and an alligator clip, and the other club is attached to the oscilloscope (not shown) using a single black insulated wire and an alligator clip.

Figure 6. Golf clubs as antennas
(courtesy of Ronald Nelson, Summer 2021).

IV. Grading Guidelines and Suggestions for Improvement

The rubric used to score the students' projects during the most recent offering of Antennas & Propagation is shown in Figure 7. The assignment is graded out of 20 points. This project accounts for 10% of the students overall course grade.

The students' performance on this project, as collected across three recent offerings of Antennas & Propagation, is summarized as a histogram in Figure 8. Historically, the mean grade has been 87%, the median grade has been 90%, and the standard deviation has been 10%.



Antennas & Propagation – Antenna build project – Grading rubric

completed the project: only three (four) pages, well-organized, proper grammar	+2
explained design using principles & terminology from *Fields* or *Antennas*	+2
provided a high-quality picture of the two (four) antennas	+3
presented high-quality data to support demonstration of working antennas	+3
listed equipment used to take data – enough detail to reproduce the experiment	+3
explained how the data demonstrates transmission/reception	+2
estimated signal-to-noise ratio: valid, logical	+1
estimated signal-to-noise ratio: found a reasonable value	+1
listed three ways to increase signal-to-noise ratio: valid & practical	+3

(20 points total)

Figure 7. Grading rubric for the antenna-build project, used during the Summer 2021 offering of Antennas & Propagation.

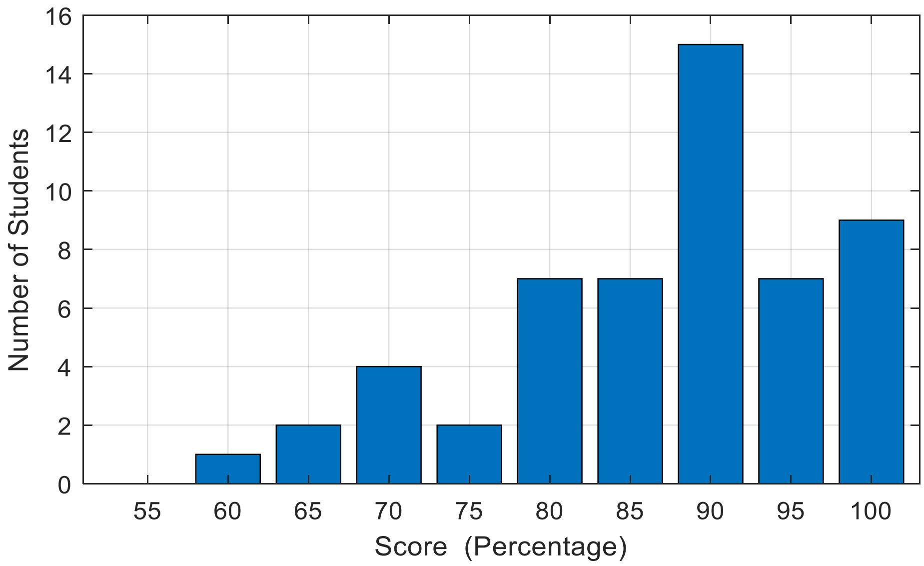


Figure 8. Scores earned by students on the antenna-build project, across 3 offerings of Antennas & Propagation

Student feedback on the project has been overwhelmingly positive. In the future, the author intends to implement several changes to this project:

- Allow students to borrow an RF signal generator (e.g. the Agilent N9310A) so that higher frequencies may be transmitted.
- Allow students to borrow a spectrum analyzer (e.g. the Agilent E4411B) so that higher frequencies may be received.
- Allow students to test the antennas in an anechoic chamber or at an open-air test site.
- Incorporate the design of a matching network after the signal generator, to improve the efficiency of the transmit antenna.
- For extra credit, allow students to compare the performance of different antenna designs (if they fabricate several different pairs of antennas).
- For extra credit, allow students to quantify received-signal-strength's dependence on orientation (polarization).

This project will likely be assigned again as part of the Antennas & Propagation course the next time that it is offered by the Department of Electrical & Computer Engineering at The Citadel.

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Dr. Gregory J. Mazzaro

Dr. Mazzaro earned a Bachelor of Science in Electrical Engineering from Boston University in 2004, a Master of Science from the State University of New York at Binghamton in 2006, and a Ph.D. from North Carolina State University in 2009. From 2009 to 2013, he worked as an Electronics Engineer for the United States Army Research Laboratory in Adelphi, Maryland. Dr. Mazzaro's research focuses on studying the unintended behaviors of RF electronics illuminated by electromagnetic waves and on developing radars for the remote detection and characterization of those electronics. In the Fall of 2013, Dr. Mazzaro joined the faculty of the Department of Electrical & Computer Engineering at The Citadel in Charleston, South Carolina. There, he is currently an Associate Professor and the primary instructor for *Electric Circuit Analysis*, *Electrical Laboratory*, *Electromagnetic Fields*, *Antennas & Propagation*, and *Interference Control in Electronics*.