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WIP: Collaborative Undergraduate Research Project to Develop a Remotely-Accessible, Open-Source, Portable, Software-Defined Radio-Based Antenna Range for Research, Education, and Outreach

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Collaborative Undergraduate Research Project to Develop a Remotely-Accessible, Open-source, Portable, Software Defined Radio-based Antenna Range for Research, Education, and Outreach

Abstract

Antennas are essential components of wireless devices and systems including cell phones, Wi-Fi access points / routers and client devices, military and civilian radars, public safety communication systems, and many others. Faculty and students at a teaching-focused institution, Weber State University (WSU), have developed a low-cost, portable, open-source antenna pattern measurement system (anTpaTT). In this project, a team of undergraduate engineering students at a research university, Virginia Tech (VT), are operating and enhancing the system. The enhanced anTpaTT system and the project itself provide opportunities for hands-on learning, remote laboratory exercises, and experiential and / or project-based learning. Further, it has potential to help students, including students who have visual impairments, develop spatial skills that are not only valuable but required in many engineering careers.

1. Introduction

The continued optimization of wireless communications and other radio frequency (RF) systems is an essential technological effort that has enabled the advancement of modern society. Antennas are an indispensable component of myriad vital RF systems, with applications spanning science, industry and commerce, personal communication and entertainment, public safety, and national security. Thus, antennas, along with electromagnetics more generally, "will continue to be the heart and soul of many modern technology advances ranging from wireless communications and associated phenomenal applications, to radar technologies," as well as radio astronomy, remote sensing, and others. [1]

Replenishment of the STEM workforce is essential for the US to remain competitive in the global economy. New engineers must be prepared with the necessary and essential skills to understand and design antennas and integrate antennas into wireless systems and products. Antenna engineering is a difficult subject that is "abstract and highly mathematical" [1], and challenging to many students. Also, proficiency with antennas requires the ability to visualize relationships between antenna geometry and the resulting directional characteristics of the antennas.[1] Laboratory equipment that enables hands-on experimentation and visualization software partially address these challenges.

However, research grade antenna ranges are extremely expensive, and even antenna range products intended for education are not affordable to all institutions and are not open-source. Without the ability to see "under the hood," closed-source antenna measurement systems reduce students to passive users of the measurement systems. Thus, students miss an opportunity to prepare for careers as innovators through still richer learning experiences including active study and / or customization of the measurement systems themselves. This is far from ideal, given that

[1] These directional characteristics are quantified and displayed as two- and three-dimensional plots called antenna patterns, which are measured by systems known as antenna ranges.

many of the same students will soon be relied upon to design much more complex systems and their components.

2. Background

Project-based / Problem-based learning (PBL) has been increasingly prevalent throughout engineering curricula. Pedagogically, both approaches are similar: students work collaboratively to address complex, ill-structured problems which reflect problems encountered in real life within engineering. In this pedagogical approach, students engage in self-directed learning to gather relevant knowledge and identify knowledge gaps; instructors serve as coaches to help students identify necessary information to solve these problems. Problems are framed to foster skills in knowledge acquisition and problem solving, as well as professional skills such as communication and effective teaming. There is a plethora of literature showing that PBL improves learning in engineering [2]-[12]. Implementing PBL is not trivial within engineering courses; the ill-defined problems necessarily mean that an instructor cannot anticipate all project requirements.

One approach to increase student access to physical measurements is described by the Remote Educational Antenna Laboratory (REAL). [13,14]. A single high-quality measurement facility made available for use in antenna project courses throughout the country. REAL is an extension of an operational remote laboratory developed at Carnegie Mellon in 1995-96.

The REAL model is designed to provide access to a high-quality measurement facility for engineering programs nationwide. Staff or Research Assistants at the facility would be required to maintain the remote-access laboratory. Software would also be maintained by REAL. REAL is currently used for research, although the faculty member who led its development indicated that with sufficient promotion it could become a popular educational resource [15].

A distributed approach to increase student access is the development of low-cost antenna systems. One example was made available by HVS Technologies of State College, PA [16]. There is no indication the product is still available, however the original complete system included motor control and RF calibration software.

2.1.1 Hands-on learning

Commercially-acquired laboratory equipment purchased for student exercises may offer free updates with a software license agreement, however access to source code is not allowed. In contrast, the development of the anTpaTT measurement system is not based upon a commercial model. Software is open-source, and the hardware is easily improved with access to a 3-D printer. Optimization of future anTpaTT prototype will depend upon contributions from students.

The current anTpaTT prototype consists of two subsystems. Both the RF and motor-control subsystems utilize open-source software, GNU Radio Companion (GRC) [17] and GRBL [18] respectively. Hardware comprises standard PVC tubing, commercially-available 3-D printer belts and gears, plus two custom printer-fabricated components. Future student-designed hardware modifications will only require access to CAD software and a 3-D printer.

The open-source RF software, implemented using the GNU Radio open source SDR toolkit [19] will provide additional hands-on learning opportunities for students to investigate topics in modern communication theory. Examples include digital modulation, coding/decoding and/or time-gating to reduce multipath, and narrow/broad-band noise interference mitigation.

2.1.2 3D visualization / spatial skills

Spatial visualization is a skill set, and strongly predicts success in Collegiate Engineering programs [20]-[23]. Thankfully, these skills -- such as isometric and orthographic views, object rotation, cutting places and cross-sections -- can be learned through practice materials such that of Sorby, Wysocki & Baartmans, 2003 [24]. This active approach has shown success [25], [26]. The anTpaTT project aims to build on these insights and provide students with accessible visible representations of antenna patterns.

As we and others have shown, 3D visualization and tasks can improve spatial skills and create more successful engineering students. These skills are even more important in the case of Radio Frequency where the subject matter is abstract, mathematical, and invisible. Our 2D and 3D Web-based plots provide portrayals of the antenna pattern measurement.

2.1.3 Remote laboratory exercises

The authors have developed and evaluated remote laboratory exercises covering Radio Spectrum use and management that run on a software-defined radio (SDR)-based wireless testbed [27]. Further, we have hosted related student competitions that included participation of undergraduate students [28], and local competitions for K-12 students. We have evaluated these materials from a pedagogical point of view and by their graphical and perceptual aspects [29]. These materials include: slides, videos, and interactive Web-based activities that integrate with Learning Management Systems, such as Canvas. The anTpaTT project seeks to bring these successes forward to a new level of capability and instruction.

The Covid-19 pandemic has forced many institutions to increase their online offerings and develop more robust alternatives for remote instruction. As a cost-effective kit, including hardware and software, anTpaTT offers a scalability that can bring Radio Frequency education to more students via remote curricula.

2.1.5 Electromagnetics and antenna education

To promote learning of concepts in electromagnetics, including antennas, engineering educators have embraced use of hands-on and remote laboratory resources. Proposing a way forward for the field, Iskandar outlined alternative yet complementary approaches “to revitalize [electromagnetics] education,” such as (1) Technology-based educational modules and teaching tools, including multimedia modules with strong emphasis on visualization and interactivity; (2) Flipped or inverted classroom approaches and project-based learning; and (3) Development of “virtual organization” websites for teaching electromagnetics; for example one developed for joint use by 28 schools across the Hawaiian Islands, leading to shared resources for larger-scale and even global learning communities for electromagnetics [1].

Examples of recent innovations in electromagnetics education that involve antennas include several related to radar and radio astronomy. One team developed a ground penetrating radar prototype for education that lets users control parameters such as transmitted signal waveform, frequency range, and period using a graphical interface [30]. Another devised a close range millimeter wave scanning radar that operates at 94 GHz, for use in a touring exhibit [31]. Yet another group of educators offered an in-person short course in which teams of students built, used, and in some cases improved small radars using relatively-inexpensive (US$360) kits [32]. This led to a self-paced massive open online course built around construction and use of a similar kit that had been upgraded for scalability [33]. Another project aimed to promote interest in science and technology through development of a small radio telescope for use at universities and high schools. The authors surveyed available systems, including a low cost system "Jove" from NASA (costing approximately US$250 including kit and other required items), and a US$6,000 system from MIT's Haystack Observatory, before developing their own kit based on a reflector antenna and other receiving equipment originally designed for satellite reception, at a cost of approximately 6,000 Euros. [34].

Engineering educators have described various approaches to and resources for hands-on learning related to antennas. These include: (1) A methodology to teach antennas using a modular building kit and low-cost measurement system (although the cost is not specified in the paper and a related product web page found by Internet search was not accessible) to measure antenna properties including patterns at L-band (1-2 GHz) and X-band (8-12 GHz) [35]; (2) An extensive antenna trainer kit that consists of various types of printed-circuit antennas for use at microwave and / or millimeter wave frequencies, developed for graduate-level education on the topic [36]; and (3) A hardware and software based demonstration system for undergraduate education that uses acoustic sensors to illustrate beamforming (which is mathematically similar whether acoustic sensors or electromagnetic sensors -- antennas -- are used in the system) enabled by digital signal processing [37]. Although less flexible than custom designs and construction, a commercial, Lego™ - like kit for building antennas enables assembly of a variety of antenna types without the use of specialized tools or techniques [38].

In the specific area of antenna ranges, commercial products exist for bench-top antenna pattern measurements [39], Faculty have reported on an antenna kit developed for use by their own students [40], and a research grade antenna range has been used for remote measurements to support education [13]. Affordable solutions to measure antenna radiation patterns have periodically been investigated by amateur radio enthusiasts and teaching laboratories. One interesting example from the 1990s utilizes several frequency-specific signal sources, an analog X-Y (strip chart) recorder, and a manually-steered television antenna rotator for position control. Received power is measured with an analog spectrum analyzer [41]. However, such solutions are not available commercially. Further, the data sheet for the closest commercial alternative to the anTpaTT system [39] does not mention open-source software, and that system operates in two specific frequency bands (915 MHz and 10.5 GHz) rather than the much wider range enabled by the SDRs used in the anTpaTT system. Additionally, the system in [39] appears not to perform true two-axis measurements (which result in three-dimensional antenna patterns), and measures only E- and H-plane patterns, with the option to show both of these principal-plane patterns or interpolate between them to synthesize an approximate three-dimensional pattern. The closed-source software and limited frequency options of [39] hinder students' ability to customize the system and also severely limit its utility for undergraduate research and design projects that use frequency bands other than the two supported by the system. Meanwhile, the REAL system [13, 14], while of high quality, did not provide the option of replication and modification for local or regional use. Reported educational use of the REAL system was limited to peer institutions. Limited availability of the PI due to an appointment as department head hindered promotion and dissemination efforts, although the PI indicated that he believed there was potential for greater interest in the system if given extensive promotion over time [15].

2.2 The anTpaTT system

Electrical Engineering faculty at WSU recognized the value of a low-cost antenna radiation pattern measurement capability to enhance a curriculum in electromagnetics and wireless communications. In the near term, the space and budget requirements for a research-grade antenna-pattern measurement system (antenna positioning system, anechoic chamber, and dedicated network analyzer) are beyond the department's reach. A short-term goal of the engineering department has been to acquire an affordable, education-grade laboratory resource for undergraduate courses in electromagnetics and wireless communications.

In contrast to the system described in [39], anTpaTT [42] is customizable, and while turn-key installation will be supported, it also provides ample opportunities for student projects to enhance or modify its functionality, adapt the system to other applications (e.g., a software-defined scanning radar). Further, by simply replacing the source antenna and ensuring compliance with FCC Part 15 rules, the range can be used to make measurements at any frequency between 150 MHz and 6 GHz, and the frequency range can be extended through addition of radio frequency up- and down-converters or replacement of the original radios with future higher-frequency products. Also, unlike [13], which although an excellent resource, is not easily replicated, the proposed system is affordable and intended to support local as well as online use. In addition, while the range described in [13] is remotely accessible, reported use of the system has been limited to institutions of similar size and research activity, the system proposed here can be replicated and shared within pre-existing communities or networks of institutions and STEM educators, including but not limited to those of WSU and VT. The ease with which anTpaTT can be adopted as a local or community resource can give faculty and student users a greater sense of ownership of and investment in the resource. This will satisfy the prevalent desire among faculty to have a new resource yet also control how it is used in their classes [15].

Table 1. Comparison of proposed anTpaTT antenna measurement system and alternatives

System	**anTpaTT Prototypes** [42]	**LabVolt** [39]	**REAL** [13]-[15]	**HVS** [16]
Quality	Prototype	Educational	Professional / Research	Educational
Availability	Low (only two units, no standardized design)	Available for purchase	Low (Educational use currently not supported)	Unavailable/ out of production
Frequency Range	2.4 GHz (ISM / Wi-Fi)	915 MHz or 10.5 GHz	TBD	N/A
Open Source	RF and Motor Control subsystems utilize open-source Software	No	No	N/A
Customizability by Users	Low due to minimal documentation	Low	N/A	N/A
Reproducibility by Users	Low due to lack of standardized design	None (proprietary)	Low (requires custom development or purchase of research-grade range)	N/A
Remote Operation and Monitoring	SSH access for developers, no monitoring	Not mentioned in product literature	No	N/A
Cost for Educational Use	Less than US$1,500 excluding engineering costs and computer	Low tens of thousands US dollars per station	Was free but no longer supported	N/A
Documentation / Support	Open source documentation under development			

A more current single-frequency system with automated position control inspired the anTpaTT measurement system developed at WSU. Picco and Martin [43] utilized commercially-available 2.4 GHz wireless routers for both transmit and receive. The received signal strength indicator (RSSI) was measured between routers and available once the original firmware is replaced with open-source (DD-WRT) software. Antenna position control and RF signal measurement were realized using National Instruments LabVIEW [44].

The Picco and Martin (P&M) prototype was developed and results were published in 2011. Since the publication of their results, SDRs have become viable for student projects. In addition, the tremendous growth of three-dimensional printer technology has made available both open-source position control software and hardware well-suited for integration to a pattern measurement system.

2.2.1 AnTpaTT Prototypes #1 and #2

Two WSU undergraduates reconstructed the P&M system as part of a senior capstone project. The reconstructed system utilized readily-available Linksys routers connected to the reference antenna (SOURCE) and the antenna-under-test (AUT). Open-source firmware (DD-WRT) was loaded on the routers to access the RSSI level versus position. National Instruments LabVIEW software controlled two stepper motors for elevation and azimuth orientation of the AUT.

The senior project obtained coarse pattern measurements of a test antenna, however difficulties mentioned in the original article reappeared with the WSU recreation of the P&M prototype. Challenges encountered with the 1st prototype included a) motor control hardware allowed one direction of travel, b) a homemade belt was constructed that introduced slippage and resulting measurement errors, c) router firmware required a standard Wi-Fi 'handshake' between transmit and receive Wi-Fi routers. The WSU prototype required approximately fifteen seconds per sample.

WSU was awarded a Utah NASA Space Grant to develop a second prototype based upon the P&M system with hardware design and software modifications. The RF subsystem would integrate software-defined-radios (SDRs) for the Transmit-Receive link. The position control system would incorporate open-source GRBL software developed for 3-D printers. Low-cost, commercially-available synchronous gears and belts would be considered as a potential solution to a significant problem with the original prototype.

The GNU Radio software library [19] was chosen for the WSU project to maintain a flexible nature similar to LabVIEW, without the cost incurred using commercial software. GNU Radio Companion is a Linux-based open-source software platform for communication and signal processing that is well-suited for student-initiated code development.

Figure 1 shows the WSU anTpaTT prototype. The system includes a belt-drive antenna positioner as well as a 2.4 GHz, ¼-wave monopole antenna and its pattern measured using the prototype system.

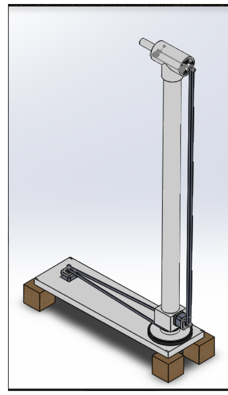
2.2.3 Current and Future Work on anTpaTT

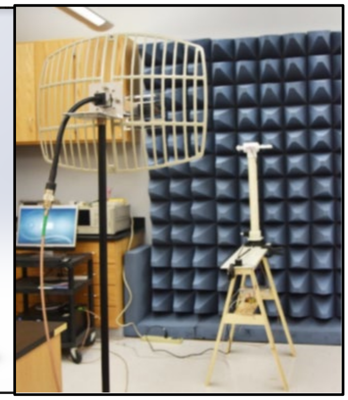
The continued development of anTpaTT will focus on mechanical improvements and applied research to improve antenna pattern measurements in non-anechoic environments.

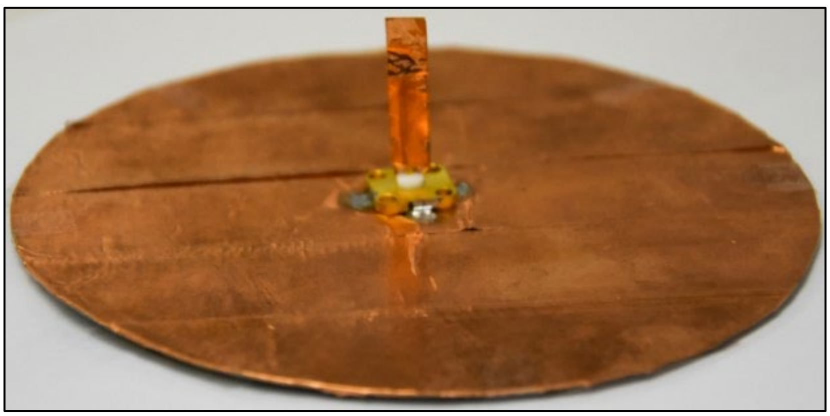
Mechanical Improvements

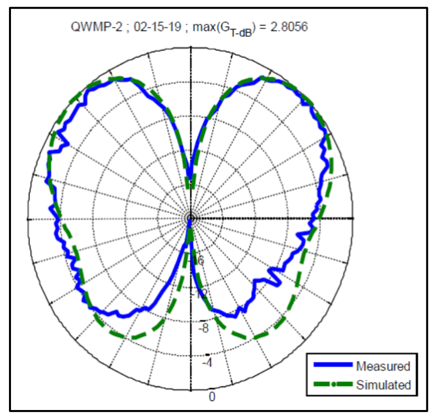
- A long-term goal for the system is the ability to generate three-dimensional pattern plots. A significant obstacle to the end is the connection of the coaxial cable to the AUT. Different methods of connecting the AUT will be investigated. RF rotary joints and possibly slip rings that will allow the positioner to turn in elevation will be investigated.
- Control of the position and confirmation of a reset could be improved with the incorporation of stop-switches for both azimuth and elevation belts. Belt tensioners will also be investigated.
- Antenna pattern measurements in non-anechoic environments

Figure 1. Immediate right: CAD Rendering of Antenna Pattern measurement system. Emphasis was placed on use of commercial PVC material with 3-D printer hardware including synchronous belts and gears. Right: WSU antenna range configured for Principal Plane (two-dimensional) Pattern Measurement for the Yagi-Uda prototype designed for WiFi band operation (*f=2.4 GHz*). Below, left: 2.4 GHz monopole antenna. Below, right: E-plane pattern measured using anTpaTT Prototype 1 (solid blue) and simulated pattern (dashed green) of 2.4 GHz monopole antenna.









Currently two students are investigating the use of modulation methods and network protocols to improve noise and interference mitigation for antenna pattern measurements in non-anechoic environments. It is anticipated antenna pattern measurement experiments with narrow- and wide-band noise interferers will be created to assess noise-mitigation strategies.

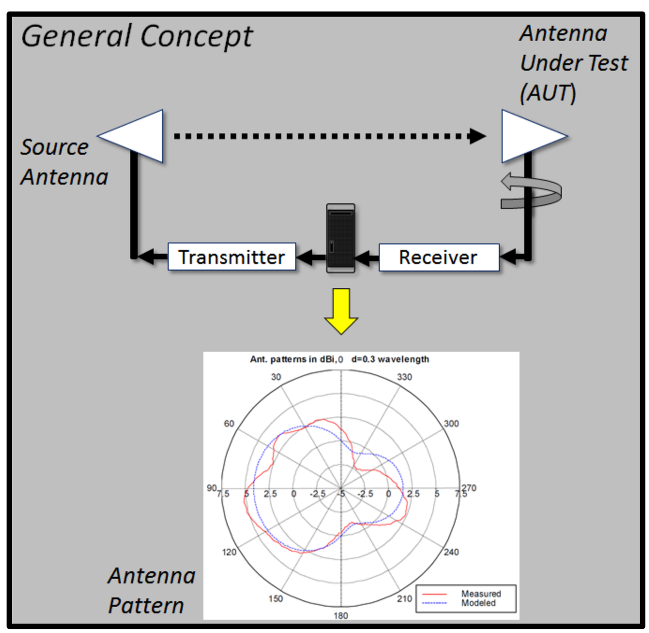
2.2.2 Collaboration on Vertically Integrated Project (VIP) at VT

The WSU and VT PIs, as well as an WSU IT professional and non-traditional MS student, are collaborating to organize an undergraduate project around the range and related topics, with much-appreciated but limited support from the Virginia Space Grant Consortium and volunteer student effort. Over 50 students responded to the initial announcement of the project, which currently involves over 20 VT (VT) undergraduates. These students are taking initial steps to build, test, and enhance an antenna range based on the design developed by faculty and students at WSU. Initial work at VT is building on a second prototype system supplied by WSU and shown in Figure 2.

Figure 2. anTpaTT Prototype 2 at VT:
Upper left: Entire system showing source antenna (left), control / processing computer and SDRs (lower center), and positioner with antenna under test (AUT) (right)
Lower left: detail of Arduino board and power supply for positioner stepper motor control.
Right: antenna positioner with AUT and stepper motor.

Project meetings, hosted on Zoom began July 1, 2020, are held weekly when the project is fully staffed, and, have involved both VT and WSU researchers. Guest speakers have included an author of popular texts on Antennas and related topics. A project kickoff meeting and Canvas site for the project are used to help orient students to the project. Resources used include material on wireless communications and radio-wave propagation fundamentals, as well as antennas and antenna measurements. Figure 3 is an example from these background materials that describes at a high level the concept of antenna pattern measurement using antenna ranges. The students are organized into teams that correspond to subsystems of the range and associated technologies. Nicholas Polys is advising two teams of students who are developing a proof-of-concept remote access and monitoring capability and a web-based user interface for the range as a first step towards its use in remote learning and research. Other teams of students are becoming familiar with software defined radio and various types of antennas that can be built and tested (both advised by Carl Dietrich), and motor control for the positioners and three-dimensional printing of custom-designed parts (both with advising from WSU PI Christian Hearn). The students will also explore ways to enhance portability of the range to support classroom demonstrations and STEM outreach.

Figure 3. Antenna ranges enable students to measure directional characteristics of antennas, including antennas that the students themselves design and / or construct, and to understand better the relationship between an antenna's geometry and the antenna's gain (a measure of the effectiveness for transmitting or receiving) in various directions. A radio signal is transmitted using a source antenna and received using the antenna under test (AUT) at multiple angles of interest relative to the AUT's direction of strongest transmission and reception. The AUT's directional characteristics are calculated based on measurements of the received signals at each angle, and are represented as two- or three-dimensional plots known as antenna patterns.



The effectiveness of project-based learning has been studied extensively. We expect that students will gain similar benefits from this team project that integrates tasks and subsystems that involve multiple sub-disciplines within electrical engineering, computer engineering, computer science, and mechanical engineering.

The range itself will serve as a resource for interactive, remote as well as in-person, hands-on learning. Few systems that serve either role have been developed for electromagnetics education generally or antenna education specifically, and still fewer are publicly available. A literature search identified three alternatives including two commercially produced antenna ranges for use in labs and a remotely accessible, industrial-grade antenna range at another research university. One of the companies appears to have ceased operation. The other company provides well-equipped antenna measurement stations, but at a cost in the low tens of thousands of US dollars per station. The principal investigator whose team built the university-based range indicated that it is currently used as needed for research, and administrative responsibilities had prevented the level of effort necessary to publicize the range. Further, the investigator indicated that engineering educators might prefer to use resources that they develop themselves.

Based on the literature search, the portable range is poised to fill a unique niche in antenna education, as a low-cost, customizable system that can be used locally or remotely as a tool for education and research and also as a subject of research and development projects.

3. Student participation, antenna range subsystems and project teams

A diverse group of over 35 undergraduate students and a graduate student has participated in the project. Multiple students have participated as volunteers and others have earned independent study or undergraduate research credit from related work.
The antenna range project involved multiple subsystems and student teams that included the following:

- Positioner / Motor Control
- 3-D printing
- Software-defined radio
- Signal processing

4. Results / Assessment

Results of the project to date are reported below, including development efforts, educational and student research applications. We present a summary of student performance on pre- and post-quizzes associated with online learning modules on radio frequency (RF) systems and the RF spectrum provided to student participants to orient them to antenna applications, and summarize dissemination efforts. Pre- and post-surveys for students who participate in the project may be developed and provided to future cohorts of participants.

4.1 System Development Progress

The team of undergraduate researchers are developing a proof-of-concept remote access and monitoring capability for the range as a first step towards its use in remote learning and research.

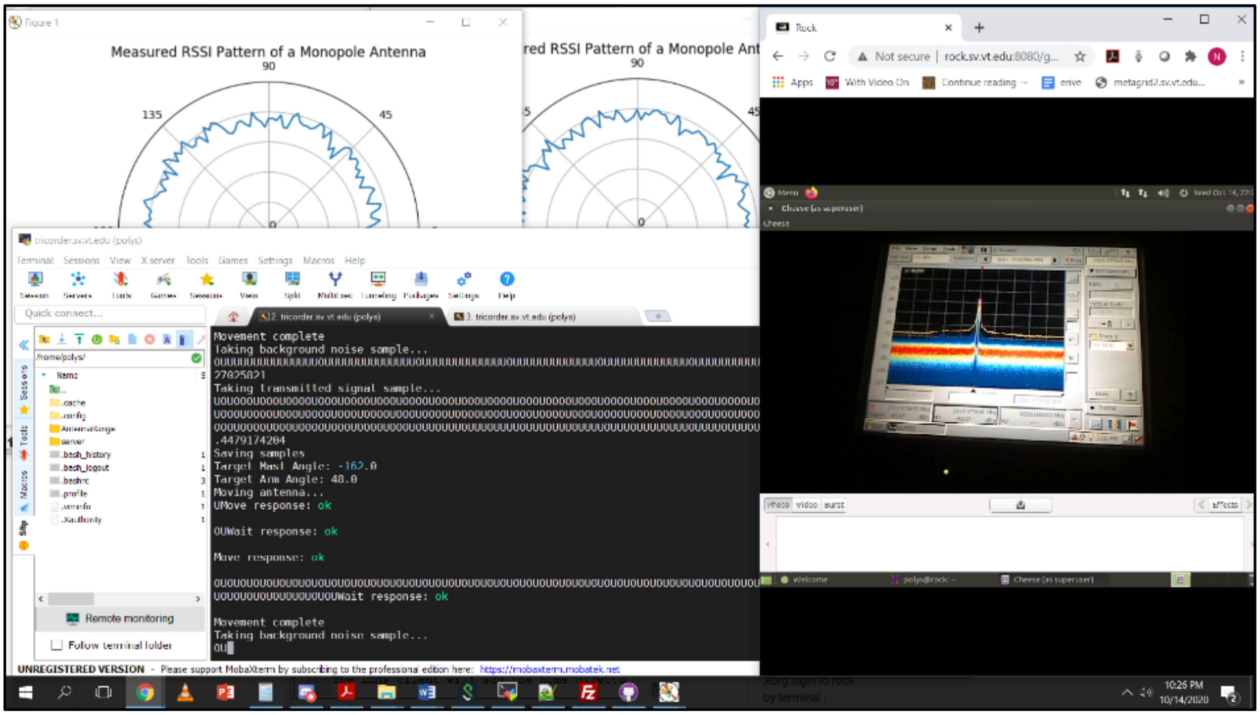


Figure 4. A remote desktop interface to the anTpaTT system is a first step towards the system's use as a resource for online learning.

Currently the range is accessible using a standard web browser to provide access to a remote Linux desktop, as shown in Figure 4. To monitor the range's operation, the range or a co-located spectrum analyzer can be viewed using a webcam and associated application. Students at VT are developing a web page that will provide access to the range and related materials. In addition to enabling operation of the range, the web page will display measured antenna patterns as shown in Figure 5 and antenna designs such as those shown in Figure 6. The students have increased modularity of the range's Python-based motor-control software, and have updated the software to work with a more recent version of the language. The students have also developed software to read antenna pattern measurement files and convert them to a format that can be used to render the patterns using three-dimensional graphics or even produce three-dimensional physical antenna pattern models using additive manufacturing.

4.2 Dissemination, use in Instruction, Master's Project / Thesis Research, and Potential for use in Undergraduate Research and Capstone Projects

The WSU anTpaTT prototype has been a success in terms of dissemination, graduate research, and classroom demonstrations. In particular, the Arduino-based position control subsystem generates student interest with open-source adaptability and 'moving parts' which include stepper motors, synchronous belts, and gears. In addition, industrial affiliates have expressed positive interest in and support of the new RF measurement capability.In 2019, the anTpaTT was deployed for student outreach (DoD contractor Engineer's week). Later in the year, anTpaTT was a presentation topic for a state-wide RF and Wireless symposium. During 2020, WSU presented anTpaTT-specific topics at two virtual conferences.

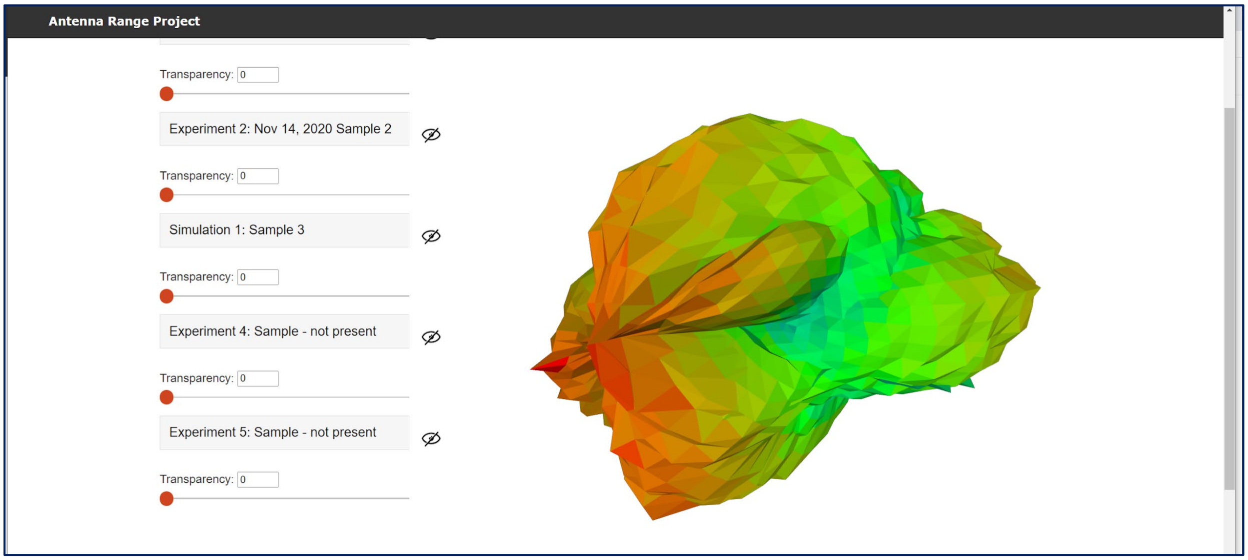


Figure 5. interactive 3D model of an Antenna measurement published to project website; surface is manifold and 3D print-able

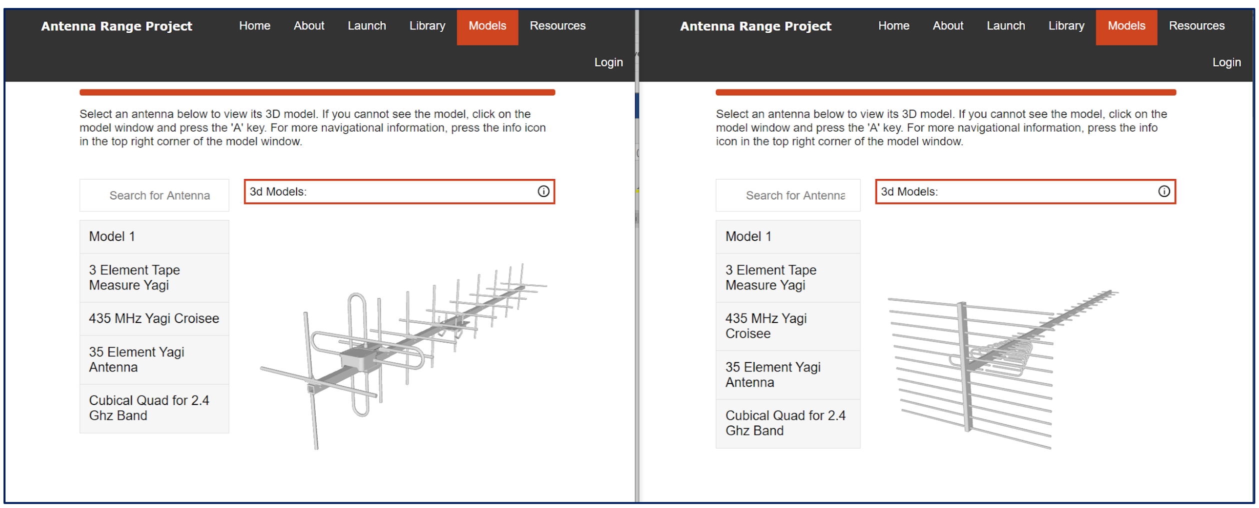


Figure 6. Interactive 3D models of two antennas on the website with WWW resources

The author was invited to submit an extended paper to an IEEE journal special section.WSU . The IEEE journal manuscript describing the technical development and applications is currently under review.

To date, three graduate students have utilized the anTpaTT prototype for applied research topics. The focus of their research is measurement fidelity in non-anechoic environments.

- The master's project of the first student developed and validated the SDR and motor control code. He is credited with coding and validating a clever and effective noise-subtraction method of measuring antenna patterns.

- The department’s first thesis student developed a second method employing coherent Amplitude Modulation. Both RF modes are currently integrated to the system, and the user may choose during setup. He completed the thesis requirement with a quantitative statistical analysis comparing the two methods.
- A third student is completing an assessment of using network protocols for interference mitigation.

The WSU author had the privilege of teaching a senior/first-year graduate student class on antennas and RF propagation in the Fall 2020. The anTpaTT system was demonstrated and measured results were compared to simulated results as part of the exercise.

Students employed by a DoD contractor expressed appreciation for ‘real-world’ applications that applied directly to their job(s). Course evaluations were positive, and the department plans to continue a long-term plan to build an applied-EM curriculum.

The anTpaTT system also offers opportunities for a wide variety of undergraduate research and senior capstone projects due to its interdisciplinary nature; potential topics include signal processing to improve pattern measurement accuracy, antenna positioner design, enhancement of the remote-access user interface as well as use of the range to measure antennas designed by students or used by students in RF systems.

Table 2. Descriptive statistics of online module quiz scores for VIP antenna range project group

Quiz	N	Mean	Standard Deviation
FCW-01 (Pre)	25	38.6667	20.31761
FCW-01 (Post)	22	83.4327	15.28862
FCW-02 (Pre)	22	40.0994	15.05042
FCW-02 (Post)	22	73.1023	14.46984
FCW-03 (Pre)	20	50.5357	18.69375
FCW-03 (Post)	18	86.7063	14.68995
FCW-04 (Pre)	17	57.2549	17.16890
FCW-04 (Post)	15	80.8889	17.61433
RFS-01 (Pre)	17	43.5294	25.72479
RFS-01 (Post)	16	85.0000	17.12698
RFS-02 (Pre)	16	53.7841	23.40198
RFS-02 (Post)	14	89.3961	14.00588
RFS-03 (Pre)	14	52.2857	23.26881
RFS-03 (Post)	14	76.6905	18.07982

4.3 Results from Related Online Learning Modules used by Project Participants

Preliminary results of the pre- and post-tests for the online modules indicate that participants had substantially increased average scores after each module as shown in Table 2. The anonymized data will be analyzed for inclusion in a full paper, and results may be compared with those of groups of students who used the modules in other settings.

The range is currently accessible by Internet using Guacamole, a remote desktop application that runs in a standard web browser, or using free SSH software such as MobaXterm. Figure 4 shows the remote desktop interface.

5. Conclusions and future work

The anTpaTT system can enhance undergraduate engineering education as a tool for teaching and learning electromagnetics, specifically antennas. It provides further value as the focus of an interdisciplinary undergraduate engineering project that has potential to persist for many years, several cohorts of students, and multiple generations of the anTpaTT system. Further, due to its portability and online accessibility, anTpaTT is a useful tool for outreach to pre-collegiate students.

Future work includes development of a secure web interface that does not require direct access to the operating system on the range computer but does allow remote operation of the range and storage of measurement parameters and results. We also plan to enhance the range's portability, to increase its utility for use in classroom instruction and in STEM outreach. Additionally, the students are investigating techniques to improve measurements, including investigation of the tradeoff between speed and accuracy for measurements of common types of directional and omnidirectional antennas that can be achieved by varying angular resolution of the measurements and possibly interpolating between measurement points, and mitigation of antenna pattern distortion that is caused by reflected signals.

References

[1] M. F. Iskander, "Technology-based global revitalization of electromagnetic education," *2015 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting*, 2015, pp. 1019-1020, doi: 10.1109/APS.2015.7304897.

[2] D. M. Douglas, et al., "Writing in the engineering design lab: How problem based learning provides a context for student writing," *American Society for Engineering Education Annual Conference and Exposition,* 2004.

[3] P. A. Johnson, "Problem-Based Cooperative Learning in the Engineering Classroom," *Journal of Professional Issues in Engineering Education and Practice*, vol. 125, no. 1, p. 8-11, 1999.

[4] J. J. Kellar et al., "A problem based learning approach for freshman engineering," *30th Annual Frontiers in Education Conference. Building on A Century of Progress in Engineering Education. Conference Proceedings (IEEE Cat. No.00CH37135)*, 2000, pp. F2G/7-F2G10 vol.2, doi: 10.1109/FIE.2000.896561.

[5] M. C. LaPlaca, W. C. Newstetter and A. P. Yoganathan, "Problem-based learning in biomedical engineering curricula," *31st Annual Frontiers in Education Conference. Impact on*

Engineering and Science Education. Conference Proceedings (Cat. No.01CH37193), 2001, pp. F3E-16, doi: 10.1109/FIE.2001.963748

[6] C. McIntyre, "Problem-based learning as applied to the construction and engineering capstone course at North Dakota State University," *32nd Annual Frontiers in Education*, 2002, pp. F2D-F2D, doi: 10.1109/FIE.2002.1158157.

[7] J. C. Perrenet, P. A. J. Bouhuijs, and J. G. M. M. Smits, "The Suitability of Problem-based Learning for Engineering Education: Theory and Practice", *Teaching in Higher Education*, vol. 5, no. 3, pp. 345-358, Jul. 1, 2000, doi: 10.1080/713699144.

[8] A. Striegel and D. T. Rover, "Problem-based learning in an introductory computer engineering course," *32nd Annual Frontiers in Education*, 2002, pp. F1G7-F1G12, doi: 10.1109/FIE.2002.1158138.

[9] K. Williams and G. Pender, "Problem-Based Learning Approach to Construction Management Teaching". *Journal of Professional Issues in Engineering Education and Practice*, vol. 128, no. 1, pp. 19-24, Jan. 2002, doi: 10.1061/10523928128.

[10] R.M. Capraro, M.M. Capraro and J.R. Morgan, *STEM Project-Based Learning: An Integrated Science, Technology, Engineering, and Mathematics (STEM) Approach*, 2nd ed. Springer Science & Business Media, 2013.

[11] S. Palmer and W. Hall, "An evaluation of a project-based learning initiative in engineering education", *European Journal of Engineering Education*, vol. 36, no.4, pp.357-365, Aug. 2011, doi: 10.1080/03043797.2011.593095.

[12] N. Hosseinzadeh and M. R. Hesamzadeh, "A course in power system analysis based on project based learning methodology," *2009 IEEE Power & Energy Society General Meeting*, 2009, pp. 1-6, doi: 10.1109/PES.2009.5275257.

[13] D. D. Stancil, N. Gist and Yi Jiang, "REAL: the remote educational antenna laboratory," *2007 IEEE Antennas and Propagation Society International Symposium*, 2007, pp. 5399-5402, doi: 10.1109/APS.2007.4396768.

[14] D. D. Stancil, S. K. Sharma and A. L. Fay, "The remote educational antenna laboratory: making it easier to add projects to antenna courses [education column]," in *IEEE Antennas and Propagation Magazine*, vol. 56, no. 1, pp. 211-220, Feb. 2014, doi: 10.1109/MAP.2014.6821782.

[15] D. D. Stancil, *personal communication*, July 15, 2020.

[16] HVS Technologies, "Low-Cost Antenna Measurement Systems," *Microwave Journal*, Mar. 1, 2001. Accessed May 19, 2020. [Online]. Available: https://www.microwavejournal.com/articles/3158-low-cost-antenna-measurement-systems

[17] "Guided Tutorial GRC [GNU Radio Companion]," *GNU Radio.* https://wiki.gnuradio.org/index.php/Guided_Tutorial_GRC (accessed May 13, 2021).

[18] GRBL: Motion control for makers. https://diymachining.com/grbl/ (accessed May 13, 2021).

[19] "The Free & Open Source Radio Ecosystem · GNU Radio," *GNU Radio*. http://www.gnuradio.org/ (accessed May 13, 2021).

[20] S. A. Sorby, B. J. Baartmans, "A Course for the Development of 3-D Spatial Visualization Skills," *Engineering Design Graphics Journal*, vol. 60, no. 1, pp. 13-20, Winter 1996.

[21] S. A. Sorby, B. J. Baartmans, "The development and assessment of a course for enhancing the 3-D spatial visualization skills of first year engineering students," *Journal of Engineering Education*, vol. 89, no. 3, pp. 301-7, Jul. 2000.

[22] S. A. Sorby, "Developing 3-D spatial visualization skills," *Engineering Design Graphics Journal*, vol. 63, no. 2, Aug. 13, 2009.

[23] S. Sorby, B. Casey, N. Veurink, A. Dulaney, "The role of spatial training in improving spatial and calculus performance in engineering students," *Learning and Individual Differences*, vol. 26, pp. 20-29, Aug. 1, 2013.

[24] S. Sorby, B. Baartmans, A. Wysocki, NSF Award DUE9752660: Multi-Media Software for the Development of 3-D Spatial Visualization Ability, Feb. 15, 1998.

[25] D. Bairaktarova, M. Reyes, N. Nassr, D. T. Carlton, "Spatial Skills Development of Engineering Students: Identifying Instructional Tools to Incorporate into Existing Curricula," *ASEE Annual Conference*, 2015.

[26] C. Cohen, D. Bairaktarova, "A Cognitive Approach to Spatial Visualization Assessment for First-year Engineering Students," *The Engineering Design Graphics Journal*, vol. 82, no. 3, Fall 2018.

[27] J. Garcia-Sheridan, S. Kim, R. Goff, V. Marojevic, N. Polys, A. Mohammed, C. Dietrich, "Instructional strategies and design for immersive wireless communication tutorials and exercises." *ASEE Annual Conference*, 2017.

[28] J. Garcia-Sheridan, V. Marojevic, R. Goff, N. Polys, C. B. Dietrich, "Lessons Learned from a Radio Spectrum Coexistence Competition: A Road Map to Engagement in Informal Education of Wireless Communication," *ASEE Annual Conference*, 2018.

[29] A. Mohammed, N. F. Polys, V. Marojevic, R. M. Goff, C. B. Dietrich, "Evaluating multi-view representations of a Web3D streaming server," *Proc. 22nd Int'l Conf. 3D Web Technology,* 2017.

[30] M. Chizh, A. Pietrelli, V. Ferrara and A. Zhuravlev, "Development of embedded and user-side software for interactive setup of a frequency-modulated continuous wave ground penetrating radar dedicated to educational purposes," *2017 IEEE International Conference on Microwaves, Antennas, Communications and Electronic Systems (COMCAS)*, Tel-Aviv, 2017, pp. 1-5.

[31] D. G. Macfarlane and D. A. Robertson, "SAFIRE: A close range real time millimetre wave radar for public education," *2007 Joint 32nd International Conference on Infrared and Millimeter Waves and the 15th International Conference on Terahertz Electronics*, 2007, pp. 924-925, doi: 10.1109/ICIMW.2007.4516794.

[32] G. L. Charvat, A. J. Fenn and B. T. Perry, "The MIT IAP radar course: Build a small radar system capable of sensing range, Doppler, and synthetic aperture (SAR) imaging," *2012 IEEE Radar Conference*, 2012, pp. 0138-0144, doi: 10.1109/RADAR.2012.6212126.

[33] K. E. Kolodziej *et al*., "Build-a-Radar Self-Paced Massive Open Online Course (MOOC)," *2019 IEEE Radar Conference (RadarConf)*, 2019, pp. 1-5, doi: 10.1109/RADAR.2019.8835726.

[34] R. S. Bhatia *et al*., "A Simple Radio Telescope Operating at Ku Band for Educational Purposes," in *IEEE Antennas and Propagation Magazine*, vol. 48, no. 5, pp. 144-152, Oct. 2006, doi: 10.1109/MAP.2006.277116.

[35] J. L. Besada, L. de Haro Ariet, B. Galocha and M. A. Salas-Natera, "ASYTRAIN: A new methodology for teaching and learning antennas," *2013 7th European Conference on Antennas and Propagation (EuCAP)*, 2013, pp. 3479-3481.

[36] S. K. Koul, "Popularizing Microwave Education and Research in India," *2011 IEEE MTT-S International Microwave Symposium*, 2011, pp. 1-4, doi: 10.1109/MWSYM.2011.5972985.

[37] M. G. Morrow, T. B. Welch, C. H. G. Wright and G. W. P. York, "Demonstration platform for real-time beamforming," *2001 IEEE International Conference on Acoustics, Speech, and Signal Processing. Proceedings (Cat. No.01CH37221)*, 2001, pp. 2693-2696 vol.5, doi: 10.1109/ICASSP.2001.940201.

[38] Anten'it: Game changing antenna technology. http://www.antenit.com. (accessed May 19, 2021).

[39] "Antenna Training and Measuring System: Festo LabVolt Series Datasheet" Festo Didactic, Inc., Eatontown, NJ, USA, Rep. 582074 (8092-00), May 2021. Accessed: May 19, 2021. [Online]. Available: https://labvolt.festo.com/solutions/9_telecommunications/69-8092-00_antenna_training_and_measuring_system.

[40] K. F. Warnick, E. Levine and H. Matzner, "IEEE publishes a revision of the standard for definitions of terms for antennas: educational kit for antennas and radiation [education column]," in *IEEE Antennas and Propagation Magazine*, vol. 56, no. 3, pp. 208-214, Jun. 2014, doi: 10.1109/MAP.2014.6867714.

[41] F. J. Dietrich, "Backyard range-a real backyard (actually front yard, garage and driveway) antenna range on a shoestring," in *IEEE Antennas and Propagation Magazine*, vol. 34, no. 5, pp. 78-80, Oct. 1992, doi: 10.1109/74.163821.

[42] C. W. Hearn, D. S. Birch, D. Newton and S. L. Chatlin, "Open-Source Antenna Pattern Measurement System," *2020 Antenna Measurement Techniques Association Symposium (AMTA)*, 2020, pp. 1-6.

[43] V. Picco and K. Martin, "An Automated Antenna Measurement System Utilizing Wi-Fi Hardware," in *IEEE Antennas and Propagation Magazine*, vol. 53, no. 6, pp. 173-184, Dec. 2011, doi: 10.1109/MAP.2011.6157745.

[44] What is LabView? – NI. https://www.ni.com/en-us/shop/labview.html. (accessed May 26, 2021).