IEEE AP-S Student Design Challenge 2011: Radiation Patterns on a Budget

MSU Spartans: Andrew Temme, *Student Member, IEEE,* Donald VanderLaan, *Student Member, IEEE,* and Stephen Zajac, *Student Member, IEEE*

***Abstract*—An important characteristic of an antenna is the radiation pattern which determines in which direction(s) radiation is concentrated. Typical antenna radiation pattern measurement systems consist of measurement equipment and a controlled environment. Both of these elements can individually be prohibitively expensive, in terms of both cost and laboratory space. This paper outlines a low-cost (less than $1500) system for use at 2.4 GHz that is portable and requires a limited amount of space. Measurement is accomplished using a self-contained RF system, a simply constructed antenna rotator, a readily available data acquisition and motor controller circuit, and Matlab. A key feature of this system is an extremely low-cost and simple rotatory joint which eliminates cable twisting.**

***Index Terms*—Antenna measurements, Antenna radiation patterns, IEEE Antennas and Propagation Society, Student activities, Student experiments**

I. Introduction

THE radiation pattern of an antenna determines in what directions radiation from the antenna is concentrated. This allows for a signal to be sent or received in one particular direction or in multiple directions. When receiving a signal, the radiation pattern can help to reduce noise and increase the signal-to-noise ratio (SNR).

While simulations provide relatively good predictions of antenna patterns, differences from simulations can be substantial due to construction techniques and factors not included in simulations.

Typical antenna pattern measurement ranges vary in cost from thousands of to hundreds of thousands of dollars. Measurement equipment alone can be more than ten thousand dollars, not to mention construction materials, manufacturing and installation. This high cost can be prohibitive for schools and small businesses. For these users, extreme accuracy may not be needed. For such a case, the design may be simplified and the cost significantly reduced.

The objective of this project is to design an antenna radiation pattern measurement system with ±0.5 dB of accuracy if placed in an anechoic environment on a budget of $1500.

II. Goals and Specifications

As given in the Design Challenge announcement, the goals and specifications are the following:

- Design a measurement system that can be used to find the gain and radiation pattern of a test antenna. An anechoic chamber is not required, so inaccuracies due to reflections by nearby objects are inevitable. However, a reasonable argument must be presented that the gain measurement accuracy would be ±0.5 dB in an anechoic environment.
- The system must be safe and durable, easily reproducible by others, inexpensive, and portable so that it can be demonstrated at the symposium.
- The system must operate at 2.4 GHz, generate its own signal, have its own power supply, and fit on a table or two closely spaced tables. Readily available software (e.g., student versions of C, Matlab, Visual Basic, LabView) or free software packages may be used.
- The total cost for reproduction of the system must be less than $1500. All equipment and software (except for a computer, if needed) must be included in the budget. The use of a computer is allowed and does not have to be included in the $1500 budget [1].

III. System Overview

To determine the radiation pattern of an antenna, herein referred to as the antenna under test (AUT), one needs an RF energy source, a reference antenna, a platform for rotating either the reference antenna or the AUT, and an RF power detector. One antenna is kept stationary while the second antenna is rotated relative to the other antenna. The RF signal is transmitted from one antenna and received by the other antenna. The received signal is measured and recorded in relation to the angle between a reference point and the AUT.

The system outlined in this paper keeps the reference antenna stationary and uses it as the transmitting antenna while the AUT is rotated while receiving the transmitted signal.

The assembled system is shown in operation in Fig. 1.

A. Theory of Operation

Power is supplied to the system from a standard 120 VAC wall outlet which is converted to 5, 12, and 42 VDC. The 5 VDC supply is used to power the RF source, amplifiers, and detector along with other low-power electronics. The 12 VDC supply is used to power the control logic of the data acquisition

The authors are graduate students in the Department of Electrical and Computer Engineering, Michigan State University, East Lansing, MI, 48824 USA e-mail: temmeand@msu.edu.

Fig. 1. Assembled system.

and motor controller circuit while the 42 VDC is used to power the motor.

The 5 V and 12 V power supplies are implemented using IC linear regulators, as opposed to switching regulators. This choice was made to avoid the interference that switching regulators can generate. This interference at the fundamental switching frequency can be quite significant, with harmonics extending well into the frequency range of the selected power detector. The 42 V power supply is implemented using a discrete MOSFET as a linear regulator. This produces a higher output current limit than IC regulators can provide, allowing the system to drive more demanding motor loads.

The 120 VAC is first transformed down to a lower AC voltage using a toroidal transformer. The secondary voltage of these transformers was picked to allow for a 2 V drop across the diode bridge, and a 2 V to 7 V drop across the liner regulator, ensuring that the power supply stays in regulation at all times. This voltage is then full wave rectified by a diode bridge, and smoothed by a filter capacitor. The resulting DC voltage is finally regulated down to the appropriate voltage by the linear regulator in each power supply. Printed circuit boards for all three power supplies were provided by [2], and customized to fit the specific voltage requirements of the project.

The RF signal is generated using a voltage controlled oscillator (VCO) operating between 2.315 and 2.536 GHz. The signal is amplified to approximately 16 dBm before being transmitted from the reference antenna.

The reference antenna is a stationary, reflector type antenna purchased from [3]. This antenna was selected for its relatively high gain (15 dBi) and narrow beamwidth (16° horizontal, 21° vertical) [3]. This helps to focus the transmitted power on the AUT while helping to reduce reflections from surrounding areas.

Given the above reference antenna and assuming a separation between the two antennas of one meter, the path loss

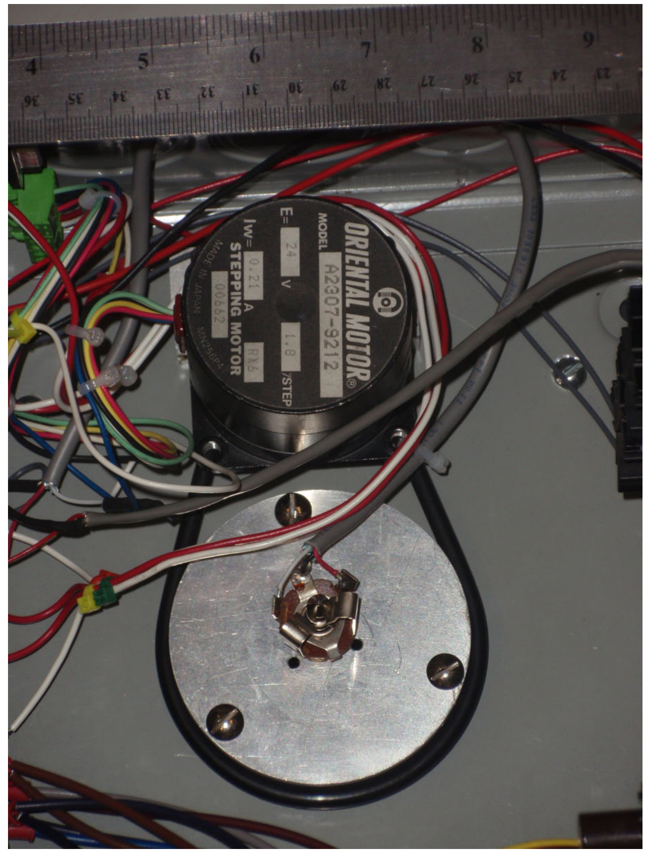


Fig. 2. Rotary joint which eliminates twisting in the cables.

is calculated as 40.05 dB using the Friis equaiton [4]. The received signal is amplified by 14 dB, passed to a filter and then to a logarithmic-law power detector. The detector has a dynamic range of -60 dBm to 0 dBm. Typical insertion loss of the filter is 1.8 dB at the operating frequency. Given the above values, the gain of the AUT can theoretically have a maximum value of -1.5 dBi while nulls can be measured down to -60 dBi. If the amplifier on the receiver end is removed, these values change to -47.5 and 12.5 dBi.

The AUT is mounted on a styrofoam antenna stand which sits on top of a small, rotating table. A power measurement is taken at a user specified number of angles as the AUT is rotated a full 360°.

Rotation is achieved using a low-cost stepper motor and motor controller, which is controlled by the computer over an RS-232 connection. Cost and feature set were considered when choosing a controller, and the selected model provides up to four digital inputs/outputs (selectable) and two, 8-bit analog inputs. However only four inputs/outputs may be used simultaneously, which was sufficient for our application.

The rotating table is supported using a hollow, low-cost circular ball-bearing "lazy-susan" turn-table. The motor controller operates a motor which is connected to a hollow shaft on the rotatory table by a rubber belt. This hollow shaft in mounted through the "lazy-susan" bearing. The mechanical gear ratio was found to be 2.7397 by counting the number of steps needed to rotate the table 10 continuous revolutions. Combined with 360 half-steps, the angular resolution of the

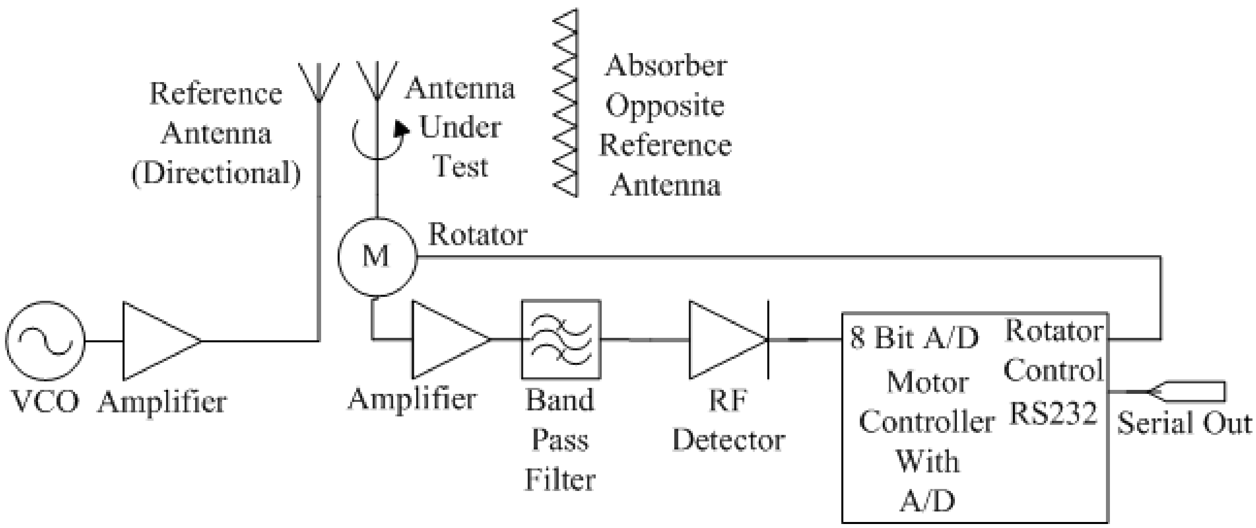


Fig. 3. Block diagram of system.

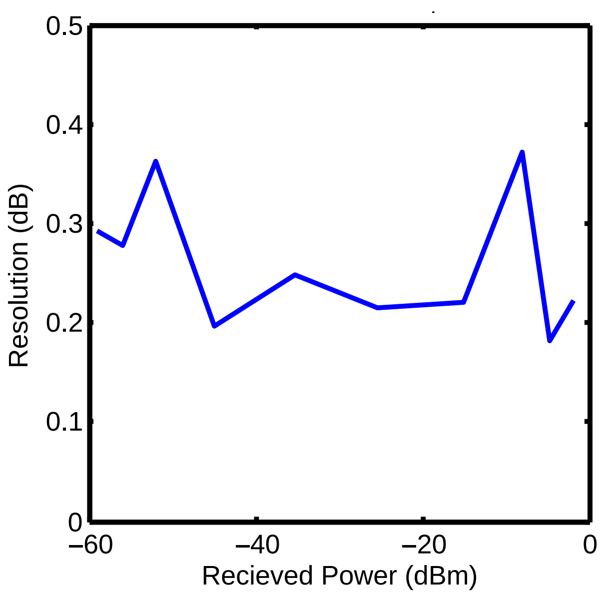


Fig. 4. Detector resolution versus input power.

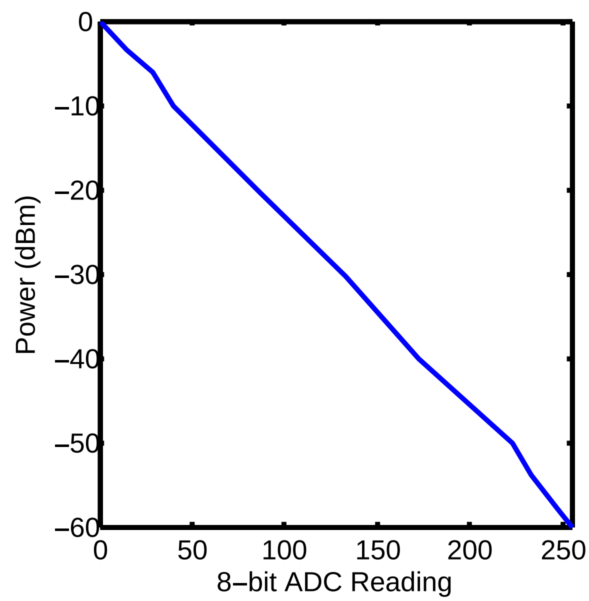


Fig. 5. Calibration data for power detector.

mechanical rotator is 0.365°, alternately put, the rotator can point the antenna in 986 unique directions.

The power detector outputs a DC signal between 0.5 and 2.2 V. This output signal, ground connection, and the power for the detector are carried through the rotator table using a 6.35 mm TRS plug and jack which serves as a rotatory joint connector as shown in Fig. 2. This rotatory joint eliminates twisting of the cables which is typically a major problem. Commercial rotatory joints are expensive whereas the rotatory joint used here costs less than ten dollars.

The TRS plug is mounted inside the hollow shaft fixed to the rotation plate, such that the TRS plug, hollow drive shaft, and "lazy-susan" bearing are all concentric and rotate about the same axis, which itself is at the center of the rotation plate. Once through the rotator table, the DC signal is amplified to 0 and 5 V – to utilize all 8 ADC bits – and carried to the analog to digital converter on the motor controller board. Here it is read and transmitted to the computer over an RS-232 link.

B. System Accuracy

An ideal anechoic environment has two defining features that would make an antenna pattern measurement system more accurate. First, all six sides of the room are lined with RF absorber material to prevent multiple reflections that would affect the accuracy of the system. Second, the entire room is shielded from external radiation that could also affect system accuracy. With a budget of $1500 and a requirement that the system be portable, these two criteria must be met through alternative means.

To reduce multiple reflections our approach is two-fold. First, the reference antenna was selected to have a very narrow

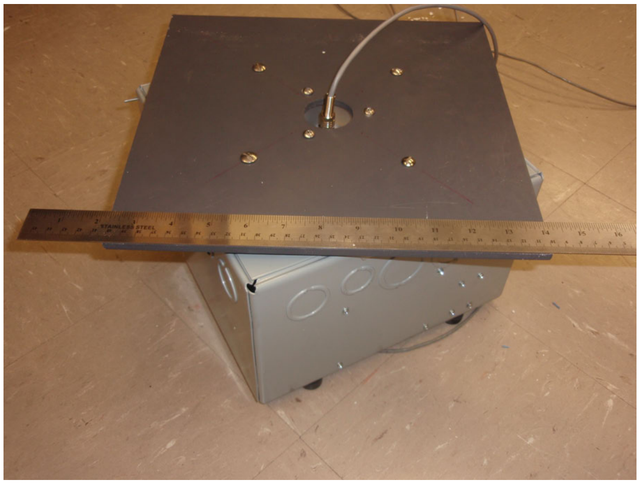


Fig. 6. Rotator table top.

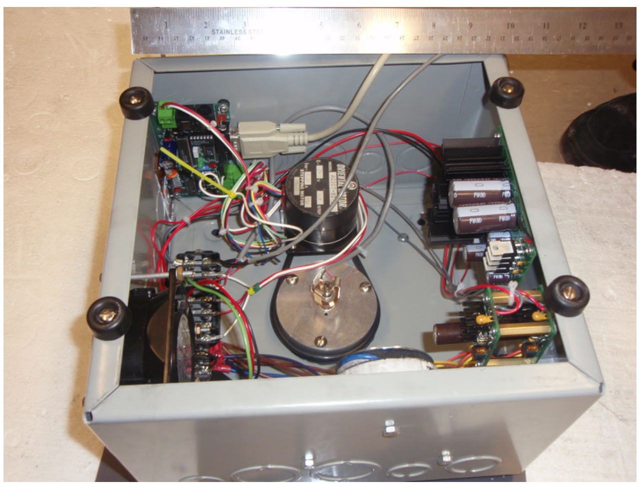


Fig. 7. Rotator base.

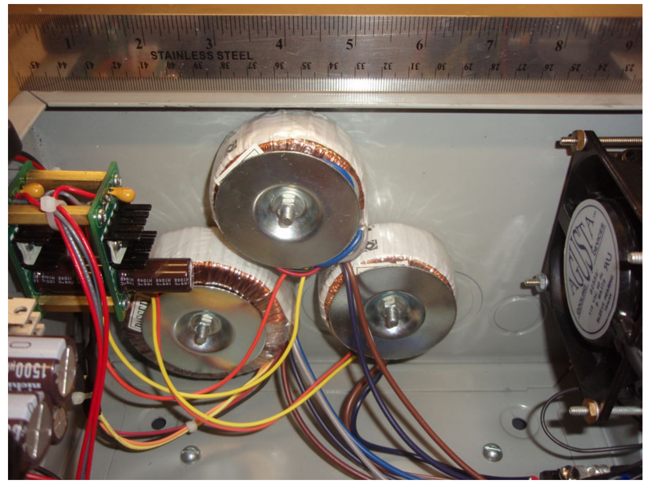


Fig. 8. Transformers (right), power supplies (left), and rotatory joint (bottom).

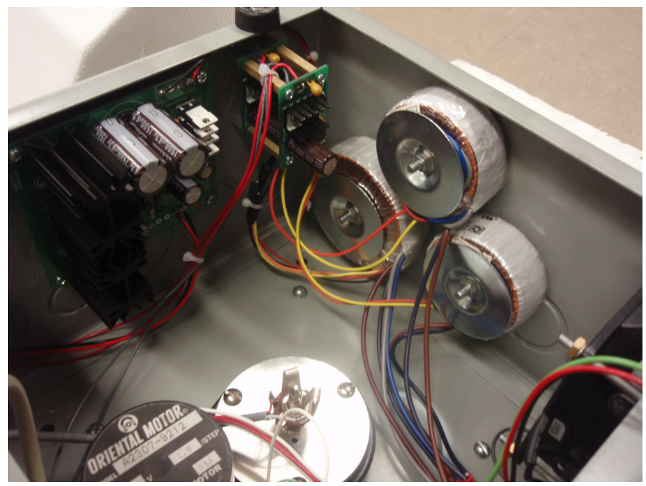


Fig. 9. Transformers (right), power supplies (left), and rotatory joint (bottom).

beamwidth such that at a distance of six feet, the main beam has a diameter of less than two feet. Second, a single RF absorber is placed behind the antenna being measured and in the path of the reference antenna. The industry standard size of RF absorber material is a two foot by two foot square, which in this setup will absorb most of the radiated power from the transmitted antenna which would otherwise be reflected.

The choice of RF absorber material comes down to two factors; size and absorption performance in dB at a given frequency. In general, the absorption is directly proportional to the height of the material. For example, an absorber with a height of 72 inches will outperform a three inch high absorber in terms of attenuation. The 72 inch high absorber also maintains this absorption much lower in frequency than the three inch model. In this application at 2.4 GHz the ideal height is approximately eight inches for a pyramidal absorber. The specific model selected has a one way absorption of -35 dB. This means that if a metal surface were to be placed directly behind the absorber and the incident signal strength is 0 dBm, the reflected signal will travel through the absorber twice. The reflected signal strength will then be -70 dBm, which is below the lower limit of our power detector. The only concern then becomes reflections of the side lobes of the reference antenna, which are very small due to the choice a narrow beamwidth antenna.

The second criteria of an anechoic environment is the reduction of interference from external signals. With modern spectrum analyzers the resolution bandwidth can go as low at 1 Hz, making it very easy to distinguish between the test signal and interference. The only exception is the rare case where the interference is within 1 Hz of the test signal. Due to budget requirements our project uses a diode detector with a very wide bandwidth of 8 GHz. This type of detector is inexpensive, but has the drawback of essentially acting as a spectrum analyzer with the resolution bandwidth set to 8 GHz. This means that it is impossible to distinguish between power at different or multiple frequencies. The solution is to put a bandpass filter in front of the power detector. The Mini-circuits bandpass filter currently in use has a -3 db bandwidth of 220 MHz, while a coupled line bandpass filter under development for this project has a -3 db bandwidth of 120 MHz, see Section VIII-B for more discussion of this filter design. This is far from the 1 Hz resolution bandwidth of a spectrum analyzer, but much better than the 8 GHz resolution bandwidth of the unfiltered power

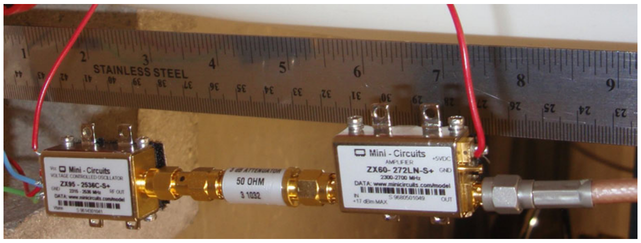


Fig. 10. VCO (left), 3 dB attenuator (center), 14 dB linear amplifier (right).

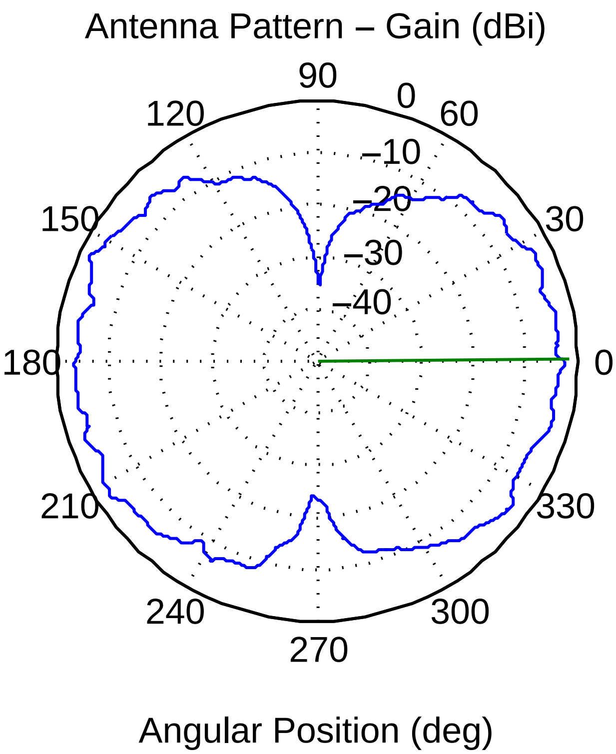


Fig. 11. Pattern for a dipole antenna.

detector.

The accuracy of absolute gain measurements is determined by a reference dipole tuned to resonate exactly at 2.4 GHz. The gain of the main lobe of this antenna is defined as 0 dBd, and the gain of all other antennas will be referenced to this dipole. The gain relative to an isotropic radiator is then simply dBi = dBd + 2.2 dB.

The detector was characterized over the input power range for power received versus voltage read. The results are shown in Fig. 4. Using this data, the resolution of the system was derived and is given in Fig. 4. Gain measurements can be resolved to better than ±0.5 dB over the entire detected power range.

IV. Schematics, Parts, and Budget

A. System Schematics

Fig. 3 shows a block diagram of the system. Schematics for the power supplies can be found online at [2]. Motor controller documentation is available from [5]. Datasheets for

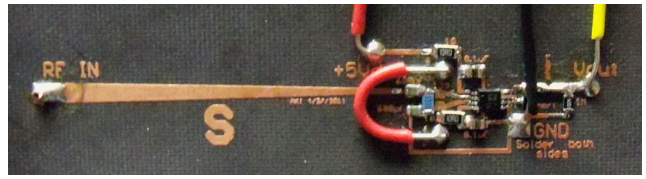


Fig. 12. Microstrip based power detector.

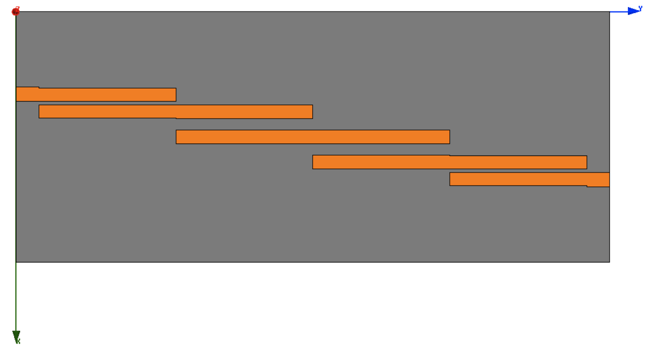


Fig. 13. Filter design.

RF component are available from [6]. Assembly instructions for the reference antenna are available from [3].

B. List of Parts and Budget

Table I gives a list of parts and the associated cost. The total cost to replicate the system is $1,047.83.

V. Assembly Instructions

A. Rotator Top and Cable Rotator

In the top of the rotator base, use a hole saw to cut a hole that is slightly larger than the hollow shaft. Also drill holes for mounting the lazy-susan bearing and all other components. Attach the plastic rotator table top to the lazy-susan bearing and then the lazy-susan bearing to the rotator base. Install the 6.35 mm TRS plug through the hollow shaft. Fig. 6 shows the rotator table top.

Mount the motor controller, motor, power socket, and any other desired accessories on the inside of the rotator base. Fig. 7 shows one possible assembly configuration.

B. Power Supplies

Assemble power supply kits according to the supplier's instructions. Mount the power supply circuit boards and associated transformers inside the rotator base. Fig. 9 shows the power supplies and transformers.

C. RF Components

1) RF Source: Connect the VCO (ZX95-2536C+) to the 3 dB attenuator (VAT-3+). Connect the amplifier (ZX60-272LN+) to the other end of the attenuator using a SMA Male To SMA Male barrel adapter (SM-SM50+). See Fig. 10. Tighten connections to 8 in. lbs.

TABLE I
BUDGET AND PARTS LIST

Qty.	Item	Description	Supplier	Part Number	Unit Price	Total
1	Lazy Susan	Lazy Susan Bearing, 6in	Ace Hardware	9548	$ 6.50	$6.50
2	Components	1.5in extruded TO-220 heatsink	AMB Audio Shop	529802B00000	$ 2.00	$4.00
1	Components	International Rectifier power MOSFET	AMB Audio Shop	IRLZ24N	$ 3.50	$3.50
1	Power Supply	Power Supply Circuit Boards	AMB Audio Shop	Sigma 11	$ 10.00	$10.00
2	Circuit Boards	Power Supply Circuit Boards	AMB Audio Shop	Sigma 25	$ 7.00	$14.00
1	Motor	Stepper Motor	Anaheim Automation	17L9	$ 97.00	$97.00
1	Transformer	15VA, 12V + 12V	Avel Lindberg	Y236002	$ 20.23	$20.23
1	Transformer	15VA, 9V + 9V	Avel Lindberg	Y236001	$ 20.23	$20.23
1	Transformer	50VA, 18V + 18V	Avel Lindberg	Y236204	$ 25.51	$25.51
1	Absorber	2ft x 2ft absorber	ETS-Lindgren	EHP-8PCL	$ 60.00	$60.00
1	Mounting Hardware	Mounting Hardware	Hardware store		$ 20.00	$20.00
1	Reflector Antenna	2.4 GHz 15 dBi Die-cast Grid Antenna	L-Com	HG2415G-NF	$ 36.62	$36.62
1	Cinder Block	Cinder block	Lowes		$ 1.00	$1.00
1	Clamp	Clamp	Lowes		$ 5.00	$5.00
1	PVC Pipe	PVC pipe, Schedule 40, 1 1/4in, 6ft	Lowes		$ 2.33	$2.33
2	Antenna Stand	Rose Covers used as antennas stands	Lowes		$ 6.23	$12.46
1	Matlab	Matlab Student Version	MathWorks		$ 100.00	$100.00
1	Rotator Base	Indoor Steel Enclosure, 10in by 10in by 6in	McMaster-Carr	75065K38	$ 27.79	$27.79
1	VCO	2.4GHz - 2.67GHz Oscillator	Mini-circuits	ZX95-2536C-S+	$ 44.95	$44.95
1	Attenuator	3dB Attenuator	Mini-circuits	VAT-3+	$ 11.95	$11.95
1	Filter	Bandpass filter	Mini-circuits	VBF-2360+	$ 34.95	$34.95
2	Amplifier	Power Amplifier	Mini-circuits	ZX60-272LN-S+	$ 39.95	$79.90
1	Detector	Power Detector	Mini-circuits	ZX47-60-S+	$ 89.95	$89.95
1	Components	Misc. Components: potentiometers, heat shrink, terminal blocks, etc. as per personal manufacturing preference	Mouser		$ 30.00	$30.00
1	Adapter	N-Male to SMA Female adapter	Mouser	523-242113	$ 7.50	$7.50
1	Cable	SMA Male RG142, 36in.	Mouser	523-135101-07-36.00	$ 25.49	$25.49
1	Adapter	SMA-Female to SMA-Female adapter	Mouser	523-132169	$ 3.97	$3.97
1	Adapter	SMA-Male to SMA-Male adapter	Mouser	523-132168	$ 5.16	$5.16
1	Components	Power Supply Components	Mouser/AMB Audio		$ 66.84	$66.84
1	Hollow Pipe	Schedule 80 Al Bare Pipe 6061 T6 - 10in	OnlineMetals.com		$ 22.00	$22.00
1	Motor Controller	Stepper Motor Controller	Pontech	STP100	$ 159.00	$159.00
					Total	**$1,047.83**

2) RF Receiver: The receiver consists of an amplifier, filter, and power detector. Connect the filter (VBF-2360+) between the amplifier (ZX60-272LN+) and the RF detector (ZX47-60-S+). Tighten connections to 8 in. lbs. Attach the detector to the top of the rotator table and connect power, ground, and signal cables from the rotatory joint cable to the detector.

D. Reference Antenna

Assemble the reference reflector antenna according to the supplier's instructions [3]. Using the supplied mounting hardware, mount the reference antenna to the top of the PVC pipe according to the supplier's instructions. Use a C-clamp to attach the pipe to the cinder block or create any other stand for the antenna. Run a DC power cable to the reference antenna from the rotator base. Connect the DC power cable to RF source components assembled earlier. Using an N-to-SMA adapter, connect the RF source to the reference antenna. Use a potentiometer to adjust the V_{tune}. The reference antenna should be between four and six feet from the rotator base.

E. Antenna Stand

Glue the bases of two rose covers together to form a stand for the test antenna using Elmer's glue. Remove just enough styrofoam from the bottom of the stand (top of one of the rose covers) for the detector and cables so that the stand sits flush on top of the rotator table. Place a small hole in the top of the stand and feed an SMA cable through the hole and connect it to the RF detector. Position the stand on the rotator table top and affix using Velcro or other suitable method that will keep the stand upright when a test antenna placed on top. The unconnected end of the SMA cable is the antenna under test port (AUT port).

VI. OPERATING INSTRUCTIONS

Always use a grounding wrist strap or other grounding device when touching any metal parts of the system including cable connectors or antennas.

The antenna pattern measurement system emits RF energy whenever power is turned on at the base of the rotator. Turn off power whenever making any connections or when working in front of the reference antenna.

A. Measurement Preparation

The antenna under test (AUT) should be placed on top of the styrofoam antenna stand. Align the reference antenna to be coplanar with the desired measurement plane of the AUT. Align the polarizations of the AUT and reference antenna. Ensure the AUT is secured and will not move during multiple, complete revolutions.

B. Software

Execute the `AntennaPatternCentralControl.m` script to obtain a pattern measurement.

VII. Example Results

Using the system outlined above, the radiation pattern of a tuned dipole antenna was measured and is plotted in Fig. 11. One can see the expected figure-eight pattern of a dipole antenna. The pattern also shows the maximum gain of the dipole to be between approximately -2 and -3 dBi. Other measured antennas included monopoles and antennas from [7].

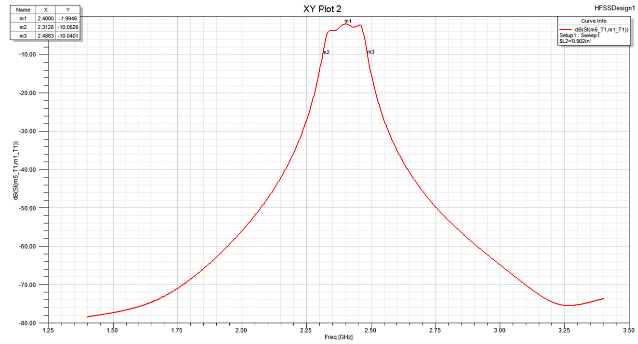


Fig. 14. Response of the described filter design.

VIII. Future Work

A. Power Detector

A microstrip based power detector was prototyped for the system and is shown in Fig. 12. The selected power detector is an Analog Devices Logarithmic Detector AD8313 [8].

Connection to the circuit board is made using an SMA jack. The circuit board design is derived from the suggested design given in the datasheet found online at [8]. Fabrication of the circuit board was done in house using a photo etching process. The circuit is constructed on 31 mil thick Rogers Duroid 5880 circuit board that was sent as a sample from Rogers.

Initial testing showed inconsistent results in measured power. Resistors and matching networks were varied in order to adjust the slope of the output and the transferred power. A coaxial power detector from Mini-circuits was substituted into the current design while work continues on the microstrip based power detector.

B. Microstrip Filters

A filter is needed for the microstrip based power detector presented in the previous section. A design procedure for side coupled bandpass filters is presented by Pozar in [9]. Lumped element filters are normally designed using lowpass filter prototype values, which are then frequency and impedance scaled to meet a specific filter application. Pozar's method uses the same lowpass filter prototype values, but implements resistor and capacitor values with edge coupled microstrip lines instead of lumped elements.

This first step is to pick the order and desired response of the filter. An N^{th} order filter is implemented using N+1 edge coupled microstrip lines, where the roll-off between the pass band and stop band is $N \times 20$ dB/dec. A choice of N=3 provides a good compromise between filter size and attenuation performance. Filter response is specified in terms of pass-band ripple and stop-band attenuation. For example, Butterworth-type filters have a flat pass-band, while Chebyshev-type filters have higher stop-band attenuation, at the expense of pass-band ripple For this project, stop-band attenuation is more important that a flat pass-band, so 3dB equal ripple lowpass filter prototype constants were selected.

The next step is to set the fractional bandwidth of the filter, which is defined as BW/FO. This fractional bandwidth, along with the low-pass prototype constants are then used to calculate the admittance inverter constants for each edge-coupled microstrip section. Finally, the admittance inverter constants can be used to determine the required even and odd-mode impedances of each microstrip section.

Given a specific circuit board material and thickness, the width (W) of each microstrip, and the spacing (S) between adjacent microstrip lines can be numerically determined to implement the required even and odd-mode impedances. The length (L) of each edge-coupled microstrip section determines the center frequency of the filter, and should be a quarter wavelength. With this length picked to give a center frequency of 2.4 GHz, the filter design is now complete.

Ansoft HFSS [10] was used to verify the design shown in Fig. 13. The dimensions of the completed filter are 3.75 in x 2 in, which is small enough to be placed on the antenna rotator platform. The simulated attenuation performance S_{21} is shown in Fig. 14. The -3 dB bandwidth is about 120 MHz, and the insertion loss at 2.4 GHz is 2 dB. To decrease the bandwidth, the odd mode impedance can be increased, which effectively increases the spacing (S) between adjacent microstrip lines. This also increases the insertion loss since the coupling between microstrip lines is reduced, so there is a minimum practical bandwidth that can be obtained. An insertion loss of 2 dB was determined to be a reasonable compromise for reduced bandwidth.

IX. Conclusion

The system described herein is a low-cost implementation of an antenna pattern acquisition system for characterization at 2.4 GHz. The system satisfies all the announcement requirements: accuracy to within ± 0.5 dB for anechoic operation, durable, portable, reproducible, self contained and stand-alone, and implementable for under \$1500 - which doesn't include the price of a control computer.

In addition to the aforementioned requirements, a number of other features and innovations were added to further the utility of the system. First, antenna rotation systems often deal with cord tangling problems as the cord wraps around the antenna stand. Not only does this require the antenna to reverse rotation and unwrap the cord after pattern acquisition, but it also presents the possibility that the cord may catch on an anechoic spike and tip the entire antenna and stand over - landing on and damaging the anechoic floor. Systems that bypass this requirement often employ an RF rotary joint, which has finite life and - of significant concern here - can be very costly. Instead of transferring the RF signal across the plane of rotation, this implementation moves the detector across the rotation plane such that it is fixed with respect to the rotating antenna-under-test coordinate system. Therefore, the rotary joint must only pass very low frequency signals. A $5 TRS plug and socket (intended for audio applications) is more then sufficient, and although not intended for extended rotation, is easily and cheaply replaced should the need arise.

Another innovation, concerning the reduction of pattern acquisition time and the increase of angular sampling, is that of the application of the "equivalent time sampling" modes often seen in oscilloscope technology. As rotation is achieved using a stepper motor, either the motor must be stopped at each angle for measurement, or must be rotated continuously and slowly enough to acquire the gain at the desired number of angular samples. The latter requires the system to be able to index the current position, such as to compensate for acceleration and a non-ideal motion profile - which was implemented in our system. However, continuous rotation at low velocities is prone to resonance and requires a controller either with micro-stepping or electronic viscosity, features which are found only on more cost-prohibitive controllers. To alleviate this problem, the antenna was instead rotated at a rate above resonance and an "equivalent sampling" methodology was used. The antenna makes multiple revolutions, each filling in samples between those taken in prior rotations - just as an "equivalent time sampling" oscilloscope requires multiple periods in order to obtain a sufficiently sampled waveform. For oscilloscope application, this meant it was restricted to repetitive waveforms. However here this is not a restriction - a complete rotation of the antenna presents the system exactly as it was any integer number of rotations past. Therefore, this system is able to acquire very high angular sampling while still keeping acquisition time to a minimum. Acquisition time greatly depends on the accuracy desired, but ranges from under 10 seconds for crude estimates to anything on up.

The system was experimentally found to have a dynamic range of 60 dB, more then adequate for most antenna characterization. The system is currently setup to measure patterns falling into either -61.6 to -1.5 dBi or -47.5 to 12.5 dBi, however additional amplifiers or attenuators can be inserted to achieve most practical ranges with less then 60 dB of dynamic range.

ACKNOWLEDGMENT

The authors would like to thank Dr. Edward Rothwell for his guidance on this project and Raoul Ouedraogo for his help in the manufacturing of the needed circuit boards.

This material is partially based upon works supported by the National Science Foundation Graduate Research Fellowship under Grant No. DGE0802267.

REFERENCES

[1] IEEE Antennas Propagation Society, "IEEE AP-S Student Design Challenge 2011: Radiation Patterns on a Budget," http://www.apsursi2011.org/StudentDesignChallenge.asp.

[2] AMB Audio Laboratories, "The sigma11 Regulated Power Supply," http://www.amb.org/audio/sigma11/.

[3] L-com Global Connectivity, "2.4 GHz 15 dBi Die-cast Grid Antenna - 12in N-Female Connector - HG2415G-NF," http://www.l-com.com/item.aspx?id=21694.

[4] David Archer, "LearningMeasure.com - Friis Transmission Equation Calculator," http://www.learningmeasure.com/cgi-bin/calculators/friis.pl.

[5] Pontech, "STP100 — PONTECH," http://www.pontech.com/details/120.

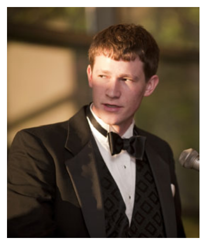
[6] Mini-Circuits, "Mini-Circuits RF/IF Designer's Guide," http://www.minicircuits.com/.

[7] R. Ouedraogo and E. Rothwell, "Metamaterial inspired patch antenna miniaturization technique," in *Antennas and Propagation Society International Symposium (APSURSI), 2010 IEEE*, july 2010, pp. 1 –4.

[8] Analog Devices, "AD8313 | 0.1 - 2.5 GHz, 70 dB Logarithmic Detector/Controller | Detectors | RF/IF ICs | Analog Devices," http://www.analog.com/en/rfif-components/detectors/ad8313/products/product.html.

[9] D. M. Pozar, *Microwave Engineering*. Wiley, New York, 1997.

[10] Ansoft, "Hfss," http://www.ansoft.com/products/hf/hfss/.



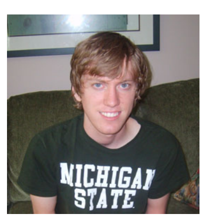
Andrew Temme (M'09) earned his B.S. degree in electrical engineering from Michigan State University, East Lansing, MI, in May, 2010.

As an undergraduate he worked in the Smart Microsystems Laboratory, Michigan State University, before joining the Electromagnetics Research Group in 2008 where he remains. His interests include through-wall radar, antenna design, and microwave measurement techniques.

Don VanderLaan (M'11) completed a B.S. in electrical engineering at Michigan State University in May 2009.

Don is an NSF Graduate Research Fellowship recipient, and works with the Biomedical Ultrasonics & Electromagnetics laboratory at Michigan State University. Interests are thermal therapy/hyperthermia treatment achieved through focused ultrasound, as well as modeling wave propagation in tissue and similarly dispersive media.

He is currently researching the theoretical constraints causality imposes on dispersion relations for Green's function-based tissue modeling.



Stephen Zajac (M'06) received his B.S. degree in electrical engineering from Michigan State University in 2009, and is currently working towards the M.S. degree in electrical engineering, also at Michigan State University.

Stephen is a graduate teaching assistant in the engineering department, having taught lab courses ranging from circuits to optics. He is also a graduate research assistant at the National Superconducting Cyclotron Laboratory, working on high power RF amplifier development. His interests include circuit design at audio and microwave frequencies, along with practical applications of EM theory.