The MIT IAP Radar Course: Build a Small Radar System Capable of Sensing Range, Doppler, and Synthetic Aperture (SAR) Imaging*

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***Abstract*—MIT Lincoln Laboratory sponsored a radar short course at MIT campus during the January 2011 Independent Activities Period (IAP). The objective of this course was to generate student interest in applied electromagnetics, antennas, radio frequency (RF) electronics, analog circuits, and signal processing by building a short-range radar sensor and using it in a series of field tests. Lectures on the fundamentals of radar, modular RF design, antennas, pulse compression and synthetic aperture radar (SAR) imaging were presented. Teams of three students built a radar system from a kit. This kit was developed by the authors and uses a frequency modulated continuous wave (FMCW) architecture. To save costs, empty metal coffee cans are used for antennas, components are mounted on a wood block, the system uses only six coaxial microwave parts, analog circuitry on a solderless breadboard, and runs on eight AA batteries. Analog data is acquired by the audio input port on a laptop computer. The total cost of each kit was $360 which made this radar technology accessible to students. Of the nine student groups, all succeeded in building their radar, acquiring Doppler vs. time and range vs. time plots, seven succeeded in acquiring SAR imagery, and some groups improved the radar system. By presenting these difficult topics at a high level while at the same time making a radar kit and performing field experiments, students became self motivated to explore these topics and much interest in radar design was generated.**

I. Introduction

Electromagnetics as a field of study is not always a favorite of the undergraduate student. Students must first understand the fundamentals in order to achieve the level of understanding necessary to work on the more interesting sensor systems. Understanding the fundamentals requires numerous courses over years of study. These courses tend to be tedious, difficult, and often discouraging to students.

Recently MIT Lincoln Laboratory sponsored a short radar course at MIT campus during the January 2011 IAP, where the objective was to generate interest in applied electromagnetics, including antennas, scattering, and RF design, by skipping ahead of the in-depth theoretical background to building a short-range radar sensor and using it in a series of field tests. The philosophy was that students have a self interest in making their radar work properly thereby providing a self-motivated learning experience and (hopefully) a long-term interest in electromagnetics.

A series of lectures on the basics of radar, modular RF design, antennas, pulse compression and SAR imaging were presented. Teams of three students received a radar kit. Nine teams participated in the course.

To make this level of radar technology accessible to students, a low-cost radar kit was developed by the authors with a total cost of $360 in materials per kit. The radar kit was an S-band FMCW radar centered at 2.4 GHz with less than 20 mW of transmit power. To reduce cost, the antennas (transmit and receive) were made from coffee cans in an open-ended circular waveguide configuration. All components were mounted on a block of wood similar to an early 1920s radio set providing a clear outline of the radar's design. The analog signal chain was implemented on a solderless breadboard for quick fabrication and easy modification. The video output and transmit synchronization pulses were fed into the right and left audio inputs of a laptop computer for digitization. To make the kit portable it runs on eight AA batteries.

The radar operates in three modes; Doppler, ranging, and SAR imaging. To record data, a student uses a .wav recorder program (for example, 'Audacity') in the computer. MATLAB scripts read the .wav data, process, then form the appropriate plots.

Of the nine student groups all succeeded in building their radar, acquiring Doppler vs. time and range vs. time plots. Seven of the nine groups succeeded in acquiring at least one SAR image. Some groups made improvements on the radar kit design.

Most students were from MIT but a small contingent were from Northeastern University, one built this radar as an independent study at Michigan State University (MSU), another at Whittenberg University, and two senior design projects are

TABLE I
COURSE SYLLABUS.

Day 1	Introduction to Radar Lecture Modular RF Design Lecture
Day 2	Antennas Lecture Radar Kit Technical Explanation Lecture Build Kit & Doppler Experiment Assignment
Day 3	Pulse Compression Lecture Ranging Experiment Assignment
Day 4	SAR Imaging Lecture SAR Imaging Experiment Assignment
Day 5	SAR Imaging Competition

being developed at MSU. Adaptation by other institutions is encouraged.

Great enthusiasm was generated after each field test where, results were presented from each team and discussed. Students were engaged throughout the course and would continue to ask questions on how to improve the performance of their radar sets and how to make more sophisticated systems. Many students discussed electromagnetic scattering theory at length when trying to interpret their SAR imagery.

The class model will be described in this paper starting with the course syllabus in Section II followed by a technical description of the radar kit in Section III and experiments are described in Section IV. Student built radar kits and measured results are shown in Section V. Summary and next steps will be discussed in Section VI.

II. SYLLABUS

Class met twice per week for two hours each session spanning three weeks. Lectures were presented with the goal of introducing enough material to understand how radar works and how the radar kit functions (syllabus shown in Table I). Each slide show is available on the web [1].

An introduction to radar lecture was presented showing the reasons for developing radar during the second world war. Some basic concepts were introduced, including the radar range equation and a discussion of a variety of radar modes and types.

A modular RF design lecture was presented to break the radar system down into blocks and show how those blocks work together. The radar kit was used as a case study, where the signal path from the FMCW ramp generation to the video op-amp was presented.

The introduction to antennas lecture presents essential concepts including; aperture size, beamwidth, directivity, and gain. The relationship and trade-space between these concepts is discussed and the coffee can antenna is used as a case study.

An interactive kit build is presented where the students begin construction of their radar kits. This lecture includes step-by-step fabrication instructions with documentation. Students complete the radar build on their own time.

A Doppler radar experiment is assigned for homework, where students go into the field and record then process

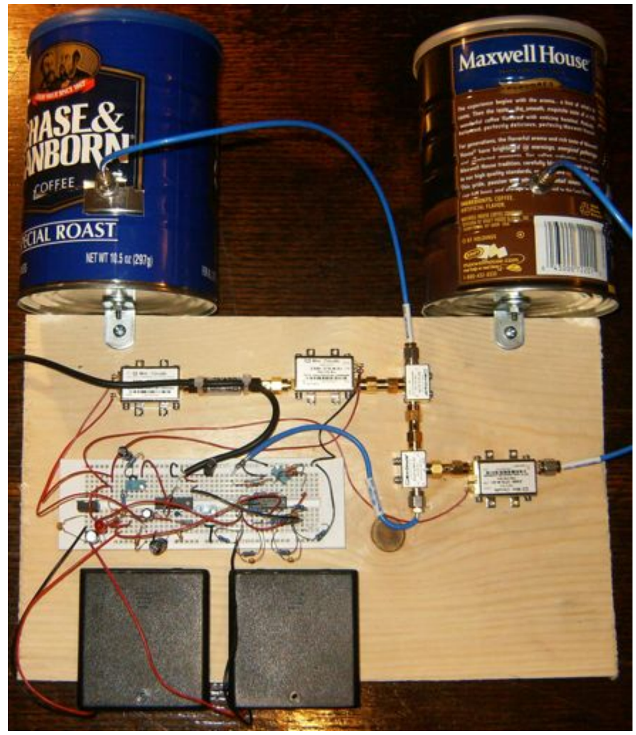


Fig. 1. Photo of completed radar kit.

Doppler spectrum of moving targets such as vehicles on a busy street. Doppler time intensity (DTI) plots are made of these data. Results are discussed in class.

Pulse compression using linear FM waveforms is explained using the radar kit as a case study. Students learn that by frequency modulating the radar transmitter and multiplying the scattered receive signal coherently by the transmit waveform, then, taking the Fourier transform of the result provides range-to-target information.

A ranging experiment is assigned for homework, where students measure the range to moving targets then produce a range-time intensity (RTI) plot. Results are discussed in class.

SAR imaging and the concept of digital beamforming are presented. The Range Migration SAR algorithm [2] is discussed. How to acquire a SAR image using the radar kit is shown.

A SAR imaging experiment is assigned for homework, where the students acquire then process a SAR image of urban terrain.

During the SAR imaging experiment, a challenge to acquire the most interesting image is made to the students thereby initiating a SAR imaging competition.

III. EDUCATIONAL RADAR KIT

Only Doppler radar kits exist in the commercial market, therefore a kit was developed by the authors that provides a high-enough degree of sophistication to enable college-level experiments including DTI, RTI, and SAR imaging (Fig. 1). Details and complete bill of material are published [1].

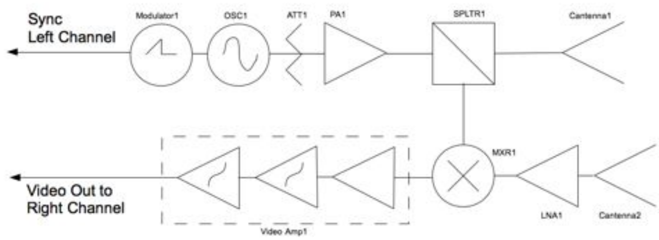


Fig. 2. Radar kit block diagram.

A low-cost implementation was essential to make this level of radar technology accessible to students. Each kit costs approximately $360 making it possible to fund a class of 24 students in teams of three. Costs are reduced in the kit by choosing a simple FMCW architecture, using coffee cans for antennas, and mounting everything on a wood block. Analog circuitry was implemented on a solderless breadboard so that fabrication could occur anywhere on the students' own time (in a dorm room for example), without the need for laboratory space.

A. FMCW Front End

Modular RF components were used because of ease of fabrication (making each module from scratch is time prohibitive) and understanding. When looking at the completed radar kit it is apparent how the radar system works.

An FMCW radar architecture was chosen because of its simplicity. It is not difficult to generate slow 20 ms wide-band linear FM chirps using a voltage controlled oscillator (VCO) and a ramp generator, then de-chirp down to audio frequency range which can be digitized inexpensively using the audio input port of a laptop computer. The center frequency is 2.4 GHz with a chirp bandwidth adjustable up to 330 MHz. An equivalent short pulse radar system would require a significantly more complicated (and expensive) wide-band digitization system.

B. Coffee Can Antennas

To reduce the transmit-to-receive mutual coupling, separate transmit and receive antennas are used. For the laptop radar application, a simple metal coffee can acting as an open-ended circular waveguide antenna is attractive, due to its low cost and good performance in terms of reflection coefficient, gain, and beamwidth. A typical metal coffee can with diameter approximately 10 cm has the dominant TE11 circular waveguide mode cutoff wavelength [3] of approximately 17 cm corresponding to a cutoff frequency of 1.8 GHz, which allows good performance for the laptop radar operation at 2.4 GHz. At 2.4 GHz, the free space wavelength is 12.5 cm, and to excite the TE11 mode a one-quarter wavelength monopole thin wire probe with length 3.125 cm (as measured from the tip of the probe to the inside metal surface of the coffee can) is used. The monopole wire probe is conveniently installed within the coffee can by extending the center pin of a SMA bulkhead receptacle jack. At 2.4 GHz, the coffee can has a guide wavelength of 18.5 cm and, to provide a good impedance match, the monopole wire probe is spaced one quarter of the guide wavelength (4.6 cm) from the back wall of the waveguide [4]. A plastic cover, which is typically used to seal the coffee can after it is opened, also serves as a microwave transparent radome material. Another example of the use of metal cans for fabricating low cost, simple antennas has been described [5].

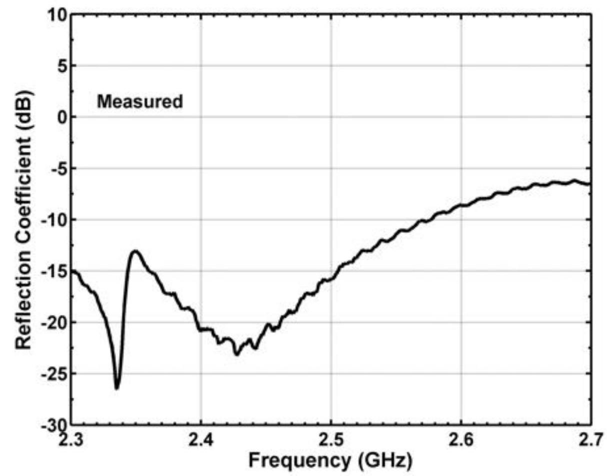


Fig. 3. Measured reflection coefficient for laptop radar coffee can antenna.

The measured reflection coefficient versus frequency of a typical coffee can antenna is shown in Figure 3. Over the 2.4 to 2.5 GHz Industrial, Scientific, Medical (ISM) band, the maximum reflection coefficient is -15.7 dB, which corresponds to a voltage standing wave ratio of 1.39:1. Far-field gain radiation patterns (E-plane and H-plane cuts) were measured in an anechoic chamber and the results at 2.4 GHz are shown in Figure 4. The measured peak gain is 7.2 dBi and the half-power beamwidth is 72 degrees. Referring to the laptop radar in Figure 1, the center-to-center spacing of two vertically polarized coffee cans is typically about 20 cm, and the measured transmit/receive mutual coupling (S21) at 2.4 GHz is -39 dB. Thus for this simple design with two circular waveguide antennas for transmit and receive, students are made aware of a number of important topics in antenna design including waveguides, probes, polarization, reflection coefficient, gain, radiation patterns, transmit power density, receive power, antenna arrays, and mutual coupling.

C. Video Amplifier, Modulator, and Data Acquisition

The analog modulator (Fig. 5) is based on the Exar Corporation XR-2206 function generator, which is capable of producing a linear ramp and a synchronization pulse where the rising edge coincides with the start of the up-ramp. The synchronization pulse is fed into the left channel of the laptop audio input.

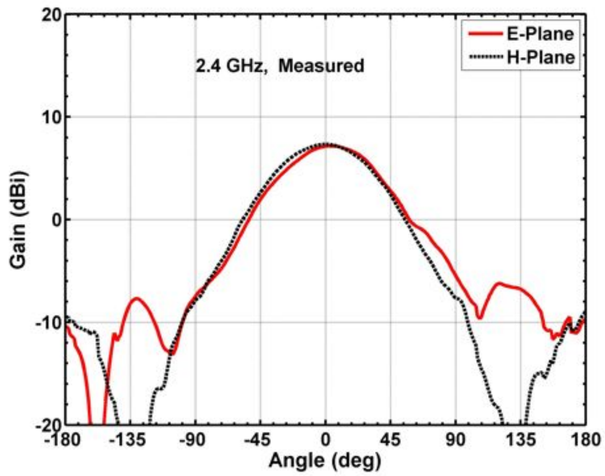


Fig. 4. Measured far-field gain radiation patterns for laptop radar coffee can antenna.

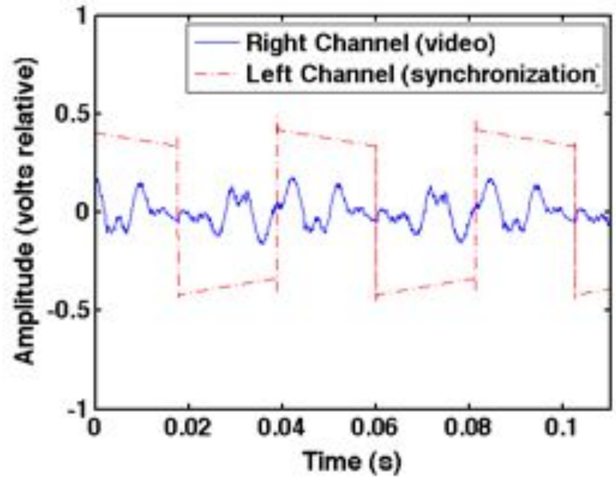


Fig. 6. Range data is triggered in software using a MATLAB script which searches for the rising edges on the left channel.

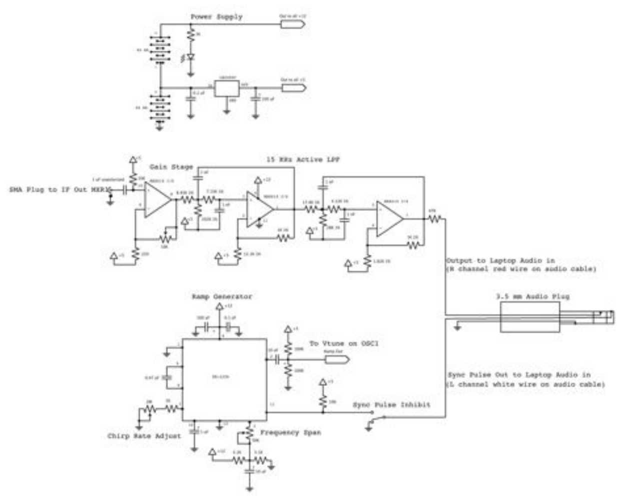


Fig. 5. Schematic of modulator, video amplifier, and power supply.

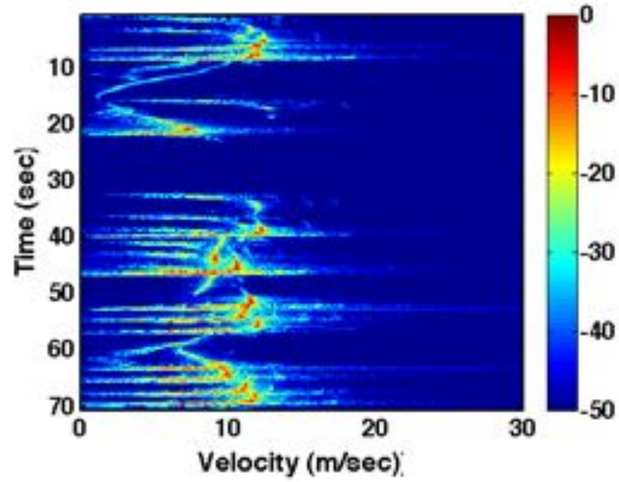


Fig. 7. A DTI plot of passing vehicles on a busy street.

The video amplifier (Fig. 5) uses a quad low-noise op-amp, the Maxim Integrated Products MAX-414, which provides video gain followed by a 4th order 15 kHz anti-aliasing filter. The video output is fed into the right channel of the laptop audio input.

Eight AA batteries power the radar system, providing regulated 5 volts for the microwave modules and op-amp bias and 12 volts for the modulator.

Analog data is fed into the stereo audio input port of any laptop where a .wav recorder is used to acquire data. Left channel is used for the transmit synchronization pulse where the rising edge corresponds to start of the transmit up-chirp and the Right channel is the video signal from the video amplifier (Fig. 6). Both channels are recorded when ranging targets.

IV. Experiments

Three experiments can be performed using the radar kit; Doppler, ranging, and SAR imaging as described below.

A. Doppler

Doppler is acquired by connecting the V_{tune} input of the VCO (OSC1) to a steady DC voltage and recording a .wav file while directing the radar at moving targets. A MATLAB script reads the .wav file and generates a DTI plot by ignoring the synchronization pulses (Left channel) and parsing the video data (right channel) into 100 ms blocks then computing the Fourier transform. The log magnitude of the result is plotted as a DTI plot, where, for example more than a dozen vehicles traveling at a velocity of up to about 13 m/s are observed (Fig. 7).

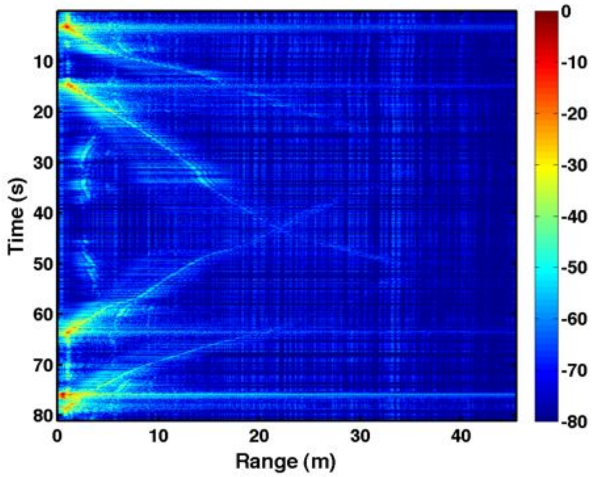


Fig. 8. An RTI plot of two people walking towards then away from a wooded area.

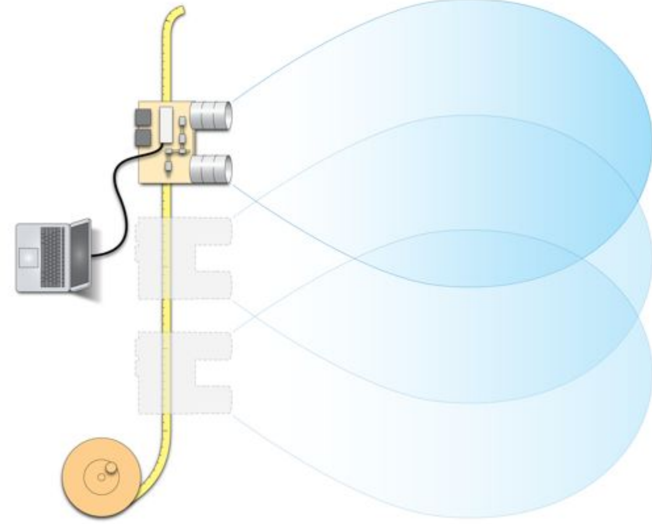


Fig. 9. Manual SAR imaging using a tape measure to align the sensor.

B. Ranging

In this experiment, the radar is directed toward groups of moving targets, such as automobiles or pedestrians. Both the right and the left audio channels are recorded using a .wav recorder (Fig. 6). A MATLAB script reads the .wav and examines the left-channel synchronization pulses looking for rising edges. Starting at the time of the rising edge, the script then computes an inverse discrete Fourier transform (IDFT) on 20 ms of data from the right channel. The logarithmic magnitude of the result is range-to-target. Coherent pulse-to-pulse subtraction is used to reject stationary clutter by about 25 dB allowing the ranging mode to be used to observe only moving targets. Ranging results for two walking pedestrians are plotted as a RTI plot (Fig. 8).

C. SAR Imaging

SAR imagery is acquired manually. A measuring tape supplied with the radar kit is deployed in a straight line. The student lines up the radar's edge with the start of the tape. A toggle switch in-line with the left channel mutes the synchronization pulses. The student starts a .wav recording program, moves the radar into position, un-mutes the synchronization pulses for 1-2s, mutes them, moves the radar 5.08 cm (2 inches), then un-mutes the synchronization pulses, and the process repeats over an aperture length of at least 2.4 m (8 feet) (Fig. 9). A MATLAB script looks for groups of synchronization pulses in the left channel and assumes that each group represents another 5.08 cm of radar displacement (Fig. 10). The MATLAB script further parses each individual pulse within the group and coherently integrates them resulting in a range profile for every 5.08 cm increment along a linear path. These data are fed into an S-band Range Migration SAR imaging algorithm [6]. Although somewhat coarse, SAR imagery of terrain lines up well with ground truth (Fig. 11).

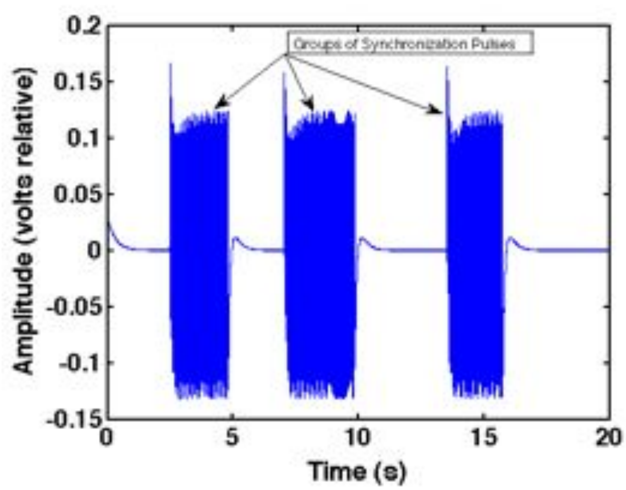


Fig. 10. Synchronization pulse muting by toggle switch breaks up the groups of pulses digitized by the left channel, where groups of sync pulses represent 5.08 cm increments along the SAR linear path.

V. Results

The educational radar kits described in the previous sections provide valuable experience for the students in the class. Students taking part in this course are given the opportunity to work on a radar system that is both affordable and teaches the basics of radar through a hands-on approach. This tool has turned out to be invaluable as part of the educational experience. The students in the course have shown great enthusiasm for this activity and have successfully constructed working radars in all cases.

A. Student Built Radar Sets

Several of these radars are shown in Figure 12, including two built on the conventional wooden base plates. The third

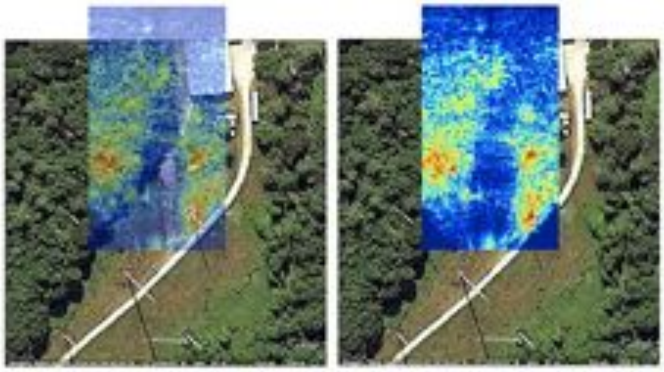


Fig. 11. SAR image of terrain.

Fig. 12. Student-built radar kits.

radar shown in this figure was built by a rather enthusiastic team of students who constructed a Plexiglas platform for their radar, along with a portable rail for taking SAR images around campus (shown in action on a cold January day in New England). Several students have kept in touch about their continued improvements to the coffee can radar system, including upgrades to the data acquisition and signal processing.

B. Doppler-Time Intensity (DTI) Experiment & Results

Several results of Doppler experiments are shown in Figure 13. The first images, labeled (a) and (b), are results of a popular, easy to find scene in the local urban area. Each of these plots show velocity versus time for an observation of traffic, where the stop-and-go action of vehicles can be seen distinctly. There is an interesting phenomenon seen in image (a), as cars drive under an overpass. This experiment provides what appears as extremely fast acceleration which is actually the overpass blocking the returns from the vehicles. The image labeled (c) is a unique image of a swinging pendulum which accelerates and decelerates through its periodic motion as time progresses, creating a repeating Doppler pattern. The last image, labeled (d), is a Doppler signature of a glass elevator as it moves between floors and stops to load and unload.

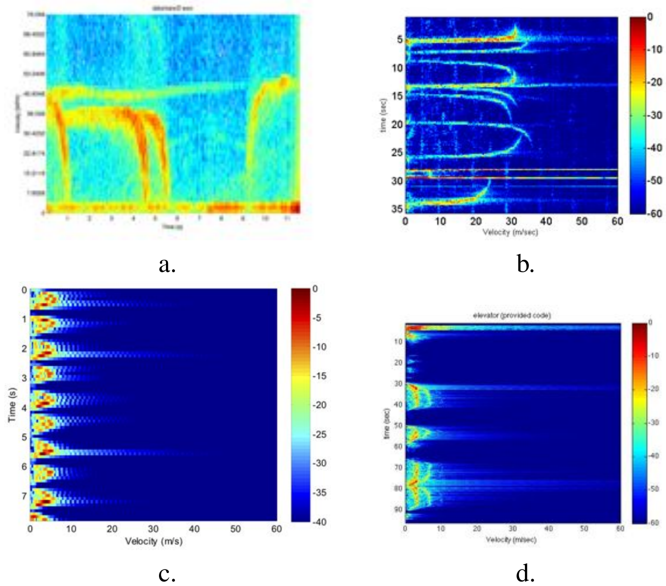


Fig. 13. Doppler results; moving traffic (a and b), pendulum (c), and glass elevator (d).

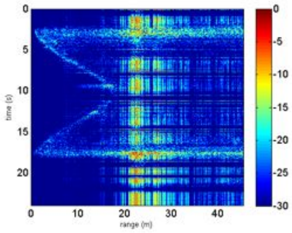
These images represent a small sample of the often interesting and inventive DTI experiments that the students in the course designed and carried out.

C. Range-Time Intensity (RTI) Experiment & Results

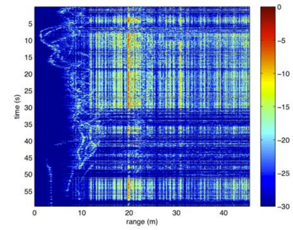
In addition to interesting DTI plots, many inventive RTI experiments were also designed by the students in the course. Figure 14 shows a number of results from these RTI experiments. The first RTI plot, labeled (a), shows a person walking first down a hallway away from the radar system operating in ranging mode, then back again. Image (b) shows six people involved in a three-on-three practice of ultimate Frisbee, with rapidly changing returns from the numerous fast moving players in the scene. The last two images show both a single person (c), and multiple individuals (d), walking down a hallway. These images are noticeably clearer than others, as they utilize an improved 2-pulse clutter rejection algorithm which subtracts the magnitude of the range profiles rather than using coherent subtraction, which is not as effective for this radar system because the rising edge of the left-channel synchronization pulses are under-sampled at audio frequency sample rates.

D. SAR Imaging Experiment & Results

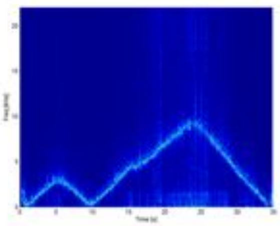
Of the many SAR imaging experiments conducted by students, the best imagery were often captured late at night, when activity on campus was minimal. The best of these results were submitted in the course as a final competition. The top image produced during the course period is shown in Figure 15. This is a SAR image of the outdoor statue, "La Grande Voile," by Alexander Calder on the campus of MIT in Cambridge, Massachusetts which shows a unique spiraling image due to the metallic sails. To commemorate



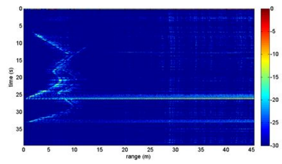
a.



b.



c.



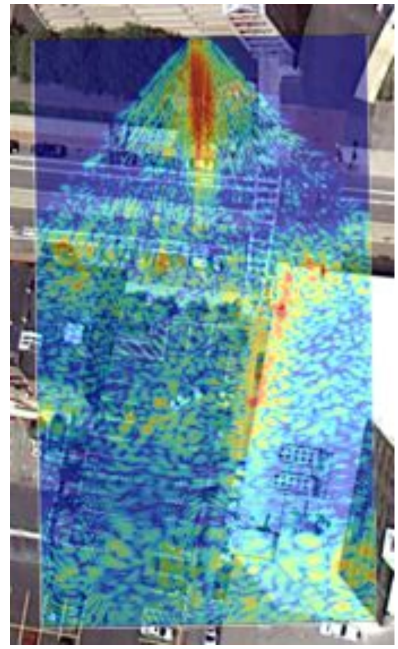
d.

Fig. 14. Ranging results; one person walking down a hallway then back (a), the MIT ultimate frissbee team 3-on-3 practice (b), one and multiple people down the hallway using an improved 2-pulse clutter rejection algorithm (c and d respectively).

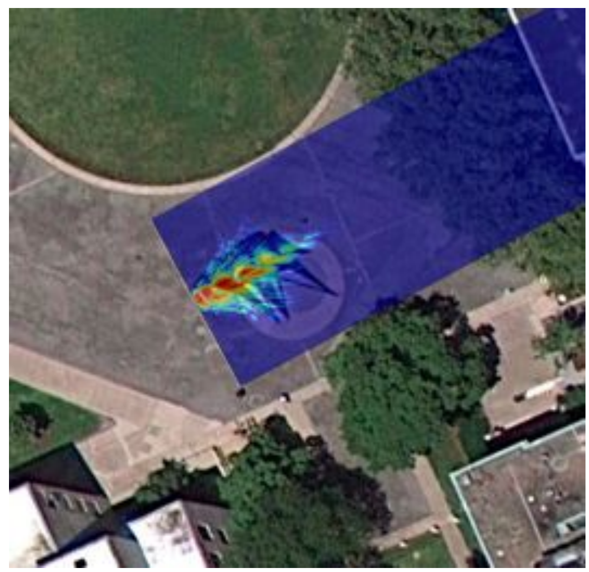
the completion of the course, the team that produced this image was awarded a trophy built of the same coffee cans that comprised the antennas in the radar system.

VI. Conclusions

It can be difficult to introduce the current generation of students to the field of applied electromagnetics, because other fields of study offer practical results with less prerequisite knowledge. By presenting applied electromagnetics, RF design, and signal processing at a high level while at the same time making a radar and performing field experiments, students became self motivated to explore these topics. All students succeeded in learning about radars, making radar kits, and left the course enthusiastic about radar systems and curious about electromagnetic scattering, thereby generating a long-term interest in this field of study. Using this course model, a phased array radar course is planned for the MIT IAP January 2012.



a.



b.

Fig. 15. SAR imagery of urban terrain; profile of buildings (a), large outdoor metal statue outdoor statue, “La Grande Voile,” by Alexander Calder (b).

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