Electronic Countermeasures for Radar

ECE 4007 Senior Design Project

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Executive Summary

The ECM team will develop an electronic countermeasure module to allow hobbyists and educators to demonstrate and innovate methods of defeating tactical radar. The system will consist of a radar and an ECM module. The radar will image a field of view that includes the ECM module. The module will detect that it is being imaged, collect data about the radar and classify it, and then attempt to jam the radar using techniques appropriate for the type of radar identified.

The radar will be built using a design originally pioneered at MIT. To reduce cost, it will output data through an audio jack, eliminating the requirement of an external ADC. Instead, this data will be captured directly from a PC sound card and analyzed using MATLAB or Octave. The ECM module will be designed around a USRP, an inexpensive software defined radio that can be programmed using the open source framework GNU Radio. The frequency of operation will be 2.4 GHz, so standard WiFi antennas can be used.

The demonstration of this project will involve imaging an area with a radar and showing that by activating the ECM module, false targets can be created. The radar will be tracking incorrect information about the real target as well as incorrect information about other false targets.

Current countermeasure units cost at least a million dollars, require high level security clearances, and are unavailable to the majority of people. The ECM teams' module will have 50% of the functionality of modern countermeasure modules at 1% of the cost.

Electronic Countermeasures for Radar

1. Introduction

The Electronic Countermeasures for Radar (ECR) team will design and test a module that will classify and deceive radar using the principles of digital radio frequency memory (DRFM). The team is requesting $805 to develop a prototype of the system consisting of both a radar and a countermeasure module.

1.1 Objective

The objective of the ECR team is to design, build, and test an electronic countermeasure (ECM) module that uses the principles of DRFM to modify returning signals to a radar system. A radar capable of operating on different frequencies and incorporating different methods of radar tracking will be constructed to test the effectiveness of the ECM module. The team will design the ECM module to identify the target radar's type and frequency to determine the appropriate jamming technique with which to counter. These techniques will be based on the concept of sending fake echos back to the radar which are frequency or phase shifted to cause the radar to incorrectly assess the range and direction of the target.

1.2 Motivation

The motivation driving this project is to design a low cost radar and ECM module aimed at hobbyists and educator. Since radar and radar countermeasures are so closely related, educators often teach both concepts together. In the same way that the software defined radio field has benefitted from the availability of low cost devices [1], it is hoped that a low cost ECM module will spur innovation in a field previously relegated to large laboratories and companies.

1.3 Background

Radar systems are designed to identify a target's range, velocity, elevation (or altitude), and angle (or azimuth). Many implementations of radar systems are used in defensive systems for early warning, ground control intercept, airborne intercept, acquisition, and target tracking [2]. Jamming techniques allow a user to avoid radar detection and the implementations include: chaff (metallic strips for causing false signal returns), spot jamming (jamming power focused on a single frequency), stealth material, sweep jamming, pulse jamming, and DRFM jamming [3].

RADAR is defined as RAdio Detection And Ranging. Radar operates at various radio frequencies and their classifications along with their radar wavelengths are shown in Figure 1.

Band	Frequency Range	Radar Frequency	Radar Wavelength
VHF	30–300 MHz	220 MHz	1.36 m
UHF	300–1,000 MHz	425 MHz	0.71 m
L	1–2 GHz	1.3 GHz	23 cm
S	2–4 GHz	3.3 GHz	9.1 cm
C	4–8 GHz	5.5 GHz	5.5 cm
X	8–12 GHz	9.5 GHz	3.2 cm
K_u	12–18 GHz	15 GHz	2.0 cm
K	18–27 GHz	24 GHz	1.3 cm
K_a	27–40 GHz	35 GHz	0.86 cm

Figure 1. Radar frequency ranges and wavelengths. [1]

The principal behind radar is to send a signal to a target and listening for the echo (or reflection) from the target. Figure 2 below shows what a typical pulsed radar waveform might look like and what the reflections off the target look like.

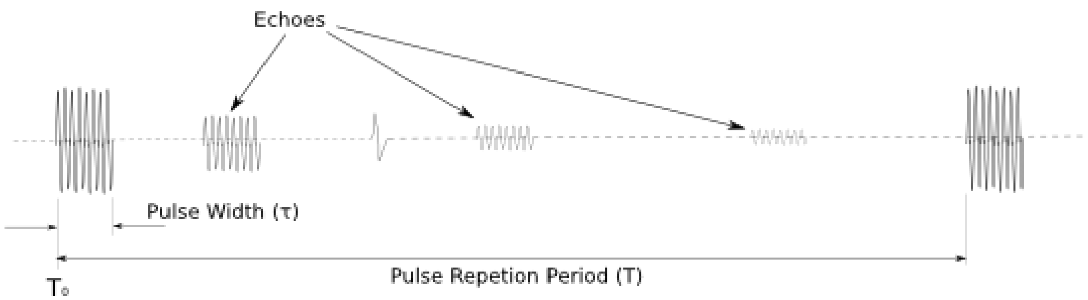

Figure 2. Typical pulsed radar waveform with reflections from target.

To calculate the wavelength (λ), the speed of light (3 x 10^8 meters/second) will be denoted by "c" and the radar frequency "f" to gain the equation λ = c / f . By denoting "t" as the measured round trip propagation time, the radar range equation is r = (c * t) / 2 . The basic radar equation can be seen in Figure 3, and the max range equation can be seen in Figure 4 [4].

$$R = \frac{P_p \, \tau \, G_t \, \sigma \, A_r}{(4\pi)^2 \, R^4 \, k \, T_s \, L}$$

P_p = transmitter power
τ = waveform duration
G_t = transmit antenna gain
σ = radar cross section
A_r = antenna aperture area
R = is radar range
K = Boltzmann's constant, 1.38×10^{-23} Joules/Kelvin
T_s = system noise temperature
L = radar system losses

Figure 3. Basic radar range equation.

$$R_{MAX} = \frac{\left[P_T G \sigma A_e\right]^{1/4}}{\left[(4\pi)^2 S_{MIN}\right]}$$

P_T = transmitted power
G = antenna gain
σ = RCS
A_e = antenna aperture area
R = range to the target

Figure 4. Max radar range equation.

The principals behind DRFM take advantage of the assumptions a radar system makes when identifying a target. The first assumption a radar makes is that the only possible reasons for a shift in frequency, phase, amplitude, or polarization is due to a reflection off of a material with a very different permittivity than air [2]. DRFM defeats this assumption by artificially shifting any or all of those physical wave properties and sending them back to the radar [5]. This causes the radar to make incorrect deductions about the material, velocity, and range of what it thinks are reflections off of a surface. Another assumption that radar makes is that electronic countermeasures used against it will not be able to keep up with the sliding time slot that it samples in and that the countermeasure won't be able to find the radar's frequency precisely enough. This was true before 1999, when DRFM systems first came into use [6]. With the proliferation of high dynamic range ADCs, fast FPGAs, and more efficient processors, it is now possible to very quickly and effectively find a radar's frequency and keep up with its sampling rate [7].

2. Project Description and Goals

The ECM team will construct a radar and ECM module to demonstrate different techniques of electronically countering radar signals. The ECM module will have an interactive menu to select the type of jamming technique to deploy. Users will be able to program and edit how the radio in the ECM module will characterize signals using Python scripts. The design project will require $805 to build the radar and ECM module that provides the following features:

- Interactive graphical user interface (GUI)
- Ability to detect and analyze radar signals

- Capability of deploying different countermeasures for jamming
- Costs less than $1400 to produce

3. Technical Specifications

The two major components of the system are the radar and the ECM module. Table 1 displays the performance specifications for the radar and Table 2 displays the specifications for the ECM module. The radar prototype will consist of a printed circuit board (PCB) attached to two antennas and a computer system. Table 1 shows the effective range of the radar to be 70 m. As shown in Table 2, an output power of 100 mW will ensure that the ECM module will be able to transmit pulses back to the radar at distances of up to and greater than the effective range of the radar. The ECM module will also be able to generate arbitrary waveforms, so it will be possible to counter a wide range of radar waveforms.

Table 1. Radar Specifications

Feature	**Specification**
Dimensions	2x3 inches
Weight	5 pounds
Transmit Power	60 mW
Operating Frequency Range	2.4 GHz
Operation Distance	Up to 70 m
Output Waveforms	Pulse train, FM chirp
Software	MATLAB and Python
Polarization	Vertical or Left Hand Circular

Table 2. ECM Module Specifications

Feature	**Specification**
Dimensions	12x8 inches
Weight	4 pounds
Transmit Power	100 mW
Operating Frequency Range	400-4400 MHz
Operating Distance	Depends on radar sensitivity, 140 m average
Output Waveforms	Arbitrary waveform generation
Software	GNU Radio and Python
Polarization	Vertical or Left Hand Circular

4. Design Approach and Details

4.1 Design Approach

System Overview

The system that will be demonstrated will consist of two parts: a radar and an ECM module. The radar will be used to collect range and velocity information from targets moving in front of it. It will remain unmodified and be used to observe the effectiveness of the ECM module. The ECM module will cause the radar to display incorrect information about the targets it is illuminating by employing a variety of tactics. It will have the capability to transmit and receive in the radar's frequency range and will perform signal analysis to characterize the type of radar that it is encountering. Once it determines what technique the radar is using, it will select the appropriate countermeasure and begin to jam. Figure 5 below shows the relationship between the radar and ECM module.

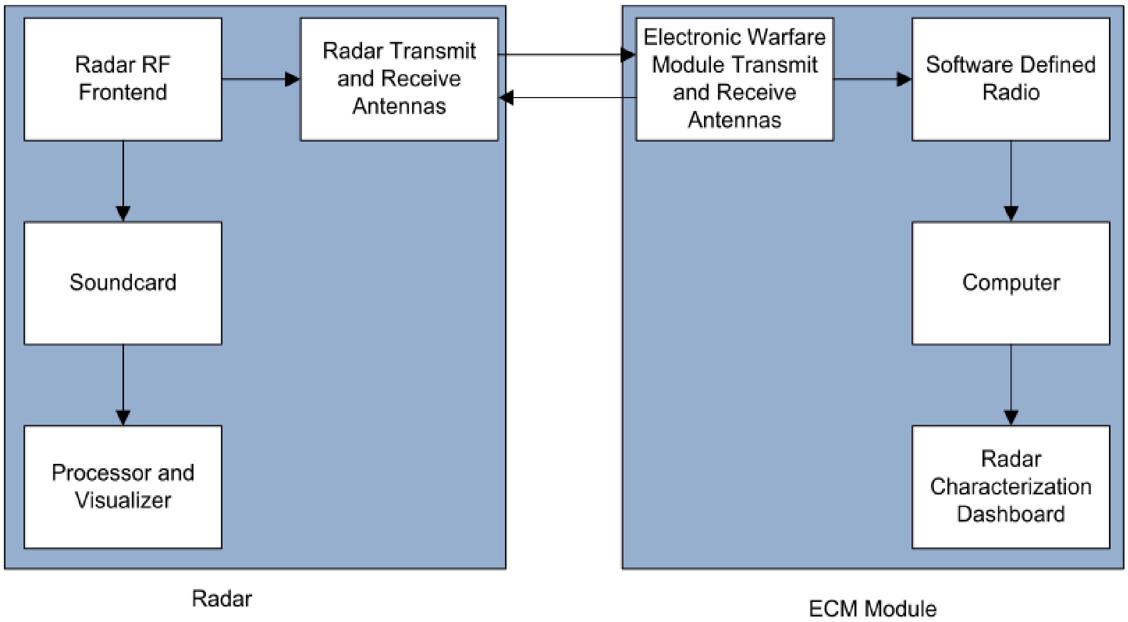

Figure 5. Block diagram of the radar and ECM module layouts.

Radar Subsystem

The radar subsystem will consist of a standard radar platform originally developed at MIT. A version using surface mount parts was designed by Tony Long and will be used for this project. The radar system diagram can be seen in Figure 6 below.

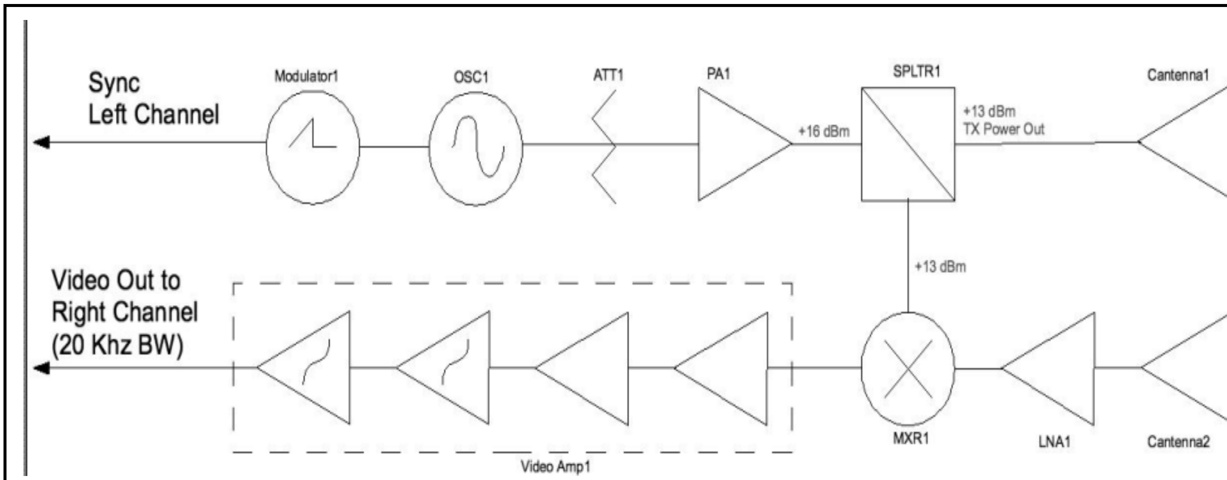

Figure 6. Block diagram of radar system components.

A voltage-controlled oscillator (VCO) generates a pure wave at 2.4 GHz which is sent to the transmit antenna. The receive side amplifies the signal it observes on the receive antenna and mixes it down to baseband using the VCO as the local oscillator. This signal is then adjusted to have a 20 KHz bandwidth and a correct amplitude to be suitable for capture from a PC stereo sound card. The right channel is used to input the receive data and the left channel is used to sync the VCO. Since the circuit board for the radar is primarily surface mount, it will be assembled using reflow. The board has test points at the VCO output, the right channel output, and the 12V supply line. The VCO output and right channel output test points will be probed using a spectrum analyzer to confirm correct functionality. The 12V supply line will be probed with an oscilloscope to ensure the noise from the power supply is within acceptable limits. Once successful, the radar will be tested using cables within inline attenuators on the TX and RX SMA connectors using a spectrum analyzer and a signal generator. Once it is determined that the radar can both transmit and receive signals correctly in the lab, directional antennas will be attached and the radar will be taken to an intersection in Tech Square to image cars driving and stopping. The data generated in this test will be sent to MATLAB to visualize range vs time. The Cartesian-temporal plot will look similar to Figure 7 below.

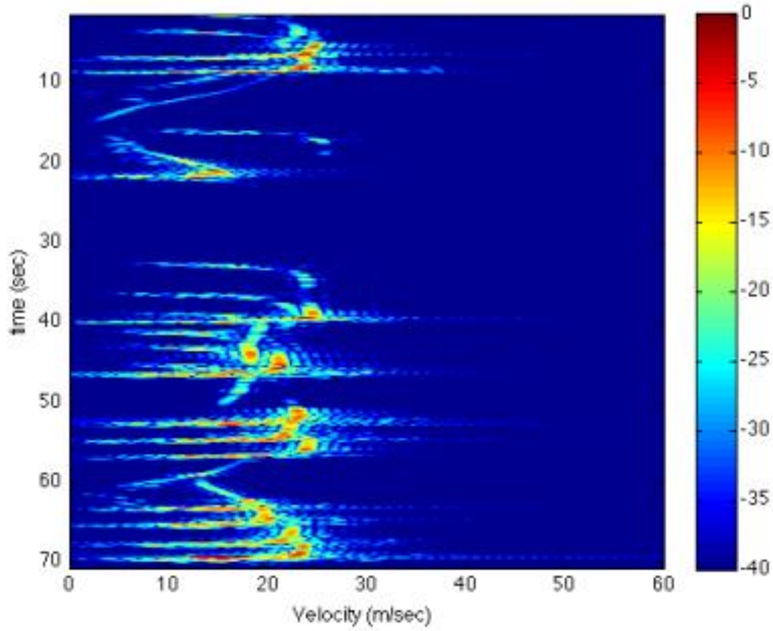

Figure 7. Cartesian-temporal plot of time vs velocity.

The data will also be visible in real-time using a polar plot showing range, azimuth, and return signal strength, which will be denoted with false color. A mockup of this interface is shown in Figure 8.

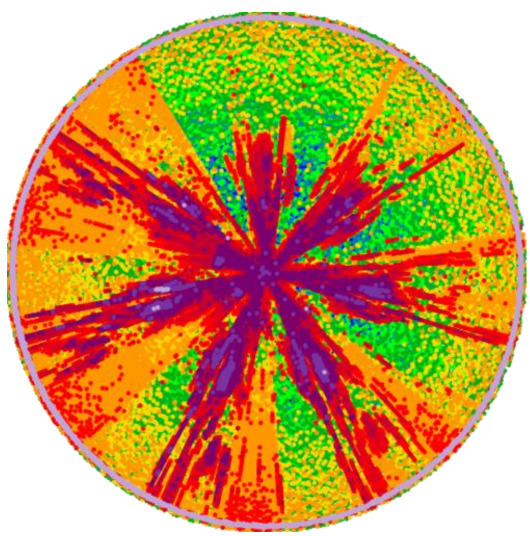

Figure 8. Mockup polar plot showing range, azimuth, and return signal strength.

Signal Characterization

The ECM module will receive incident radar waves and must determine the type of radar it is observing. It will first detect the polarization of the wave using antenna diversity by comparing the RSSI of a vertically polarized antenna and a left hand circularly polarized antenna, both with the same gain. Table 3 shows the polarization loss experienced if the radar is transmitting with a different polarization than the ECM module is receiving on.

Table 3. Polarization Loss

Transmit Antenna Polarization	Receive Antenna Polarization	Percent Lost
Vertical	Vertical	0
Vertical	Slant (45 or 135 degrees)	50
Vertical or Horizontal	Horizontal or Vertical	75
Vertical	Circular (right or left-hand)	50
Horizontal	Horizontal	0
Horizontal	Slant (45 or 135 degrees)	50
Horizontal	Circular (right or left-hand)	50
Circular (left-handed)	Circular (left-handed)	0

Once polarization is determined, the ECM module will use the appropriate antenna to sample the wave and look for a continuous wave or a pulsed wave. Next, it will look for deliberate modulation. It will detect both of these features by decomposing the frequency components using Fourier analysis and will determine the time/frequency relationship of pulses to one another using wavelet analysis. If modulation is detected, the ECM module will demodulate the samples and look for pulse compression. Once all of this critical information about the radar is acquired, the ECM module will attempt to classify the type of radar it is encountering. If it has seen the radar before, it can attempt to jam the radar using known weaknesses in the implementation. Otherwise, if it has not seen the radar before, it will continue to collect information about the radar for later analysis and will alert the user to the situation. It will not attempt to jam the radar in this instance, in case target-on-jam systems are in use. The signal characterizer in the ECM module will be written in Python using GNU Radio. Fourier and wavelet analysis will be performed within GNU Radio to characterize the radar signature. The characterization component will be tested with simulations of radar waveforms to confirm that signals can be detected correctly. Once software simulation is complete, real waveforms will be generated and transmitted to the software defined radio via cable to assess the performance under real signals. Upon success, the experiment will be repeated wirelessly using antennas. Simple waveforms will be used first, e.g. pulsed radar with no modulation. Once a particular detection algorithm is confirmed, pulsed doppler radar and other more complex methods will be tested.

Jammer Subsystem

Once the target radar is known, this subsystem will actually perform the jamming. Table 4 shows the type of radar detected and the action performed by the jammer subsystem.

Table 4. Jammer Response to Radar Type

Type of Radar	Jammer Response
Pulsed	Identify range gate, transmit pulses back
Pulse-Doppler	Identify range gate, transmit frequency shifted pulses back
Pulse compression	Identify range gate, transmit frequency shifted chirps back
Other	Collect data, do not attempt to jam.

The jammer subsystem of the ECM will consist of a universal software radio peripheral (USRP), antennas, and a computer. It will be controlled using GNU Radio, which is a framework that allows the user to write Python scripts to define how the USRP transmits and receives. It also allows the user to perform signal analysis. Figure 9 below shows the architecture of the USRP.

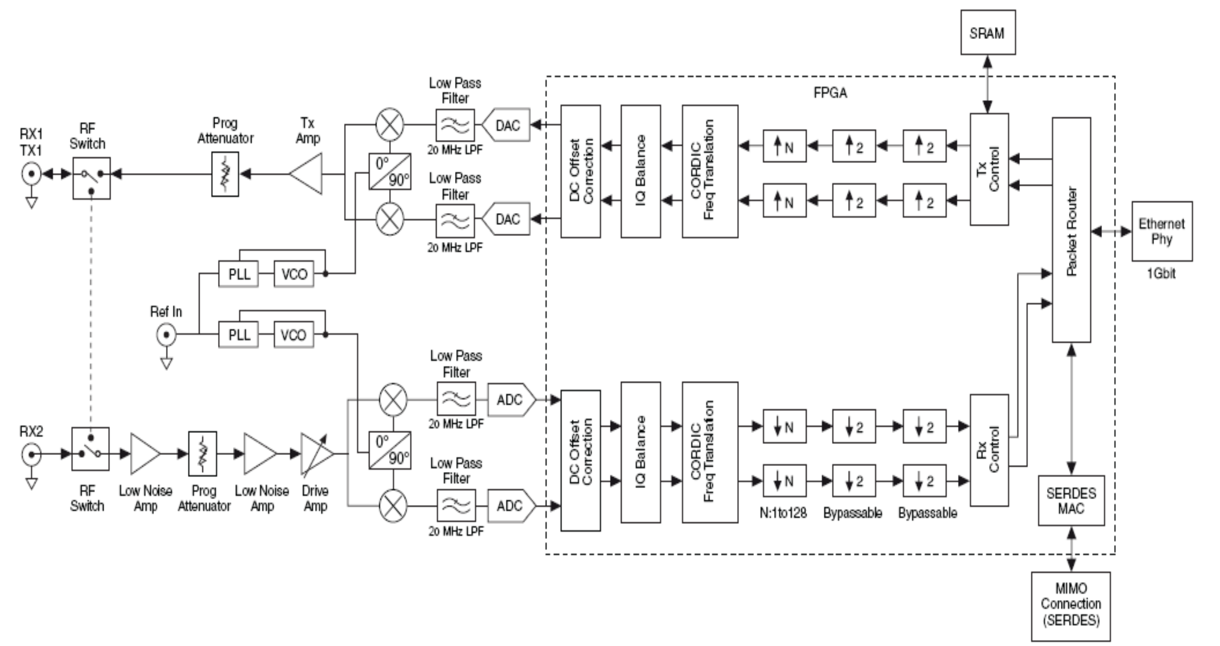

Figure 9. Block diagram of the USRP components.

Because the radar and ECM module will both operate in the 2.4 GHz band, care must be taken to ensure that WiFi doesn't interfere with the system and that the system doesn't interfere with WiFi. The demonstration will take place outdoors if possible to limit the effects of Wifi. If problems persist, the frequency of both systems will be shifted to an open Wifi channel in the ISM band covering 2.4-2.5 GHz. The use of directional antennas on both the radar and ECM module will further limit potential interference problems.

Dashboard

To command and control the ECM module, a simple GUI will be developed to let the user visualize the signal that is being analyzed as well as observe the status of the ECM and execute other countermeasure options. A mockup of the GUI can be seen below in Figure 10.

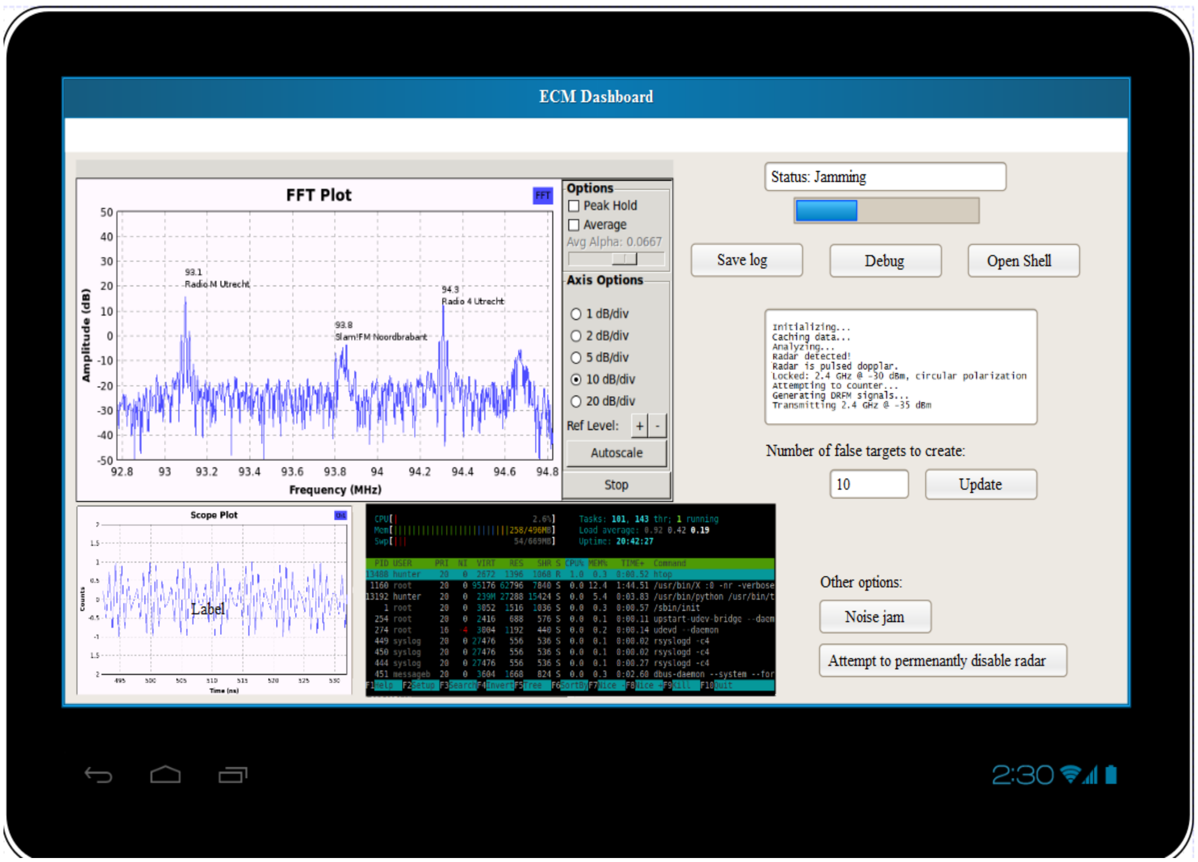

Figure 10. Mockup GUI for the ECM module.

5. Schedule Tasks and Milestones

The ECM team will be testing, researching, and implementing the proposed prototype and developing it over the next 3 months. The table in Appendix A displays all the major milestones listing their difficulty level and persons assigned to the task. Appendix B shows a

Gantt chart of all major milestones. Appendix C shows a detailed Gantt Chart with a timeline of all the tasks that need to be performed, their difficulty and the persons performing these tasks.

6. Project Demonstration

The demonstration will consist of a portable, mountable radar connected to a computer and an ECM module connected to a computer. The radar and ECM modules will be placed 30 meters from each other. The radar will be activated and will start transmitting. The ECM module, if successful, will analyze and process the signal characteristics correctly to identify the radar type. It will then send modified return pulses back to the radar, causing the radar to report incorrect target information. The demonstration of the project will take place in an open space, tentatively planned to be outdoors near the McCamish Pavillion. The results of the demonstration will be viewable on the computer screens via a custom designed GUI. The following radar transmitting methods will be demonstrated:

- Pulsed
- Pulse Doppler
- Pulse Compression

7. Cost Analysis

7.1 Market Analysis

ECM modules are a critical component in all modern aircraft and missile systems [2]. All engineers going into the avionics or electronic warfare spaces study these systems as part of their education. The cost of military-grade ECM modules range from $150,000 to $750,000 each [8].

No platform currently exists which demonstrates radar and radar countermeasures that is also affordable to universities and hobbyists and does not require a security clearance.

The target market consists of individuals and educational institutes that wish to experiment with radar and ECM. The University of Vermont, Massachusetts Institute of Technology, University of California, Davis and Michigan State University already have radar programs primarily focussed on the construction of the MIT Cantenna radar [9]. Additionally, there are at least 192 universities in the US alone that teach radar classes. Hobbyist software defined radios have become popular recently, with Ettus Research selling tens of thousands of USRPs [10]. It is expected that a large percentage of that market overlaps with the ECM target market.

7.2 Cost Analysis

The main cost associated with the production of the ECM module is the cost of the USRP. That cost is waived in the case of initial development as the required parts will be procured from team members. The cost of the antenna will be reduced because it will be possible to use standard WiFi antennas which benefit from economy of scale. The cost of the software development required for processing and modifying incoming radio waves is negligible because it is either open source or the ECM team will be writing it. Table 5 shows the breakdown of costs for parts required for the prototype.

Table 5. Component costs for prototype

Part Description	**Quantity**	**Unit Price($)**	**Total Price($)**
USRP B100	1	$640	$640
Antennas	4	$50	$200
USRP SBX Daughterboard	1	$475	$475

Three engineers will be required to complete the design and development of the ECM module. A breakdown of the number of hours that were put in by each engineer during development are shown in Table 6.

Table 6. Development hours per engineer

Task	**Hours**
Class	20
Weekly Meetings	10
Research	20
Presentation	1
Assembly	5
Testing	5
Software Development	10
Total	71

Labor costs are calculated based on the above table and assuming an average salary of $27 per hour for each engineer. Considering the number of hours required for development of the project, labor costs amount to $5751. Assuming fringe benefits of 30% of labor and an overhead of 120% of labor and material, the total development cost for the ECM module is shown in Table 7 below.

Table 7. Total Development Costs

Component	**Cost**
Labor	$5751.00
Parts	$1315.00
Fringe Benefits	$1725.30
Overhead	$8479.20
Total Development cost	$17270.50

The production run will consist of an approximation of five units being sold per week over a period of four years. This amounts to 1080 units being sold over a span of four years. There will be a discount of 5% being offered to any educational organization seeking to procure more than 50 units of the product. The selling price will be marked up by 6.71% when compared to the cost price and will be sold at a price of $3200 after taking into account fringe benefits and overhead. This amounts to a profit of $216.50 per unit sold and a profit of $56.50 per unit when sold in bulk. Assuming that all units were bought individually, this amounts to a total profit of $233,820 in a span of 4 years. The marked price is substantially lower than any ECM module available in the market and the first of its kind with respect to domestic use. Assuming that our ECM module is in production, the time taken to assemble and test the product amounts to 1.5 hours, Table 8 shows a breakdown of profit per unit.

Table 8. Breakdown of profit per unit

Expense or Income Component per Unit	Cost per Unit
Parts	$1315
Assembly Labor	$14
Test Labor	$27
Fringe Benefits	$12.3
Subtotal	$1356.3
Overhead	$1627.2
Total Input Cost	$2983.5
Selling Price	$3200.00
Profit	$216.50

8. Current Status

All parts, components, and major design features have been identified. Version control has been set up and GNU Radio has been built from source. The USRP is now capable of being controlled and can both transmit and receive correctly. Equipment for reflowing the radar board has been acquired and access to the Georgia Tech RF laboratory has been granted. Parts and the PCB for the radar will be shipping soon, although antennas have yet to be ordered. Once the radar parts are received and the radar is assembled, testing will commence. Until then, development on the USRP with GNU Radio continues.

9. References

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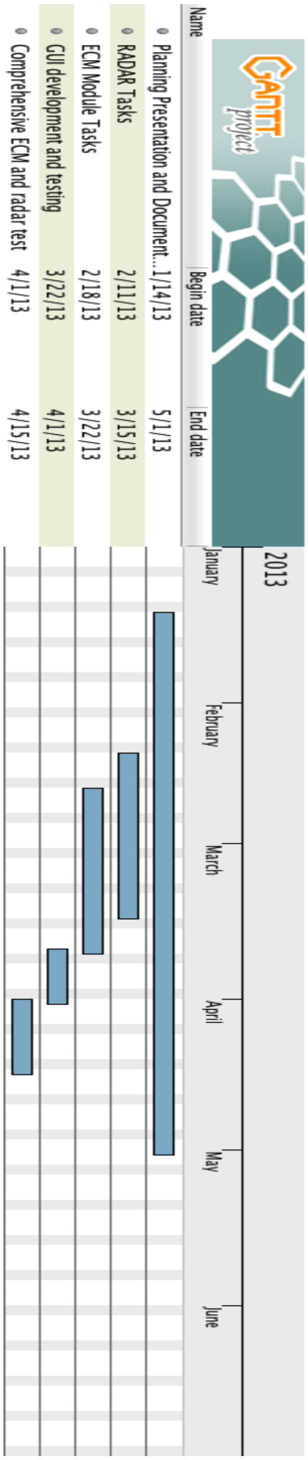
Appendix A

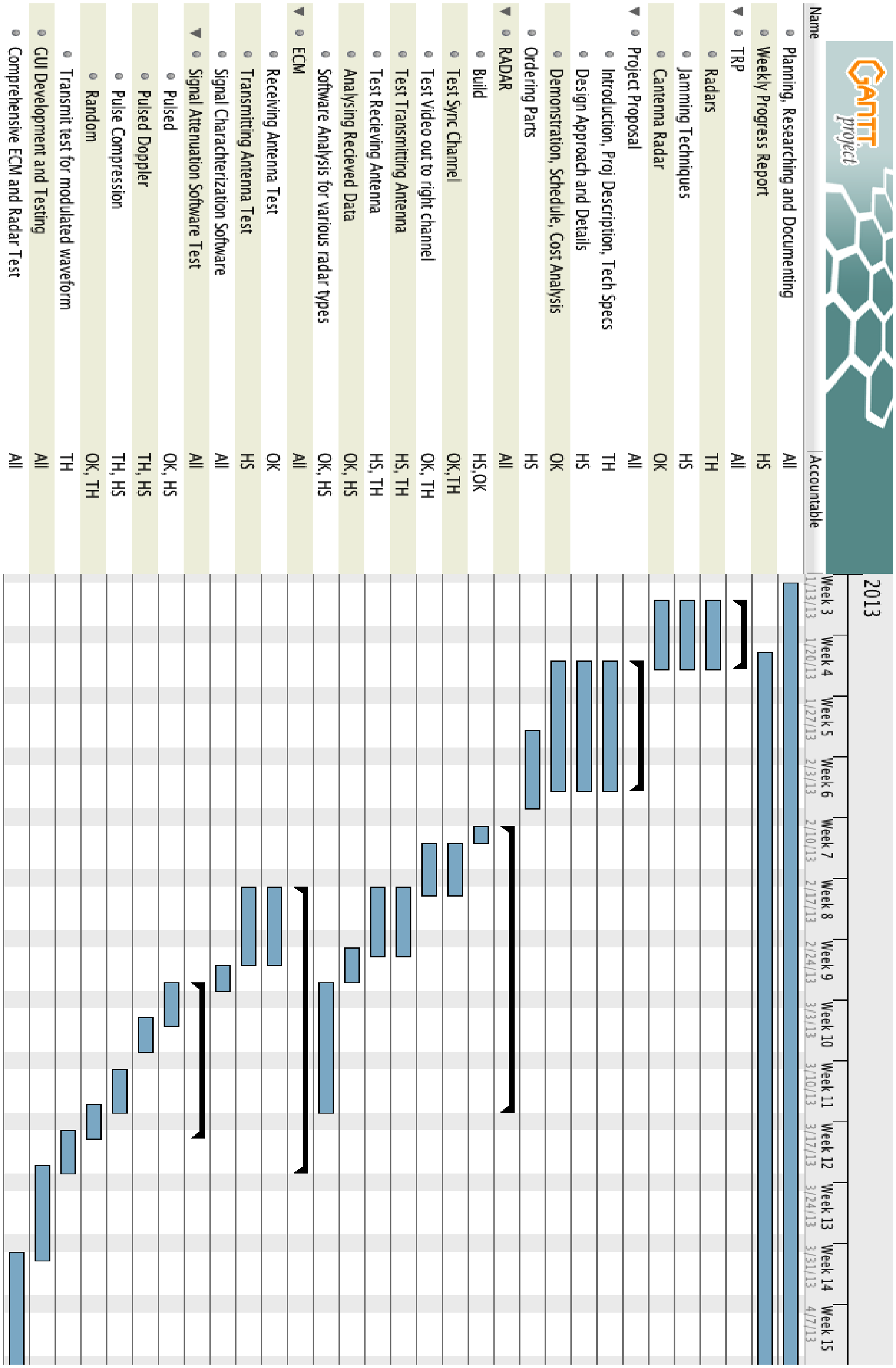
Task Name	Task Lead	Risk Level
Planning, Presentation and Documentation	All	Low
TRP	All	Low
Project Proposal	All	Low
Parts Ordering	HS	Low
PDR Presentation	All	Low
Final Project Presentation	All	Low
Final Project Documentation	All	Medium
Final Project Report	All	Medium
RADAR tasks	All	Medium
Testing Receiver and Transmitter	HS, OK	Medium
Testing Software Processing Capabilities	HS, TH	High
ECM Module tasks	All	Medium
Signal attenuation and characterization software	OK, TH	High
Testing Receiver and Transmitter	HS, TH	Medium
GUI development and testing	All	Medium
Comprehensive ECM and radar test	All	Medium

Appendix B



Name
Begin date
End date
Planning Presentation and Document... 1/14/13 5/1/13
RADAR Tasks 2/11/13 3/15/13
ECM Module Tasks 2/18/13 3/22/13
GUI development and testing 3/22/13 4/1/13
Comprehensive ECM and radar test 4/1/13 4/15/13
2013
January
February
March
April
May
June

Appendix C


2013
Name
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Week 4 1/20/13
Week 5 1/27/13
Week 6 2/3/13
Week 7 2/10/13
Week 8 2/17/13
Week 9 2/24/13
Week 10 3/3/13
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Week 14 3/31/13
Week 15 4/7/13
Planning, Researching and Documenting All
Weekly Progress Report HS
TRP All
Radars TH
Jamming Techniques HS
Cantenna Radar OK
Project Proposal All
Introduction, Proj Description, Tech Specs TH
Design Approach and Details HS
Demonstration, Schedule, Cost Analysis OK
Ordering Parts HS
RADAR All
Build HS,OK
Test Sync Channel OK,TH
Test Video out to right channel OK, TH
Test Transmitting Antenna HS, TH
Test Recieving Antenna HS, TH
Analysing Recieved Data OK, HS
Software Analysis for various radar types OK, HS
ECM All
Receiving Antenna Test OK
Transmitting Antenna Test HS
Signal Characterization Software All
Signal Attenuation Software Test All
Pulsed OK, HS
Pulsed Doppler TH, HS
Pulse Compression TH, HS
Random OK, TH
Transmit test for modulated waveform TH
GUI Development and Testing All
Comprehensive ECM and Radar Test All