Executive Summary

Detection and discrimination of live and inanimate radar targets through building walls holds great utility for public safety and disaster relief agencies. Numerous through-wall life detection schemes have been developed in recent years, but their utility has been dampened by excessive cost. The 2004 Indian Ocean tsunami and 2008 earthquake in China are prime examples of widespread disasters where the ability to quickly determine if living humans were trapped behind building rubble might have saved numerous lives. A low cost through-obstruction life detection device may have saved countless people who survived the initial disaster, only to succumb after days trapped beneath rubble.

The Naval Research Laboratory sponsored design team is developing a proof-of-concept radar that will show the utility of an inexpensive through-wall radar system. The radar system will use a National Instruments CompactRIO chassis for data acquisition and signal processing. The design team will investigate a key problem with portable through-wall radars; namely, receive sensitivity loss due to self-interference inherent in compact linear FMCW (frequency modulated continuous wave) radars. Loss of sensitivity means the radar cannot “see” as deeply through obstructions or detect smaller targets due to self-interference. Low-cost embedded microprocessors and microwave devices available as COTS items enable these interference-cancelling abilities. The final product from the design team will be a compact through-wall radar using a laptop PC for near real-time display of the one-dimensional target data.
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Introduction

A radar system developed by the Michigan State University senior design team will provide a proof-of-concept for low-cost through wall radar applications. The radar developed will not be a final production prototype, as NRL's focus for this project is on the underlying concepts of the radar versus creating a system ready for manufacture. NRL has loaned the design team several components, including the National Instruments CompactRIO chassis, equipment enclosures, and numerous microwave modules. The CompactRIO contains a 266MHz embedded processor, and a Xilinx Spartan 3 FPGA (Field Programmable Gate Array). NRL has also provided the team with the National Instruments LabVIEW suite for software and programmable hardware development. The team will design and build certain devices that are not readily available "off-the-shelf," and will develop the software necessary for the system. The radar system will use a laptop PC to display data processed by the CompactRIO. The PC will also allow the end user to adjust radar parameters dynamically.

The design team will develop a proposed method for linear FMCW radar self-interference cancellation. If time and resources are available, the design team may test the cancellation design by constructing the interference canceller. The design goal for self-interference cancellation is at least 20dB, measured by the reduction in peak level of the transmitter carrier as observed on the radar’s FFT display. This radar is an experimental system, built for the purpose of testing low-cost extensions to existing cancellation ideas in the literature. The design team will at least deliver a functional linear FMCW radar system. The design team will also develop a software method to detect movement, and display an indication that a target has been moving for at least 200ms.

A typical test target used for the radar will be water bottles covered with tin foil. These foil-covered bottles may then be compared with uncovered bottles containing water treated with table salt to more closely resemble human extremity radar reflectivity. Water bottles in the 300-500mL range are similar in diameter to a child's arm or leg. If practicable, a larger jug of the type commonly used for water coolers might be used as an approximation to a human torso. While the human body is not exactly comprised of circular cylindrical shapes, cylinder radar reflectivity is relatively well characterized in the literature. The goal of this project is not to discriminate one type of shape from another, but rather to determine the lowest observable target radar cross section (RCS) for given conditions. It is therefore essential to have radar targets with well-characterizable RCS, such as circular cylinders and corner reflectors (following [10]). By determining the minimum detectable RCS for a given distance and obstruction, the low-cost radar sensitivity may be compared with more advanced radar system.
1 Background

Linear FMCW radar techniques have been used for over sixty [1] years in a variety of applications, from aircraft altimeters to short-range high resolution synthetic aperture radar [15]. As implied in their name, Frequency Modulated Continuous Wave radars transmit at the same time as receiving. Practical concerns dictate that the transmit and receive radar antennas must be closely co-located [2-6]. The co-location (or sometimes sharing of a single transmit/receive antenna) creates a self-interference problem. Self-interference reduces the normal receive sensitivity. Reduced receive sensitivity means that very low energy radar returns coming from small and/or heavily obscured targets will be more difficult to detect.

Self-interference has two primary forms. The self-interference form of most concern may depend upon the power level and modulation used by the radar. The first form of self-interference is radar receive chain overload from the transmit carrier coupling driving the receive chain into saturation. Informally, saturation means that one or more amplifiers in the radar receive chain have been driven beyond their P1dB point. The P1dB point is a value (typically specified in dBm) that indicates the amplifier would have given 1dB more output for the given input, had the amplifier been in the linear region of operation. A saturated amplifier has effectively less gain for weak signals, thereby causing weak targets to be missed. Recent work at MSU used a band-pass technique with an HF intermediate frequency (IF) and multiple IF filter sections to filter out both the transmit carrier and undesired strong radar returns from nearby objects. Other workers from the 1960s through the present day have used various forms of vector modulation to feed an amplitude scaled, frequency shifted, and phase shifted version of the transmit carrier back into the receiver front-end. Both methods experienced success in their respective experiments.

The second form of self-interference comes from sideband noise originating in the transmitter chain. The VCO (Voltage Controlled Oscillator) is a significant source of sideband noise. Sideband noise refers to broadband undesired emissions at frequencies other than the center carrier frequency of the VCO. It is well-known in the radar industry that inexpensive VCOs generally have greater amounts of sideband noise than expensive VCOs. Because the radar is trying to detect the weakest signals possible, and the transmit and receive antennas are close together, it is possible that sideband noise overwhelms weak targets. That is, the sideband noise may be stronger than the thermal noise floor and the receive chain noise, thereby covering up otherwise visible targets. Further research into previous work with the vector modulation approach is needed to determine how successful this approach was at reducing sideband noise. Additionally, practical microwave amplifiers both create their own broadband noise, and amplify noise injected from previous stages. If vector modulation is an effective technique for reducing self-interference for sideband noise, a possibility exists that the broadband noise from amplifiers in the transmit chain is reduced.

In theory, if the real and imaginary parts of a vector $A = a + j\beta$ are known, a vector $B$
may be determined such that \( \mathbf{A} \cdot \mathbf{B} = 0 \). In the O’Hara experiment [2], analog control circuitry was used to tune the vector modulator to cancel the self-interference. More recent work [3,4] has achieved 20-30dB of cancellation with FMCW radars. Without a detailed simulation of the radar system using measured device parameters, it is not possible to predict how much self-interference cancellation can be achieved with the proposed system. Given the inexpensive devices used throughout the system, the performance benchmark is 20dB of self-interference cancellation.

![Figure 1: Linear FMCW modulation diagram (following [9])](image)

Following [14], Figure 1 shows the overall parameters of linear FMCW radar. The transmitter sweeps over a bandwidth \( W \) within time \( t_m \). If a single point scatterer exists, after time \( t_R \) the return signal appears at frequency \( f_{\text{receive}} \). Because the homodyne receiver of the linear FMCW radar is by definition locked to the transmit frequency, the radar energy received with time lag \( t_R \) appears as frequency \( f_R \) at the homodyne receiver output. It is noted that:

\[
f_m = \frac{1}{t_m}
\]

where \( t_m \) is by definition the up-ramp time of the swept waveform. The radar system designer chooses \( t_m \) and \( W \), and using:

\[
f_R = t_R W f_m = \frac{2 R t_R W f_m}{c}
\]

the range frequencies for given target distances are determined. The interference canceller typically sends an amplitude scaled, frequency shifted, and time shifted copy
of the transmitter signal into the receiver front-end, cancelling coupling from the
transmitter that appears as a very strong and close target on the FFT display.
2 Design Specifications

2.1 Primary Objectives

The primary objectives of the design project include those necessary for the design and evaluation of an FMCW radar system, along with investigation of techniques for a self-interference cancellation scheme.

2.1.1 Linear FMCW Radar System

A prerequisite to the canceller design is the design, construction, and programming of a linear FMCW radar system operating in a suitable frequency range for through-wall radar target detection. The power output of the radar should be reasonably low so as not to endanger end users with excessive microwave radiation. The radar components should be inexpensive and power conservative. Externally located linear power supplies will be used to save cost, since power supply miniaturization is not within the scope of this project. Minimal radar functionality is defined as the ability to distinguish between 0dBsm targets without a wall intervening at 5m and 7m. Most microwave components will be obtained as off-the-shelf components. The microwave devices fabricated by the team will be fully enclosed so as to prevent self-interference from being generated by the device. The importance of this system module is “5,” very important.

2.1.2 Self Cancellation

The minimum desired self-interference cancellation is 20dB, measured by the reduction in peak level of the transmitter carrier as observed on the radar’s receive FFT display. Further reduction of self-interference is desirable, but not necessary. The importance of this parameter being researched is “3,” fairly important.

2.1.3 System Survivability

The radar system need not be designed for use beyond the laboratory environment used by engineers and scientists. Since antenna design is not an emphasis of the project, the antennas’ mechanical durability beyond common laboratory usage is not a priority. All RF, baseband, and power will be provided through connectorized interfaces, with connector choices based on economy and availability. The system need not be weather resistant. The important of this system parameter is “1,” non-critical.

2.1.4 Moving Target Indicator (MTI)

The design team will also implement an MTI algorithm to indicate moving targets on the laptop FFT display. It is desired to indicate when an object with 20dB SNR has been detected to have motion within 200ms. The method of indicating that a target is moving will be developed with NRL. The importance of this parameter being researched and implemented is “4,” rather important.
3 Conceptual Design Specifications

3.1 Proposed Design Solution

The radar system design follows the common linear FMCW architecture. A brief description of each component is given in the list below.

- **VCO**: Converts voltage sweep from the FPGA into a frequency sweep
- **TX Amp.**: Increases the RF power level of the VCO’s output for better small target detection
- **TX Ant.**: Sends the linear FMCW generated by the VCO out to the target scene
- **Canceller**: Design to be determined, removes self-generated interference
- **RX Ant.**: Collects the weak signals scattered off of radar targets at the same frequency they were transmitted, with a time delay determined by the distance to the targets
- **RX Amp.**: Increases the power level of the weak scattered RF energy from the targets
- **Mixer**: Downconverts the RF frequency to near DC, so that the A/D conversion can be economically accomplished
- **Video Amp.**: Further increases the power level of the weak downconverted target signals to maximize the use of A/D dynamic range
- **FPGA**: Directly controls the A/D and D/A conversions with precise timing and buffers the data to be sent to the embedded 266MHz microprocessor
- **Host**: The embedded 266MHz microprocessor that handles all signal processing in the system, and initiates FPGA processes such as data acquisition
- **PC**: Displays graphical radar data and sends user configuration parameters to the Host

The radar architecture developed following work in [3-8,9] is shown in Figure 2.

*Figure 2: Overall Radar Architecture*
3.2 Hardware

3.2.1 Directional Coupler PCB

The directional coupler is used to remove or insert a controlled amount of RF into a circuit. The directional coupler is used by the future interference canceller circuit to inject cancellation RF. A directional coupler of the value needed (-10dB) has a 4 to 6 week lead time from a supplier (Pasternack Enterprises) willing to sell in single quantities. The Directional Coupler was designed and simulated in Sonnet, based on references [12, 13] and the personal experience of the designer. Figure 3 depicts the directional coupler PCB layout. The directional coupler PCB was simulated at better than -25dB S11 and S22, with less than 1.5dB insertion loss, and better than 3dB flatness. The directional coupler will be enclosed in a used box obtained from NRL that will be RF sealed. The as-built design will be tested to meet the simulation parameters on a vector network analyzer in the MSU EM lab. Figure 4 gives the directional coupler design decision matrix.

![Figure 3: Directional Coupler PCB Layout](image)

<table>
<thead>
<tr>
<th></th>
<th>Nelco PCB</th>
<th>Pasternack</th>
<th>E-Meca</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>VSWR</td>
<td>4</td>
<td>5</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Insertion Loss</td>
<td>4</td>
<td>5</td>
<td>5</td>
<td>0.8</td>
</tr>
<tr>
<td>Promptly Available</td>
<td>5</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>RF Leakage</td>
<td>3.5</td>
<td>5</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Cost</td>
<td>5</td>
<td>3</td>
<td>1</td>
<td>0.7</td>
</tr>
<tr>
<td>SUM</td>
<td>19.2 Best</td>
<td>18.1</td>
<td>15.7</td>
<td></td>
</tr>
</tbody>
</table>
3.2.2 Voltage Amplifiers

The voltage controlled oscillator (VCO) converts the voltage generated by the CompactRIO into frequency of a specific microwave frequency band. The CompactRIO outputs 10 volts maximum, but the VCO requires 20 volts maximum. The VCO requires input frequencies from DC-10kHz, and gain of 2 is required. Figure 5 shows a typical op amp design, and Figure 6 gives the design decision matrix. The variable attenuator and phase shifter also require an amplifier of similar specifications. If each device can be driven up to 20 volts at the necessary frequency (e.g. 5kHz), the amplifiers will be considered as meeting the design requirements.

<table>
<thead>
<tr>
<th>Input from FPGA</th>
<th>+Vcc</th>
<th>Output to Device</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Promptly Available</td>
<td>Non Inverting Op-Amp: LM741</td>
<td>one transistor amplifier</td>
<td>high-speed op-amp: THS4021</td>
</tr>
<tr>
<td>High Frequency Perf.</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Cost</td>
<td>5</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>DC and AC</td>
<td>5</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Gain factor</td>
<td>5</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>SUM</td>
<td>18.5 Best</td>
<td>12.8</td>
<td>14.4</td>
</tr>
</tbody>
</table>
The op amp chosen to perform the VCO voltage amplification [11] is the LM741. Using commonly available 10k ohm resistors and the formula seen below, the op amp is capable of producing a gain of two.

The op amp PCB can be fabricated by the ECE shop. A drawback of this design is that the LM741 op-amp has somewhat limited frequency response, but through PSPICE simulations, the LM741 appears to have enough gain bandwidth (GBW) to fulfill the VCO requirements.
3.3 Software

The software component controls the radar system and processes radar data into a meaningful format for the human operator. NRL has determined that development will be done in National Instruments (NI) LabVIEW software, utilizing the built-in FPGA and signal processing IP modules. This functionality is especially applicable when writing code for the CompactRIO Field Programmable Gate Array (FPGA), as LabVIEW automates much of the Hardware Description Language (HDL) generation process.

The software design can be divided into four major modules: analog input (AI), analog output (AO), signal processing, and display. NRL has provided an NI CompactRIO system (comprised of an FPGA, analog input and output modules, and an embedded microprocessor), as well as a laptop PC for displaying data and program control. LabVIEW software development spans three platforms: the FPGA, Host Processor, and PC. The multi-platform topology is shown in Figure 7. The display and control module will not be discussed in detail since LabVIEW contains a built-in GUI for this purpose.

3.3.1 Analog Input/Output

In order to extract meaningful information from the radar system, the analog baseband signal from the radar receiver must first be captured and converted to a digital data stream. This must occur in tandem with the generation of a linearly ramped voltage for the Voltage Controlled Oscillator (VCO) in order to control the FMCW frequency sweep. The AI module will convert radar signals reflected from targets into fixed point data. The AO module will provide the ability to control VCO sweep frequency and the interference canceller. The AI and AO modules will have the ability to operate at user controlled sampling rates. Critical design considerations for both modules are shown in Figure 8. The design considerations balance available design time and CompactRIO resources with system performance.

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The chosen design uses the FPGA to acquire and generate samples for the duration of the FMCW radar sweep and then uses a blocking scheme in order to synchronize these operations with data transfer to the processing module operating on the host microcontroller. This process is depicted in Figure 9.
3.3.2 Signal Processing
Once the analog input data has been collected from the radar, a signal processing algorithm will extract the frequency content. The algorithm processes frequency content that is displayed to the user in graphical format. It must extract distance data from time-domain data in such a way that the required distance resolution is achieved, not only for the goal of providing more accurate distance information, but also for differentiating between targets in close proximity to one another. The algorithm must also be able to detect the motion of a target. Specifically, the MTI (Moving Target Indicator) algorithm must be able to identify when a target with more than 20dB SNR has been moving for at least 200ms. Since the AI dataflow may occur at a high rate, the algorithm must also be performance-effective in terms of processing time. While more research will need to be done in order to select an appropriate transform and MTI algorithm, the team is strongly considering a zero padded fast Fourier transform (FFT). The windowing will provide less spectral leakage about targets, especially the self-interference from the transmit antenna. The zero padding helps boost processing efficiency by making the number of samples a multiple of two. The data collected over multiple radar sweeps can then be used as input into an adaptive MTI algorithm in order to detect moving targets.

4 FAST Diagram
The FAST diagram in Figure 10 depicts the “How” and “Why” of the radar system’s primary function, which is to determine distance to targets. The radar transmit path is the top leg of the diagram, and the receive path of the radar is in the bottom leg of the diagram.
## 5 Risk Analysis

The critical path of the project requires that certain software tasks be completed before the hardware can be fully tested. Alternate methods have been developed to conduct limited testing of hardware and software in a standalone fashion if the need arises. The risk analysis is shown in Figure 11.

<table>
<thead>
<tr>
<th>Meeting Specifications</th>
<th>Cost</th>
<th>Time</th>
<th>Overall project functionality</th>
<th>Difficulty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage Amplifiers</td>
<td>Low</td>
<td>Medium</td>
<td>High: radar uncontrollable w/o functionality</td>
<td>Medium: must amplify DC &amp; AC</td>
</tr>
<tr>
<td>AI/AO software</td>
<td>Medium</td>
<td>Timing is critical</td>
<td>High: radar uncontrollable w/o functionality</td>
<td>Medium: several interlocked functions</td>
</tr>
<tr>
<td>Directional Coupler</td>
<td>Medium</td>
<td>Need proper levels to be able to control cancellation</td>
<td>Medium: software can compensate for some performance difficulties</td>
<td>Medium: microwave device design</td>
</tr>
<tr>
<td>Interference Canceller</td>
<td>Medium</td>
<td>Needs several components to work together properly</td>
<td>Low: Goal is to investigate methods of cancellation. Radar will still work without canceller</td>
<td>Medium: microwave system design</td>
</tr>
<tr>
<td>Antennas</td>
<td>Low</td>
<td>Low</td>
<td>Medium: radar can continue to function with imperfect antennas</td>
<td>Medium: microwave antenna design</td>
</tr>
<tr>
<td>MTI</td>
<td>Medium</td>
<td>need to detect movement in presence of noise</td>
<td>Low: MTI is not absolutely necessary for radar to function</td>
<td>Medium: signal processing techniques</td>
</tr>
<tr>
<td>FFT</td>
<td>Medium</td>
<td>Must preserve existing SNR</td>
<td>High: radar unusable w/o functionality</td>
<td>Medium: signal processing techniques</td>
</tr>
</tbody>
</table>

*Figure 11: Risk Analysis Matrix*
6 Budget

The team decided on necessary hardware and software components necessary for the completion of the project within budget constraints. Devices such as the voltage controlled oscillator (VCO) and RF amplifiers are essential to the completion of the radar hardware. LabVIEW and the CompactRIO are necessary to facilitate the hardware/software interface. Figure 12 depicts the preliminary budget.

<table>
<thead>
<tr>
<th>Qty</th>
<th>Model</th>
<th>Description</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ZX73-2500-S</td>
<td>Variable Attenuator</td>
<td>$49.95</td>
</tr>
<tr>
<td>3</td>
<td>LM741 &amp; parts</td>
<td>Amplifier</td>
<td>$15.00</td>
</tr>
<tr>
<td>1</td>
<td>JSPHS-2484</td>
<td>Phase Shifter</td>
<td>$32.95</td>
</tr>
<tr>
<td>1</td>
<td>ZX95-2800</td>
<td>Voltage Controlled Oscillator</td>
<td>$49.95</td>
</tr>
<tr>
<td>2</td>
<td>ZX60-33LN-S</td>
<td>RF Amplifier</td>
<td>$79.95</td>
</tr>
<tr>
<td>1</td>
<td>ZX05-30W-S</td>
<td>Mixer (S-band to RF baseband)</td>
<td>$37.95</td>
</tr>
<tr>
<td>1</td>
<td>595-THS4021EVM</td>
<td>TI High-Speed Amplifier</td>
<td>$55.67</td>
</tr>
<tr>
<td>1</td>
<td>ZAPD-30-S</td>
<td>2 Way Splitter</td>
<td>$84.95</td>
</tr>
<tr>
<td>1</td>
<td>PE2202-6</td>
<td>2.0-4.0GHz -6dB Directional Coupler</td>
<td>$261.20</td>
</tr>
<tr>
<td>1</td>
<td>cRIO-9072</td>
<td>Compact RIO (FPGA and Microprocessor)</td>
<td>$1,999.00</td>
</tr>
<tr>
<td>1</td>
<td>NI LabVIEW w/FPGA and Real-Time Modules</td>
<td>$9,097.00</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>NI9263</td>
<td>cRIO Analog Output Module</td>
<td>$329.00</td>
</tr>
<tr>
<td>1</td>
<td>NI9201</td>
<td>cRIO Analog Input Module</td>
<td>$349.00</td>
</tr>
<tr>
<td>1</td>
<td>RF connectors</td>
<td></td>
<td>$86.19</td>
</tr>
<tr>
<td>1</td>
<td>Capacitors/resistors for op amps</td>
<td></td>
<td>$10.48</td>
</tr>
</tbody>
</table>

Total Cost $12,441.57
Loaned Parts $12,097.47
Cost to Team $440.77

Figure 12: Preliminary Budget

7 Project Management Plan

7.1 Personnel

Hardware and software develop will occur in parallel, and an integration phase will take place as both components near completion.

7.1.1 Individual Technical Contributions

Ali Aqel
Ali will contribute to the development of an efficient and effective algorithm for processing data obtained from the radar. He will develop an algorithm to output signals from the system’s FPGA to the radar hardware. He will specify the design requirements
for radar control output, lay out the architecture, develop the algorithm in LabVIEW, and synchronize it with the radar input algorithm.

Michael Volz
Michael will primarily be involved with the hardware portion of the project. Once the hardware and software for the radar are initially functional, he will test an existing prototype antenna design and develop a method to allow the antennas to be placed on a tabletop apart from the radar. He will also create the directional coupler research self-interference cancellation methods. Once the radar is functional, Michael will be directly involved in the creation of proper radar tests and characterization of targets.

Garrett Warnell
Garrett will work on the software module, focusing his efforts on the analog input module, as well as the signal processing algorithms that need to be researched, designed, and implemented within the system. He will research how to implement algorithms for a maximally efficient overall software design. Garrett will also assist with the design and implementation of the adaptive signal processing algorithm that will be used to control the phase shifter in order to neutralize interferers.

Scott Warren
Scott will be involved in both the software and hardware aspects of the project. He will be responsible for integration and test as the project progresses. Scott will mount various hardware modules into the final enclosure and perform testing to make sure that the modules function correctly together. This task is time-critical since the final software testing/development is dependent on the hardware. Scott will assist with the analog input and output modules, as well as with the signal processing and display modules. He will also work on the final system configuration for design day.

Michael Weingarten
Michael will be contributing to the hardware aspect of the project. He will be focusing on designing and building amplifiers for the transmit, receive, and canceller portions of the radar. An amplification circuit is necessary to drive the VCO across the desired frequency range. The receive signal also needs amplification because after passing through the mixer, the signal will be so small that only a few bits of the analog input may be used, causing excessive quantization error. The attenuator and phase shifter likewise need voltage amplification to match the CompactRIO analog output to their respective input levels. The designs created here will then be re-designed on a computer and used to create routing for PCB (printed circuit board) layout.

7.2 Project Management Chart
The current Gantt project management chart is given in Appendix A, due to the length of the chart. The necessary parts cited in the Gantt chart are available or can be fabricated at the MSU ECE shop, or else are available on loan from the Naval Research Laboratory.
7.3 Project Performance Verification

The radar system will be tested according to the design specifications using radar targets fabricated by the team. The radar targets will typically consist of tin-foil covered water bottles and 0dBsm corner reflectors. The radar system should be able to reliably distinguish between two 0dBsm targets at 5m and 7m stand-off distance. The radar should indicate when a target with at least 20dB SNR has been moving for more than 200ms. The cancellation method derived (but not necessarily built) should have a calculated self-interference calculation of at least 20dB as measured on the FFT display. The radar system performance will be verified by tests at the MSU Engineering Building. The tests will be verified by Michael Volz, who is experienced in testing radar system functionality for both the US Navy and the MSU Electromagnetics Research Group.

8 References
