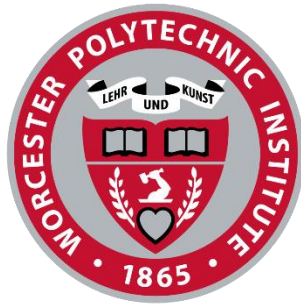


Synthetic Aperture Radar for Improving the Intermediate Physics Laboratory



WPI

This report represents the work of one or more WPI undergraduate students submitted to the faculty as evidence of completion of a degree requirement. WPI routinely publishes these reports on the web without editorial or peer review.

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Abstract

Within WPI's physics department, Ben Pollard and L. Dana are restructuring the intermediate physics laboratory course, with a plan to make it more open-ended and student led in order to maximize learning potential. Along with this change comes the need for experiments that cover broader topics to address industry relevant skills, which our IQP aims to address. We built a radar system listed on MIT's OpenCourseWare, modifying and testing the system until it was fit for use within WPI in order to introduce RF circuitry ideas into the new curriculum. With the radar completed, a technical guide was created to allow instructors to understand the system, summarizing what was learned during the IQP so that instructors are able to help students with any concerns. A lab handout was also created to lead students through the experiment, designed with specific objectives from Ben Pollard to best fit into his new course.

Authorship

Landen wrote 2.1-2.4, 3.1-3.4, 3.6, 3.8, 4.1, 5.1-5.2, and smaller miscellaneous sections.

Max wrote 3.5, 3.7, 3.9, lab guide, technical guide, and modifications to MATLAB scripts.

Both Max and Landen collaborated evenly for editing.

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Chapter 1 - Introduction

The purpose of this project was to build a radar system for education and outreach purposes. The design of our radar was adapted from an MIT OpenCourseWare project created primarily by Gregory L. Charvat (Charvat, 2011), with supplemental materials from Jonathan H. Williams, Alan J. Fenn, Steve Kogon and Jeffrey S. Herd. The original design was updated to replace discontinued components and allow for interfacing with modern computers, as well as modified to be more durable and transportable.

The design philosophy for the system was to create an inexpensive system that was portable and easy to use while being transparent and easy to modify or repair. The initial goal for the project was to investigate the potential of using the radar system for outreach to younger audiences to promote interest in the sciences. The low cost and easy assembly would fit well into a high school budget, and the higher level WPI laboratory experiments could be adapted for use as hands on demonstrations in high school courses or outreach activities. These demonstrations would act as either a replacement or a supplement for existing demonstrations, giving students a deeper understanding of wave propagation and its applications.

After the second term of this project, this initial goal was sidelined to instead focus on the integration of the radar at WPI's Intermediate Physics Lab, as several faculty members saw potential in its application. Then, along with various lab guides, this system would be integrated into the upcoming Intermediate Physics Lab course and would occupy a two week to a two and a half week time slot. The lab materials were created with input from Ben Pollard, Assistant Teaching Professor of Physics, who is redesigning the Intermediate Physics Lab for the 2023-2024 academic year to make the course open ended and include more thought-provoking experiments than what is currently included in the syllabus.

Chapter 2 - Background

This background section will be divided into subsections that most concisely convey the research progression of this project. While these subsections are broad, they each provide information required to understanding the scope for this project, reasoning some choices were made, and provided leading research questions required for us to progress in the project.

2.1 - The General Overview

WPI, being a project-based technical school, strives to provide students with a more open-ended approach to problem solving. These types of problems push students to reason through a solution, understanding each step along the way, rather than working according to an outline to reach a specified goal. While WPI tends to align with this teach yourself by doing philosophy, there are still areas where the more classical follow along approach remains. One such area is in the Intermediate Physics Laboratory course, where many of the existing experiments are thought to be too much of a straight cut process, where students can follow along to the lab manual and achieve the desired result. Because the experiments don't require much reasoning to complete, students end up not developing much of a deeper understanding for the topics involved and equipment used. The academic level of the phenomena being tested are often above the level of undergraduates and therefore must be brought down to a level that can fit into a two-week experiment. Though the radar is simpler on the surface than many of the currently studied experiments, it provides depth and a complete front-to-back understanding that otherwise isn't possible with many of the more complex topics.

Ben Pollard has been tasked with overhauling the Intermediate Physics Lab, with the goal of replacing the cut and dry experiments, replacing them with newly designed experiments that better align to an open-ended philosophy.

2.2 - The Original Project Plan

Instead of being focused on use for courses at WPI, the radar system was originally built for use in both high school physics labs and outreach activities for kids of various ages. Light and waves is a complex topic for a high school physics class, one that is often not covered in extreme detail and at the very end of the year. Combined with the surface level coverage is often basic non-interactive demonstrations, such as a vibrating string, a prism, water in a bucket, or noise cancellation in speakers via nodes. As high school students will progress into every career path, not just STEM fields, it is important that demonstrations can cater to a wide audience. The demonstrations must be as informative, engaging, and enjoyable as possible to captivate students who potentially have no interest in the topic, while also being mentally stimulating enough to provoke interested students into deeper thought.

As a system that would be operated in a classroom environment, we kept key design considerations in mind when designing the radar. From our interviews with high school teachers Dan Mitchell and Bill Waller, they advised that it must arrive to the teachers completely assembled and functioning, with little to no setup or debugging required. It must also be durable enough to withstand the classroom setting for a number of years, making the teacher's initial investment worthwhile in the long run. In the unfortunate situation that something does go wrong and requires repair, the problem must be diagnosed and the repair be performed with the average skills and equipment available in a high school. The radar must also be safe, with loose wires as secure as possible to minimize the risk of shorts or electric shock (D. Mitchell, personal communication, January 19, 2023) (B. Waller, personal communication, December 9, 2022).

2.3 - Why the Project Shifted Focus

The first two terms of this IQP consisted of mostly assembly, troubleshooting, research, and interviews. Between the second and third terms, after considering data collected from interviews and our familiarity with the relative sensitivity of the system, we shifted audience of the demonstration to WPI undergraduates. It was believed that the topics related to the radar, use of MATLAB for analyzation, and easy to follow layout of the system would fit well into the upcoming revamp of the Intermediate Physics Laboratory course at WPI. The redesign of this physics lab is being spearheaded by Ben Pollard and jointly implemented with L Dana, the Physics Department Laboratory Manager.

2.4 - The New Physics Lab

The Intermediate Physics Lab is listed with the following description and objectives:

This course offers experience in experimentation and observation for students of the sciences and others. In a series of subject units, students learn or review the physical principles underlying the phenomena to be observed and the basis for the measurement techniques employed. Principles and uses of laboratory instruments including the cathode-ray oscilloscope, meters for frequency, time, electrical and other quantities are stressed. In addition to systematic measurement procedures and data recording, strong emphasis is placed on processing of the data, preparation and interpretation of graphical presentations, and analysis of precision and accuracy, including determination and interpretation of best value, measures of error and uncertainty, linear best fit to data, and identification of systematic and random errors. Preparation of high-quality experiment reports is also emphasized. Representative experiment subjects are: mechanical motions and vibrations; free and driven electrical oscillations; electric fields and potential; magnetic materials and fields; electron beam dynamics; optics; diffraction grating spectroscopy; radioactive decay and nuclear energy measurements (*Physics | Worcester Polytechnic Institute*, n.d.).

This new Intermediate Physics Lab by Ben Pollard is expected to undergo a complete overhaul, reworking the existing structure from the ground up to better fit the academic ethos of WPI. While the old lab was structured with experiments that had a specified goal with a linear path from start to finish, the new course aims to provide a looser approach to learning. The lab environment would instead mimic situations that students would expect to encounter in their professional life by “designing the course to promote student agency, internal motivation, and project-based learning experiences” (Pollard, 2022). Along with this broad overarching goal comes a change that will be immediately perceived by students, a more open-ended course with fewer explicitly defined outcomes. Students will be expected to lead themselves along the path they feel comfortable with, becoming acquainted with their experiment over the extended lab period.

To further tie into this theme, a method dubbed Ungrading will also be applied to this course, an active learning methodology where students present their own grades at the end of the term to reflect how they believe they did in the course, with grades being instead being replaced by constructive feedback. Though this less defined structure might appear more difficult and involved to students at first glance, Ben Pollard believes that this method will improve teamwork, deepen understanding, alleviate stress, and create more lasting interest in the subject, all while keeping the workload expected of the students consistent with the previous Intermediate Physics Lab (Pollard, 2022).

Chapter 3 - Methodology

In this Methodology section, the Background section will be expanded upon to provide the leading questions that further guided project research. These questions will be coupled with the steps taken to obtain the desired results and the reasoning for how it was done, coming together to form a roadmap of the project as a whole.

3.1 - Initial System Design

The original radar design comes from a 2011 MIT Independent Activities Period course, in which they collaborated with MIT Lincoln Laboratory in order to introduce students to new information that was relevant to the research being performed at Lincoln Labs (Charvat, 2011). The syllabus and materials of this course contain images of the original build, circuit schematics, a complete BOM, and usage instructions. All of the information would be directly valuable in our assembly except the BOM, which would require re-evaluation because of several discontinued parts.

3.2 - Updating the Outdated BOM

All of the original components operated on the Industrial, Scientific, and Medical (ISM) band. This band was chosen because it is safe to be exposed to, has loose broadcast limitations, and parts are all mass produced and relatively cheap. The closest match for the discontinued Voltage Controlled Oscillator, which operated on a 2315-2536 MHz range with a 6 dBm gain, was one that instead operated from 2350-2750 MHz with a 5.5 dBm gain. Though not an exact match on either count, the decrease in power only impacts radar range and the shift in bandwidth can be compensated for in software. In case the signal was too weak to function, the 3 dB attenuator was cheap enough that it could later be replaced with something lower power to make up for the difference in signal strength. The only other

substitutions for discontinued parts were the quad op-amp, which was a drop-in replacement from the MAX414CPD+ to the LM324 with the voltages we are operating under, and the 5V Regulator, which was a simple swap to a different 5V Regulator able to handle the same load requirements as the original. Miscellaneous resistors and capacitors didn't have their exact part available, but replacements with similar specifications were found and put into the updated BOM. Upon receipt, we realized some parts were missing from the original BOM, so a reorder with the supplemental parts had to be made.

3.3 - The Decision for a PCB

Though initially the project was planned to be for high school physics demonstrations and physics outreach activities, many of the project requirements remained stagnant through the changes the project encountered. One such requirement was that the radar system be rugged enough to withstand continuous transportation and prodding from curious hands without being at risk of damage or causing an electric shock.

The assembly began as the MIT course suggested, with all components placed on a breadboard, as shown in Figs. 1 and 2, though we quickly realized that this wasn't going to be sustainable. Though it worked in a controlled lab setting with individuals familiar with the circuit, it was far too particular to be used in any other setting. Loose wires were susceptible to snagging and coming loose, requiring the operator to know exactly where it came from so it could be reinserted without damaging components. Resistors and capacitors jumping over rows often didn't make good contact with the breadboard and needed to be angled just right so a proper connection could be made. Simultaneously, all the components jumping rows created a large risk of shorting, which could either cause a faulty output reading or damage expensive components. While the breadboard allowed the circuit path to be completely visible and therefore easily followed, it was extremely crowded which could potentially overwhelm and dissuade less STEM-eager students as well as frustrate teachers.

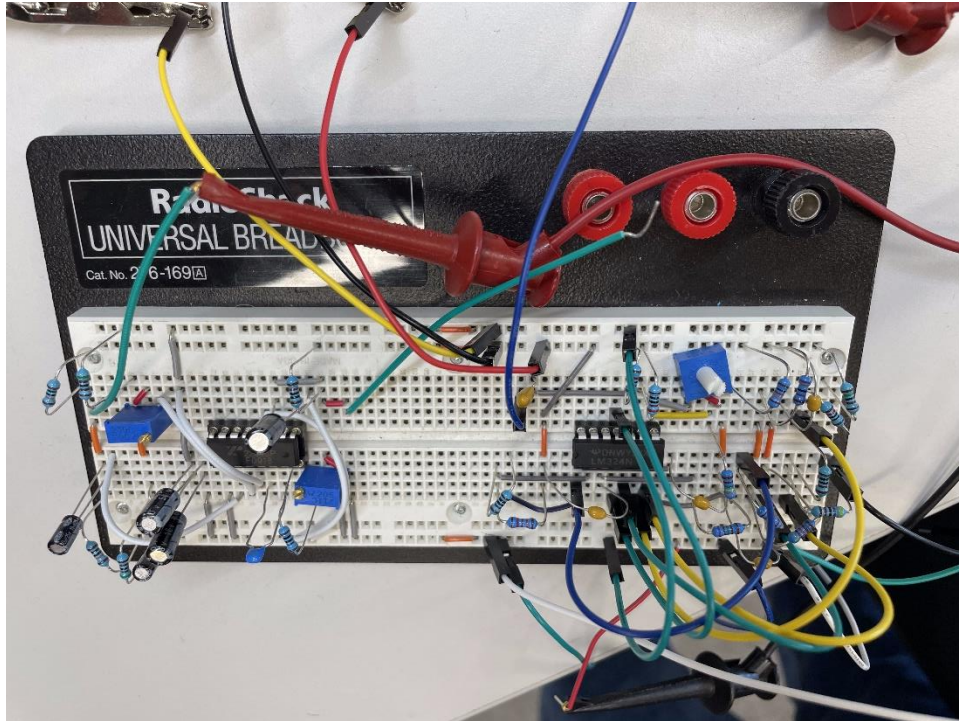


Figure 1: Breadboard Section of the Circuit showing the complexity of the connections (Kovens & Hubbard, 2023a)

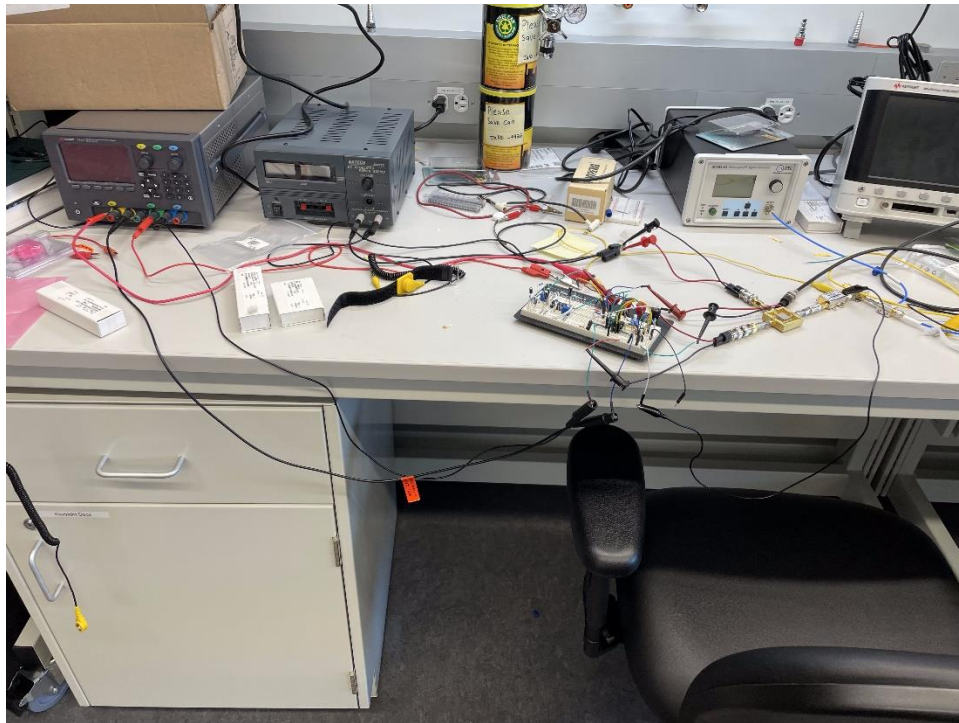


Figure 2: Entire Initial Radar Assembly that includes power supplies and other components (Kovens & Hubbard, 2023b)

Initial interviews with high school teachers also agreed that while the radar could be a valuable integration into their curriculum, the assembly that we described would not be suitable for their environment (B. Waller, personal communication, December 9, 2022). Additionally, the teachers stated that they would prefer it if the radar came completely ready-to-go as their tight schedule would make the commitment of assembly and troubleshooting difficult (D. Mitchell, personal communication, January 19, 2023).

All these issues could be solved with the integration of a PCB designed to replace the breadboard. This would secure wires and components and prevent them from being dislodged and shorting, as well as make the entire assembly far more transportable. This change would also make producing complete radar units far easier, as soldering the components into a PCB took only a single afternoon compared to the numerous days of assembly on the breadboard. Additionally, the working circuit could be potentially modified to support SMD components, allowing complete assembly straight from the factory in an even more durable and compact form factor.

3.4 - High School Teacher Interviews

Far before it was known that the project would be shifting focus from high schools to WPI, interviews had to be conducted with high school teachers in order to better understand the scope of the project and engage with stakeholders. Though much of the information gathered didn't end up being useful after the change to the Intermediate Physics Lab at WPI, some more general information the high school teachers provided did end up applying.

During the 2022 American Association of Physics Teachers, New England Section meeting that was being held on WPI, we would solicit potential interviews by approaching groups during the lunch break. This resulted in eight contacts, only two of whom followed up with the interview request; Bill Waller, a past Astronomy lecturer at the University of Washington and Tufts University and physical sciences

teacher at Rockport High School, and Dan Mitchell, a physics teacher at Duxbury High School. The goal of these interviews was to learn about how a high school physics course was structured and what is required of a demonstration, gain knowledge on good teaching practices, and get feedback on design and cost. The specific questions that were asked are listed in Appendix 7.

Bill Waller's interview focused mainly on the logistical side of implementing a lab into a high school physics course, while Dan Mitchell spoke more specifically about methods to make a lesson plan more effective. Dan said that the introduction to a topic is the most important part of the lesson. A difficult lesson plan might immediately make students frustrated and mentally disconnect with a topic, no matter how good the rest of the lesson plan is. Because of this, it's important to start simple and make progression gradual, yet meaningful. The groundwork behind the upcoming new topics should also be solid enough that students will have little difficulty building on top of it. Even with a prerequisite class, it is difficult to assume that every student will understand the material to the same degree, so reinforcing their foundation with a brief review of relevant background information can often be beneficial. Additionally, students have individual interests that vary from both the instructor and one another, and a good lesson plan reflects this. Involving a variety of subjects in the introduction can help to lure in students in ways other than the intended subject matter. Keeping up this interdisciplinary approach throughout the remainder of the lesson retains their attention and improves collaboration between individuals with different strengths. Hands on collaboration also tends to make the rest of the lesson remain productive, with students working alongside their peers to solve problems that they would struggle with on their own (D. Mitchell, personal communication, January 19, 2023).

Though high school students are younger than the students that would be taking the Intermediate Physics Lab, their advice for writing an effective curriculum proved useful when creating our lab report handout. The age difference between the high school student expected to partake in the experiment and the college students working with the radar unit in the lab is only 2-3 years, and keeping in mind

that it is likely more difficult to retain a high school student's attention than a college students', the interviewees' advice would still generally apply.

3.5 - Circuit Assembly and Testing

The first iteration of the electronic circuitry was built on a breadboard the way proposed by the MIT course. Initially, this was intended to be the final solution, as building the circuit in a breadboard eliminated the need for soldering and would make modifications simple. However, upon completing the circuit we realized this was not an adequate long-term solution. There were too many places where components could short or become disconnected from the board. Despite these issues, the breadboard build did allow us to successfully test the functionality of the electronic circuitry. We were able to measure the ramp function and sync pulse from the function generator and ensure that they were on the correct timescale and could be adjusted by the potentiometers as expected. Additionally, using a signal generator, we were able to confirm that the low-pass filter was functioning. This design did not implement the batteries, instead using a dc power supply. This design was not tested with the RF circuitry or with the audio output as the design was already compact, and we had identified that this would not be a long-term solution.

3.6 - Designing the PCB

The PCB design began by creating a schematic in KiCAD using the schematic in the MIT PowerPoint as a baseline, cross referenced with the updated component datasheets and the breadboard circuit while it was being assembled to ensure correct routing. Besides the addition of an auxiliary power and ground hub for miscellaneous components, the diagram was kept as similar to the original as possible, as shown in Figs. 3, 4, and 5.



Video Amp1

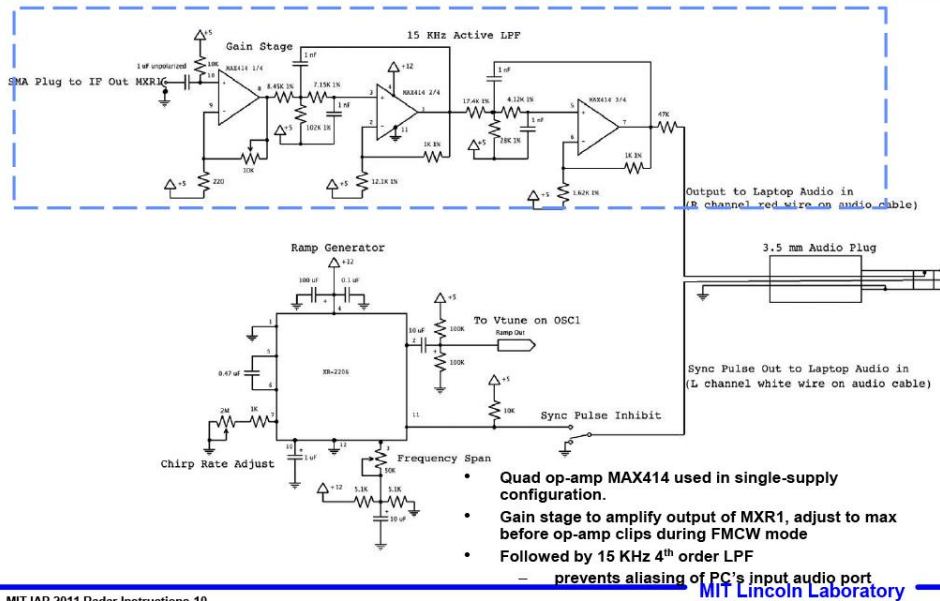
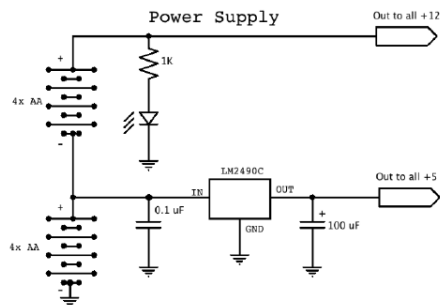


Figure 3: Video Amp and Modulator Schematic (Charvat, 2011)



Power Supply & Battery Pack



- 2 battery packs, 4x AA's in each producing 6V and 12V
- 5 VDC low-dropout regulator is fed by 6V from battery packs
 - powers RF components and provides reference voltage for analog circuits which enables single supply operation
- 12 VDC powers analog circuits including Modulator1 and Video Amp1

Figure 4: Power Supply and Battery Pack Schematic (Charvat, 2011)

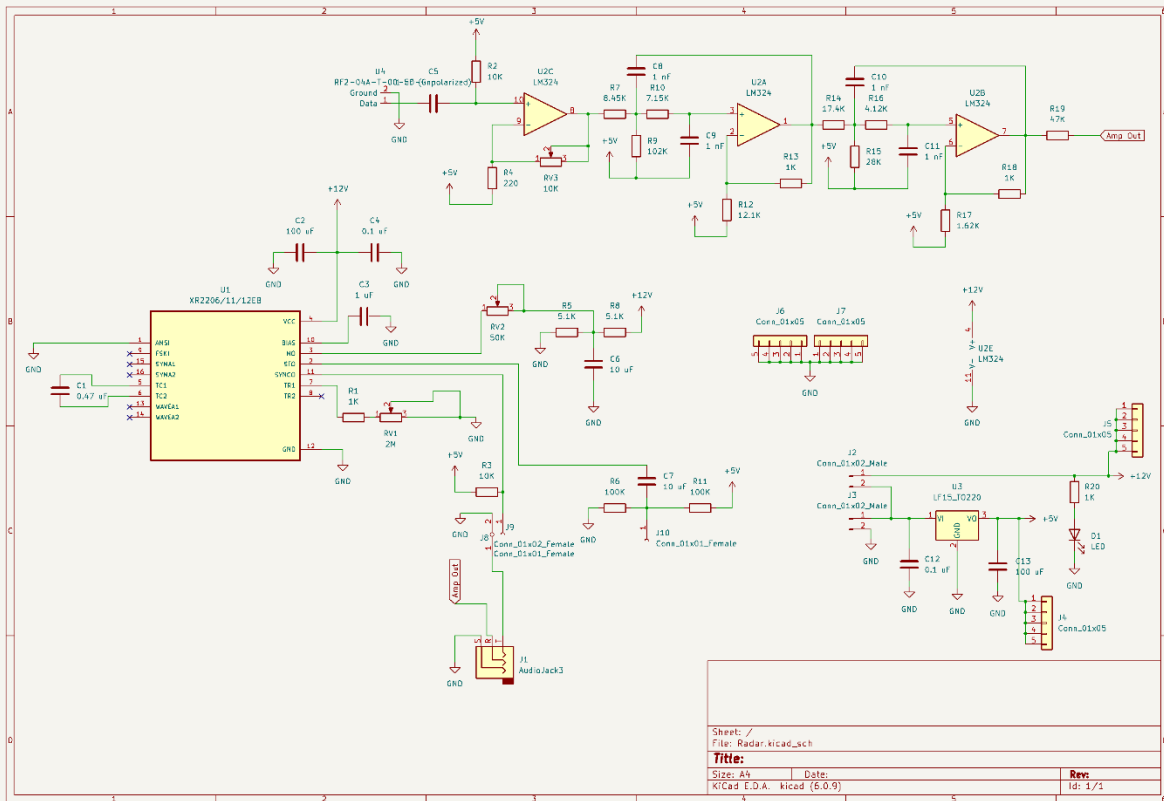


Figure 5: Schematic of PCB (Kovens, 2022b)

With the completion of the schematic shown in Figs. 5 and 6, footprints were assigned to every component to match what was used in the breadboard. This would save on cost and time since the components used in the breadboard could be taken out and dropped into the PCB without the need to re-order components. The PCB was designed alongside a 3D printed housing to make eventually securing it to a mounting board more straightforward, and the finalized Gerber files were sent off to be manufactured by OSH Park, costing \$75 and keeping additional costs low.

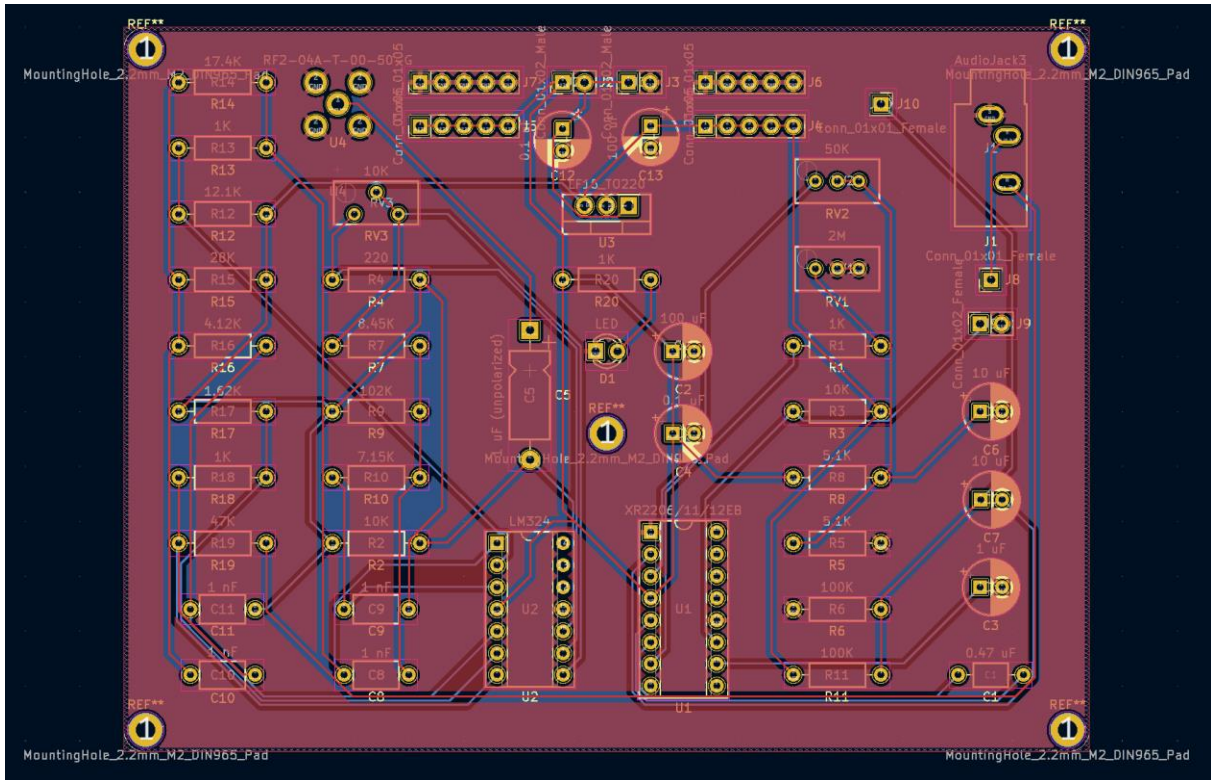


Figure 6: This photo shows the design of fabricated PCB (Kovens, 2022a)

3.7 - Final Assembly and Testing, Editing MATLAB Code

The final assembly consisted of assembling the PCB, connecting RF circuitry, creating the antenna, and mounting these components. For the PCB, all components were mounted in their intended place and connected. The only change made to our initial design was to use two RCA cables and an analog-digital converter (ADC) instead of a 3.5 mm cable for the audio output. When the MIT course was created, it was commonplace for laptops to have separate audio and microphone ports, which allowed them to record two channel audio. Most modern laptops do not have the capacity to record dual channel audio, so we included the ADC to rectify this problem. The ADC also made it simple to disconnect the sync pulse channel individually, which was originally done using a switch built into the breadboard.

Four additional cables needed to be soldered to the circuit board for the system to be functional. Two power and ground leads were needed for the two RF amplifiers, which were connected to the 5 V junctions on the top of the PCB. The substituted VCO had SMA connections, instead of leads to be soldered to. To connect the 6 V power and ramping voltage we split an SMA cable and soldered the power and ground material in the cables to an intermediate wire, and then to the board.

The antenna construction followed exactly from the MIT course instructions. We used two cans with a 5 cm diameter and a 13 cm length. A hole was drilled into the cans 3 cm from the back and an SMA solder cup with a 2.5 cm piece of stripped wire was inserted into each can. A mounting point was then drilled through the base of the can.

For the final build, all the components were mounted to a wooden board. The PCB was mounted using the included holes and was first mounted onto a 3D printed container to create space for the leads coming off the bottom of the board. The cans and RF components were screwed directly into the board as most contained holes for mounting.

The MATLAB code provided as part of the MIT course was in an incomplete state. For example, the maximum range was calculated, but the calculation was not implemented into the analysis. Similarly, the SAR script calculated the frequency bandwidth, but used constant values for the analysis instead of calling the calculated bandwidth. Additionally, the code was written to be used by students with more experience and in a course with a greater time commitment than IPL. To improve the general usability of the code, many of the variables that were set to be predetermined values from the original radar design were replaced by a calculation that uses the parameters defined at the beginning of the script. This improves the readability of the script and allows students to more easily dissect the code and understand where different variables come from.

Additionally, the notation between similar variables was made more concise, and repeated variables were removed. All the relevant variables were collected at the beginning of the script, so all the necessary inputs are together. Similarly, all the calculated variables were collected after the inputs, so that students could see how all the relevant parameters were calculated. This reduced the number of inputs that needed to be changed to run the script and makes it easier for students to understand.

The SAR analysis script was in the least complete state of the scripts and required the most work. The edits made to this script were mainly to improve readability and accessibility, similar to the changes outlined above. However, some of the elements of the script functioned incorrectly in fringe cases that could be encountered if students were testing the system outside of the standard capacity, such as using a very short sync pulse time or ramping the voltage higher than the normal range. While most of these issues were resolved, some oddities remain in the script that were outside of the scope of this project to resolve, such as the range used when performing a Stolt Interpolation requiring a greater range than expected. These remaining issues have been noted in the code and could be addressed by Ben or by an ambitious IPL student.

3.8 - Change from High Schools to WPI

It was at about this point in the project that we were contacted by Doug Petkie to change directions from the project operating within high schools to becoming part of the Intermediate Physics Lab course at WPI. For clarification on how this would change the project, we reached out to interview Ben Pollard, the professor in charge of the Intermediate Physics Lab for the 2023-2024 school year, and L. Dana, the WPI physics department lab manager. During this meeting, Ben and Dana spoke about their plans for the updated course, how the radar system could potentially fit into it, and what would be needed from us in order for it to be implemented.

Ben began the interview by mentioning a very general idea for the new course, one that puts students in charge of their own learning with a focus on collaboration and problem solving in an environment that mimics the real world. At the time of this interview, he did not have any other specific experiments planned that we could use as reference. Ben noted that we would need to procure two documents for the lab to be implemented. The first is the technical manual for the lab directors, a high-level extensive document that includes relevant equations, part numbers and specifications, circuit diagrams, troubleshooting, instructions for each measurement type, and other miscellaneous information to assist with answering students' questions. The second is the lab guide for the students, a lower-level document meant to act as a roadmap to guide students through the experiment (B. Pollard et al., personal communication, March 29, 2023).

Ben also gave some advice on creating the lab guide for students, explaining what is expected of a lab in order to best fit into the new curriculum. Though it sounds counterintuitive, less detail often results in students retaining more lab skills since they're forced to reason through problems instead of mindlessly following steps. It's best to ensure students have the proper scaffolding to learn, giving them just enough information to not be frustrated. Include whatever information would be beneficial for them to know and not much more, using this information to teach students what to do instead of showing them how to do it (B. Pollard et al., personal communication, March 29, 2023).

As for the report itself, Ben stated that it should begin with background theory. We should explain what synthetic aperture radar is, how this specific radar unit works in relation to those principles, what each physical component does, what each adjustment dial does, etc. Then, we should include an outline on how to calibrate the radar unit, telling the student what the overall goal is and how each individual component should be functioning for this to occur. This should be written at a level where students can perform the experiment without much help, but not so that students can go through the motions without understanding what is going on and how everything works. After this, we open up the

experiment to the students, guiding their progression with learning goals but allowing them to choose the path in which these goals are reached. These learning goals can be in the form of general activities, guiding questions, expected results, or other similar learning avenues (B. Pollard et al., personal communication, March 29, 2023).

3.9 - Writing the Lab Guides

In conjunction with the radar, we delivered two additional documents to Ben and Dana: a technical guide detailing the design, operation, and troubleshooting methods for the system, and a lab guide, which laid out some model experiments for students. The technical guide was designed to assist Ben and Dana with implementing the radar into the course by providing low level details on how the system operates, as well as common issues and their solutions that we ran in to while designing and testing the radar, such as reading the wrong channel from the audio file. This included creating and compiling diagrams to best illustrate the concepts needed. The guide also included general physics concepts related to radar and radar systems, which would better prepare the instructors for student questions and make improving or designing a lab easier. To make modifications easier, the technical guide also compiled the safety information for the components, and listed the limits that would damage components. The technical guide was written at a higher level, and the language or content may not be accessible to every student taking IPL.

The lab guide outlines a variety of possible experiments that IPL students could complete and was designed to be read and understood by inexperienced students. The lab guide first lays out the fundamentals of radar and the issues with implementing radar. This segues into an explanation of SAR and why it is implemented over standard radar. The details on SAR were relatively brief, as a discussion of SAR design and SAR algorithms is beyond the scope of an IPL experiment, and a broad justification of why it is implemented is all that is needed. The exact structure of IPL going forward was not completely

known, so the proposed labs encompass a wide variety of time commitments and experience requirements. Some of the proposed labs could be completed by inexperienced students in the time frame of 2-4 hours, such as taking Doppler measurements or ranging measurements. Others require a larger time commitment (6-8 hours), but are still accessible to relatively inexperienced students, such as the SAR measurement. Finally, some of the proposed labs could take a term length commitment, while also relying on a solid understanding from the student. These labs are more open ended and include labs such as testing the ranging resolution and comparing to the theoretical value or testing the absorption and reflection of different materials. These labs try to connect to larger themes in physics, and train students to address industry problems, like through wall imaging. All these experiments are designed to be more open ended and less formulaic than the previous IPL experiments and are intended to teach students laboratory skills rather than to get a correct measurement.

Chapter 4 - Findings

The findings section acts as the culmination of our project's work. In this section, there will be images of the finalized radar assembly with brief explanation as needed, as well as the procured technical guide and lab guide. Following these will be a summary of the experience of handing off the radar and documents to Ben Pollard and L. Dana, taking note of any noteworthy comments and concerns.

4.1 - The Radar

The completed radar was mounted to a board of wood for easy transport, as shown in Figs 7-9. Many problems we had with initial measurements were caused by both the antennas being too close together, as well as an amplifier not functioning correctly. This amplifier likely broke at the beginning of testing with an accidental 12V signal traveling through the 5V circuitry of the amp. Through the removal of this dead amplifier and the accompanying attenuator, as well as widening the antennas, the radar began to output the expected data. Though the radar does function without the dead amplifier and attenuator, the mixer no longer receives the expected power and is therefore unstable in the long run. The amplifier will have to be replaced to ensure the correct functionality of the radar system in the long run.

Upon completion, the radar and all the accompanying documents were handed off to Ben Pollard and L. Dana. The components in the system were explained, its functionality was demonstrated, any potential issues were disclosed, and the eventual integration into the lab course was discussed. The possibility of additional experiments was also mentioned; these will be discussed in the recommendations section. Overall, they appeared pleased with the results we were getting, and

seemed to believe the radar was involved enough to make it a valuable asset in their upcoming lab course.

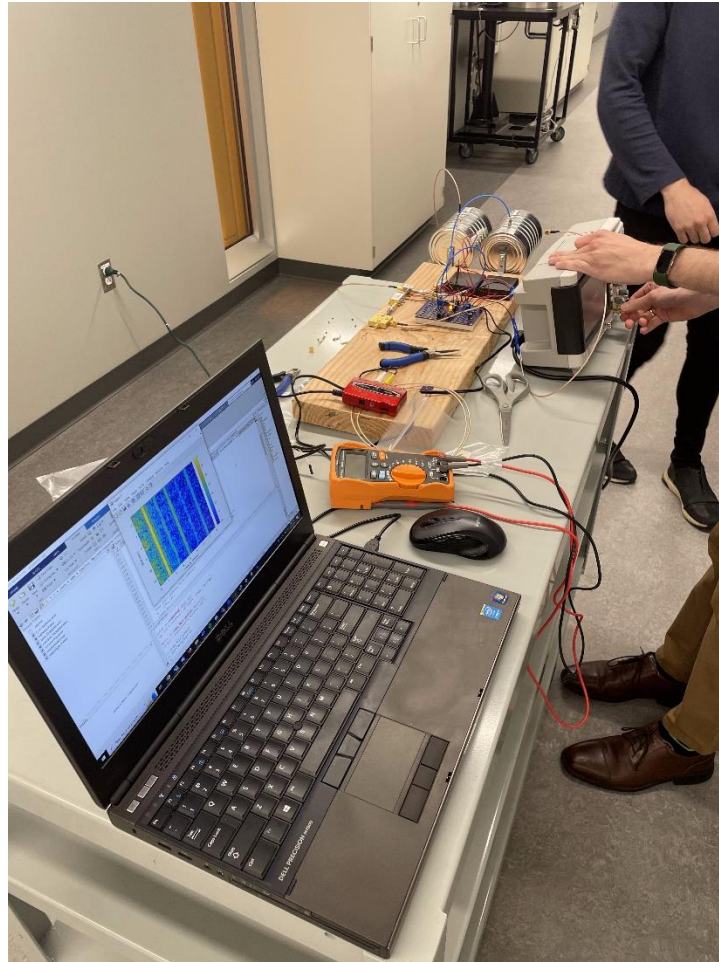


Figure 7: Testing the Radar (Kovens & Hubbard, 2023c)

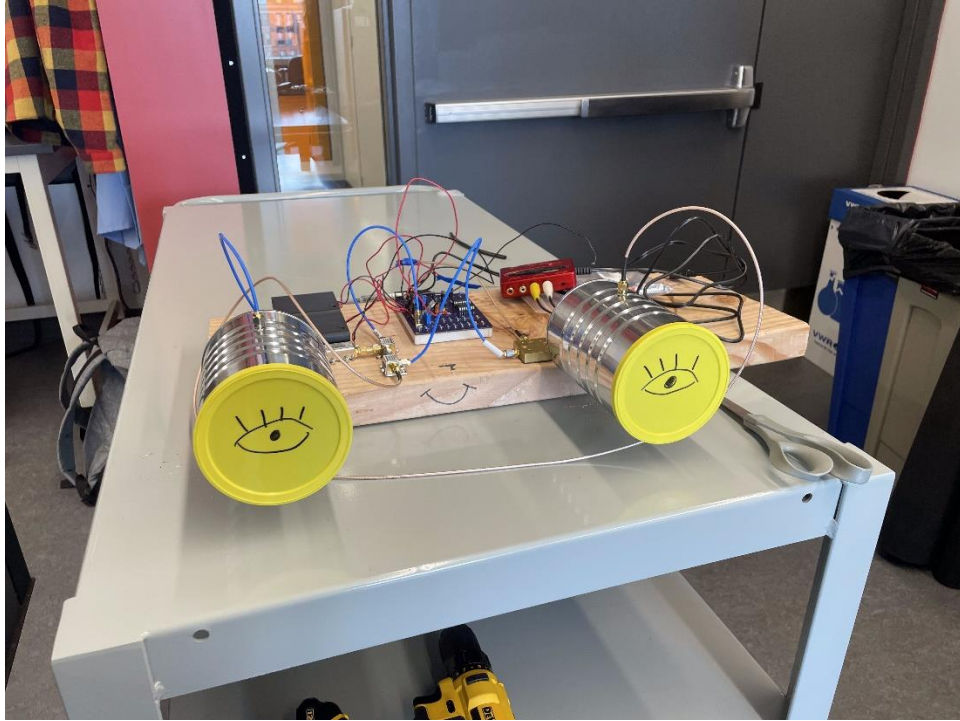


Figure 8: Front View of Completed Radar (Kovens & Hubbard, 2023d)

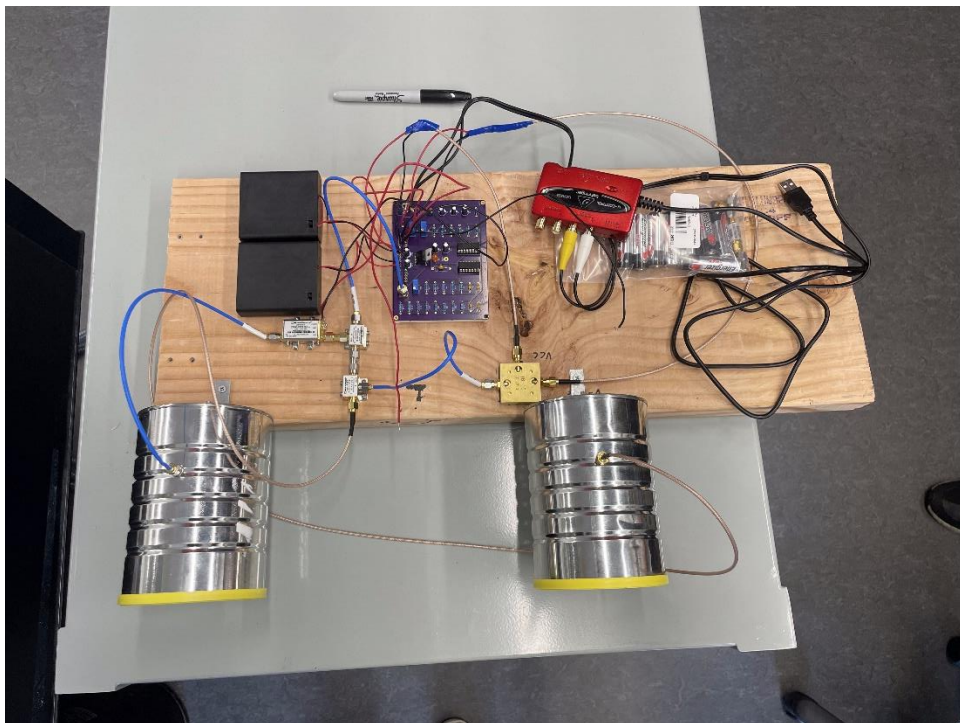


Figure 9: Top View of Completed Radar (Kovens & Hubbard, 2023e)

4.2 - The Technical Guide

Please refer to Appendix A: Technical Guide

4.3 - The Lab Handout

Please refer to Appendix B: Lab Handout

4.4 - The Edited MATLAB Scripts

Please refer to Appendices C, D, E, and F: Edited MATLAB Scripts for Doppler, Ranging, and SAR Imaging

Chapter 5 - Conclusions and Recommendations

5.1 - Conclusions

Our IQP journey began with researching and creating a synthetic aperture radar system from an MIT OpenCourseWare project for use in high schools, though this later transformed into a project that would be used in WPI's own intermediate physics laboratory course. We began the process by interviewing teachers, which even though the project scope changed, ended up proving useful for educational tactics. We researched and modified the existing radar system to our needs, designed components for it to be more functional, tested the completed system, and wrote technical and lab guides for both the professors and students of the lab course. We learned that a lab course doesn't need to involve high end complex equipment to prove effective, and it is often the more down to earth labs that engage students the most. Though we spent 3 semesters on the project, we had to boil down our process and findings into something that would be doable within the two and a half weeks of the intermediate physics lab.

Contrary to what we believed, we learned that while students may like clear cut sequential instructions, they retain information better with a more wide-scope open-ended approach to problems. This type of approach forces students to engage in critical thinking along every step of the way while also creating a larger incentive for collaboration. Too little guidance can be frustrating to students though, so there should be enough information to allow students to progress through the lab without outside help if they understand each concept, yet not so much information that students can cruise through the lab without understanding what is going on. Keeping this information in mind allowed us

to create a lab guide that we as students believe would be an enjoyable yet valuable addition to the intermediate physics lab.

5.2 - Recommendations for Research Continuation/Lab Additions

5.2.1 - Replacement Amplifier

This is the most pressing recommendation as it actively affects the function and longevity of the system. We encourage Ben and Dana to purchase a replacement as soon as possible, as well as purchase a spare if the budget allows. The longer the radar is run without the missing amplifier, the more chance there is of greater damage.

5.2.2 - Radar on automatic rails

As a possible addition to the experiment, the radar could be mounted on automatic rails to make the SAR measurement easier. The radar could move along the rails along a specified distance, enabling the sync pulse, and then disabling the sync pulse while it moves to the next measurement point. This would vastly improve both the ease of taking SAR measurements and improve the resulting images.

5.2.3 - Custom antennas

Custom antennas could possibly improve the resolution and accuracy of the measurements, and it could be interesting for students to see exactly how the changes in antenna size or shape would affect their results.

5.2.4 - Comparing Theoretical vs. Actual Resolution

Another potential addition could be having students calculating the theoretical resolution of the radar system as it is assembled, and then testing the actual resolution vs. the theoretical. With this

information, they could attempt to maximize the resolution they are getting by adjusting the radar to what they believe would produce optimal results.

5.2.5 - Altering MATLAB Parameters

Along the lines of the last suggestion, students could dig around in the MATLAB code and adjust parameters to help them better understand what the code does. Once they understand the code, they can attempt to improve it and get better visualizations from their data.

5.2.6 - Absorption of Water

Since water is a lossy dielectric (high absorption) over the operating range of this radar, an experiment could be designed around this. Students could observe and write conclusions based on differences in images of metal cylinders vs. a similarly sized water bottle, the imaging of objects underwater in a pool, or imaging of objects behind a tub of water.

5.2.7 - Through Wall Imaging

As a tangent demonstration of radar application, students could use the radar system to image walls of various materials. Students can observe how various wall materials affect the imaging results, as well as explore the potential extensions of this topic. Can they observe pipes or wires in walls, or can objects be located behind walls?

5.2.8 - Smooth vs. Rough Reflectivity

This would likely be more difficult to implement, but students could also observe the differences between smooth and rough objects. How rough does an object have to be in order for its radar image to become noticeably hazy compared to similar reflective object?

5.2.9 - Spectrum analyzer

A cheap spectrum analyzer could potentially help students understand what signals the radar is generating along its circuit path. These measurements could further their understanding by following the circuit path, observing how each individual component manipulates the signal into something that the MATLAB code can understand. An oscilloscope capable of reading the proper frequencies would also perform a similar function, but a sufficient signal generator can be had at a fraction of the cost. An example of one such spectrum analyzer is listed below.



Figure 10: Proposed Spectrum Analyzer (2023 Upgraded TinySA Ultra Spectrum Analyzer, SeeSii 4.0 Inch 100kHz to 5.3GHz Handheld Tiny Frequency Analyzer with 32Gb Card, 2-In-1 Signal Generator 100kHz to 800MHz MF/HF/VHF UHF Input,V0.4.5.1: Amazon.com: Industrial & Scientific, n.d.)

References

- 2023 Upgraded TinySA Ultra Spectrum Analyzer, SeeSii 4.0 Inch 100kHz to 5.3GHz Handheld Tiny Frequency Analyzer with 32Gb Card, 2-in-1 Signal Generator 100kHz to 800MHz MF/HF/VHF UHF Input,V0.4.5.1: Amazon.com: Industrial & Scientific. (n.d.). [www.amazon.com](https://www.amazon.com/Upgraded-TinySA-Spectrum-Frequency-Generator/dp/B0BBGK9QJB/ref=sr_1_4?keywords=spectrum+analyzer+6ghz&qid=1682616420&srefix=spectrum+anal%2Caps%2C124&sr=8-4&ufe=app_do%3Aamzn1.fos.18ed3cb5-28d5-4975-8bc7-93deae8f9840).
- Charvat, G. (2011). *Build a Small Radar System Capable of Sensing Range, Doppler, and Synthetic Aperture Radar Imaging | Supplemental Resources*. MIT OpenCourseWare. <https://ocw.mit.edu/courses/res-ll-003-build-a-small-radar-system-capable-of-sensing-range-doppler-and-synthetic-aperture-radar-imaging-january-iap-2011/>
- Kovens, L. (2022a). *Design of PCB*.
- Kovens, L. (2022b). *Schematic of PCB*.
- Kovens, L., & Hubbard, M. (2023a). *Breadboard Section of the Circuit*.
- Kovens, L., & Hubbard, M. (2023b). *Entire Initial Radar Assembly*.
- Kovens, L., & Hubbard, M. (2023c). *Testing the Radar*.
- Kovens, L., & Hubbard, M. (2023d). *Front View of Completed Radar*.
- Kovens, L., & Hubbard, M. (2023e). *Top View of Completed Radar*.
- Kozminski, J., Lewandowski, H., Beverly, N., Lindaas, S., Deardorff, D., Reagan, A., Dietz, R., Tagg, R., Eblen--Zayas, M., Williams, J., Hobbs, R., & Zwickl, B. (2014). *AAPT Recommendations for the Undergraduate Physics Laboratory Curriculum Subcommittee Membership*. https://www.aapt.org/resources/upload/labguidlinesdocument_ebendorsed_nov10.pdf

Mitchell, D. (2023, January 19). *Dan Mitchell Interview* (L. Kovens & M. Hubbard, Interviewers) [Personal communication].

Moreira, A., Prats-Iraola, P., Younis, M., Krieger, G., Hajnsek, I., & Papathanassiou, K. P. (2013). A tutorial on synthetic aperture radar. *IEEE Geoscience and Remote Sensing Magazine*, 1(1), 6–43.
<https://doi.org/10.1109/mgrs.2013.2248301>

Physics | Worcester Polytechnic Institute. (n.d.). www.wpi.edu.

<https://www.wpi.edu/academics/calendar-courses/course-descriptions/3811/physics#PH-2651>

Pollard, B. (2022, October 30). *The Global Fellows Program at the Global Lab Application for AY 2023/24*.

Pollard, B., Dana, L., & Bouchard, J. (2023, March 29). *Ben and Dana Interview* (L. Kovens & M. Hubbard, Interviewers) [Personal communication].

Waller, B. (2022, December 9). *Bill Waller Interview* (L. Kovens, Interviewer) [Personal communication].

Chapter 6 - Appendices

6.1 - Technical Guide

SAR Lab
Technical Guide

Background

For a radar system, the spatial resolution of the image, or detail of the image, is limited by the ratio of the wavelength to the antenna size. While the derivation of the exact resolution is very involved it can be shown to be approximately equal to:

$$\delta x \approx R \frac{\lambda}{L}$$

Where R is the range to the target (more specifically the slant range), λ is the wavelength and L is the length of the aperture.¹ Our choice of wavelength is largely determined by what components are easily available, and by what frequencies are legal to broadcast on.

For many radar applications weight and size limiting factors. Consequently, techniques have been developed to increase the resolution utilizing the motion of the device. One of these methods is synthetic aperture radar.

Note on ISM Band Broadcasting

International regulations permit broadcasting in the 2.4-2.483 GHz bandwidth with antennas under 1 W. This system technically broadcasts under this band for part of the bandwidth and can be tuned to broadcast over this bandwidth by increasing the height of the ramping voltage. To keep the system completely within ISM band requirements the Vtune function needs to vary from 3 V to 6 V. This can be done by connecting a 3 V battery/power supply to the Vtune connection.

What is Synthetic Aperture Radar (SAR)

A synthetic aperture radar is a radar system that takes multiple images of an object from a variety of locations and then combines these images to create a higher resolution image. This process allows the radar to act as if it has a much larger antenna/aperture, hence the name. This allows a small antenna to produce high resolution images if measurements are taken over a large enough distance. More specifically, the spatial resolution can be approximated as:

$$\delta x \approx \frac{L}{2}$$

SAR works well on fast-moving objects and is frequently used in satellites and planes as they can very easily take measurements from a variety of points.

¹ For the case of this radar L is the aperture length as the opening is flat. To be more specific it is the azimuth length. These values are pictured in the appendix

Radar Design

The radar system consists of four main components: a function generator, a low-pass filter, a mixer, and a voltage-controlled oscillator (VCO). The function generator has two outputs, a triangle wave and a square wave, each of which are adjusted by two of the potentiometers in the circuit. One of the potentiometers (RV2) controls the height of the peak of the triangle wave, while the other controls the period of both waves (RV1).

The triangle wave is fed into the voltage-controlled oscillator (VCO) and varies the frequency of the transmitted radio wave. The square wave, or sync pulse is connected directly to the audio output of the circuit and is used when analyzing the output to discern what the transmitted frequency at each time was.

The low-pass filter circuit also serves two purposes for the radar. First, it amplifies the output from the RF mixer. The degree of amplification is controlled by the final potentiometer (RV3). This potentiometer should be adjusted so that the gain is as high as possible without clipping. In practice this is difficult to measure. Second, it acts as a low-pass filter that filters out frequencies higher than $\approx 20\text{kHz}$. This is done to remove the summed frequency from the mixer which would cause aliasing in the recording.

The RF circuitry consists of a VCO, a splitter, a mixer, an attenuator, and two amplifiers. The VCO transforms a DC input into an RF output. The VCO has two inputs, only one of which is required. The VCO requires a steady 6 volt input to generate a signal, which is received on the Vcc port. With only this input the VCO outputs a single frequency². This configuration is used for doppler shift measurements. The second input, V-tune, accepts a wide range of voltages (0-15 V) and increases the output frequency linearly as the voltage increases.³

The mixer is the other key RF component. A mixer's basic purpose is to take two inputs and compare their frequencies. The standard notation is to label the reference wave LO, the experimental or measured wave RF and the output IF. For an ideal mixer⁴ the output (f_{IF}) is composed of two frequencies, which are related to the frequency of the reference wave (f_{LO}) and the frequency of the experimental wave (f_{RF}) by the relation below:

$$f_{IF} = f_{LO} \pm f_{RF}$$

However, the low pass filter eliminates the summed frequency leaving only the difference between them. This frequency will be in the range of 0~15kHz, which is in the range that can be measured by analog-digital converter (ADC).⁵

² The output frequency varies slightly with the temperature of the VCO as well

³ The experimentally measured relationship is shown in the appendix

⁴ In a non-idealized mixer, we expect to get frequencies $f_{IF} = nf_{LO} \pm mf_{RF}$ where m and n can be any odd integers. However, these modes will have small amplitudes compared to the main frequencies and the low-pass filter eliminates the high frequency modes. See Mixer Basics Primer by Marki Microwaves for a more in-depth analysis.

⁵ The ADC is rated up to 48 kHz although no frequencies that high will get past the filter

The mixer only operates within a small range of powers, so the amplifier and attenuator ensure that the mixer receives the correct amount of power. Additionally, the mixer incurs a large power loss, typically 6-8 dB (75%-85%) of the LO power, which constitutes the need for the amplifier before it is read by the ADC.

The output from the circuit is two RCA connections, one carrying the filtered output from the mixer (yellow cable) and the other carrying the sync pulse (white cable). By default the scripts expect the sync pulse on the left channel and the radar on the right. This is fed to an ADC to digitize the signal as most laptops do not have the capacity to record two channel input. The channel with the radar signal is very quiet, and when recording will appear to be completely empty. The matlab files are by default configured to read the sync pulse on the first channel and the radar on the second.

Component Safety

The VCO and the mixer are the two sensitive (and expensive) components. To avoid damaging components, do not supply the V_{cc} connection on the VCO with more than 7 V and the V_{tune} connection with more than 14.5 V. The mixer operates in a very fine range of power and should not receive power differing from 13 dBm at the LO port. Any modifications made the RF circuitry should ensure that mixer continues to receive power at 13 dBm.

Notes on Matlab Scripts and Analysis

The script does not automatically determine which channel contains the sync pulse and which contains the radar reading. Reading the wrong channel creates an easily recognizable checkerboard pattern (an example is shown in the appendix). The audio is stored as a matrix in matlab, with a column representing each channel. By default, the sync pulse is expected as the first channel and the radar as the second. This can be swapped by changing the second input of the `s` and `trig` vectors.

Doppler Measurements

Measuring a the doppler shift doesn't require a variable frequency, and consequently the sync pulse is not needed either. Consider why having a variable frequency would make the velocity measurement inaccurate.

To take a measurement:

1. Disconnect the ramping voltage from the VCO.
2. Point the antenna at the target.
3. Record an audio file using the ADC as the input device.
4. Save the audio file as a .wav file in the same directory of the matlab script
5. Edit the audioread function in the matlab script to match the name of the audio file
 - a. The frequency and pulse length should by default be correct. If a DC voltage has been added to the reference the frequency vs tuning voltage graph in the appendix to find the frequency.
6. Run the matlab script

Code notes:

- The doppler measurement does not use the sync pulse for analysis, but the sync pulse length variable is used in calculations. The sync pulse length is the resolution of the time, meaning there is one time measurement every sync pulse length.

Ranging

To take a measurement

1. Connect ramping voltage to VCO and sync pulse to ADC
2. Measure the peak voltage of the ramp function and the length of the sync pulse
3. Position radar and record audio
4. Save audio file as a .wav file
5. Adjust sync pulse time, frequency center, frequency bandwidth, and audio file name in the matlab script
 - a. This is done by referencing the datasheet from the VCO, see appendix.
 - b. The sync pulse length can be measured from the audio file or from the circuit itself.

SAR Imaging

To take a SAR measurement a yard stick or similar measuring device is needed to create equidistance points to measure at. The matlab code looks for empty spaces in the sync pulse to detect when the radar has been moved. To get a quality measurement it's recommended to measure over about 3 meters in around 5 centimeter increments. To take a measurement

1. Set up a tape measure or other tool to measure equidistance points in a straight light
2. Connect the ramp function to the VCO
3. Measure the height of the ramp function and the length of the sync pulse
4. Start recording from the first point
5. Before moving the radar we need to stop the sync pulse so that the matlab code can detect the movement.
 - a. This can be done by disconnected the sync pulse channel (white cable) from the ADC and then moving it
6. Adjust the audio file name, sync pulse time, and the frequency start and stop

Appendix A – Comments on Resolution

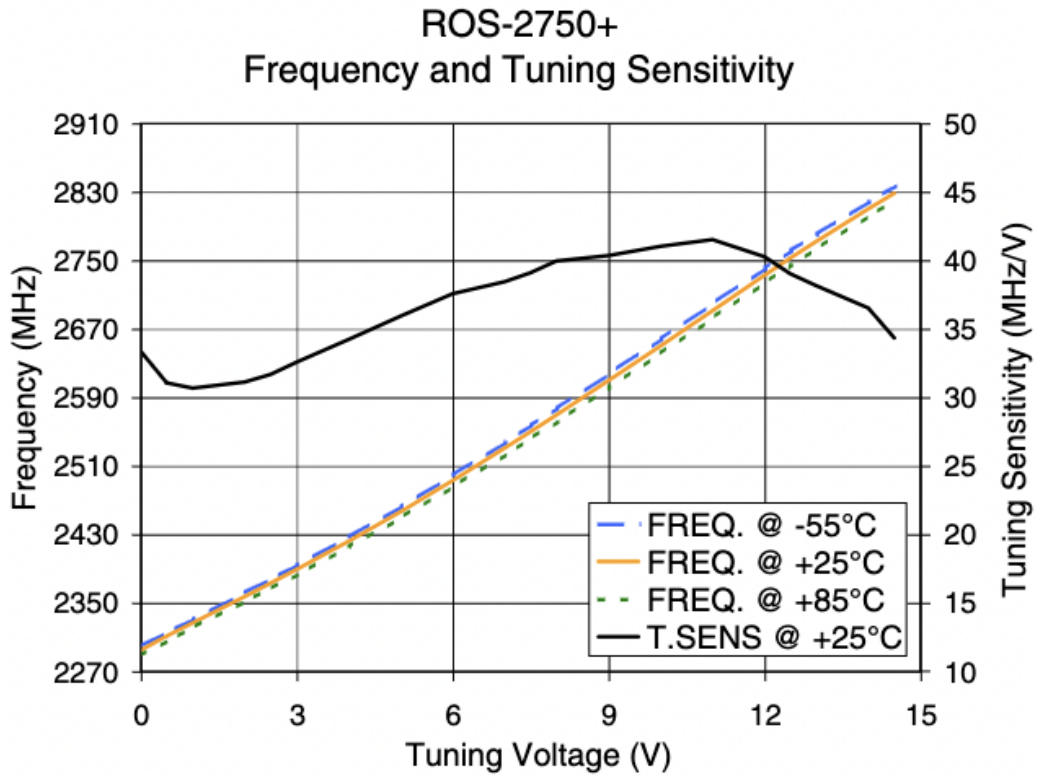
The ranging resolution can be calculated much more easily than the spatial resolution. A simple calculation for the ranging resolution is:

$$\delta R = \frac{c}{2B}$$

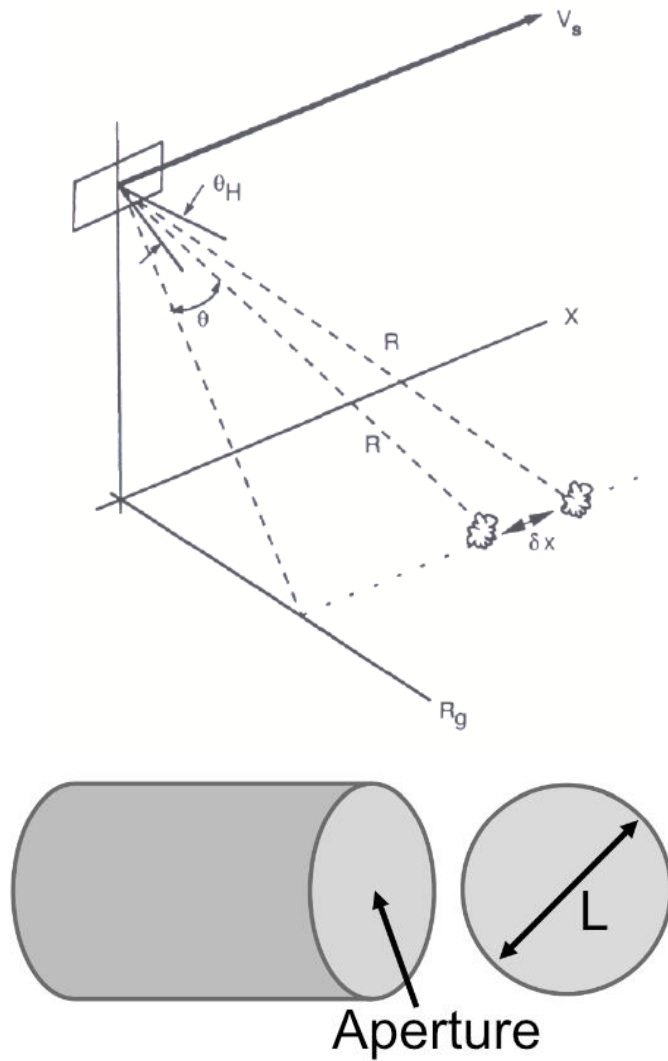
Where B is the transmission bandwidth. The typical bandwidth for this radar is 2.3 GHz-2.5GHz, which leads to a ranging resolution of ≈ 75 cm. It is important to note that this indicates that two objects closer than 75 cm cannot be distinguished by the antenna, not that objects smaller than 75 cm cannot be detected.

We can compare this to the estimated spatial resolution for ranging with and without SAR. The aperture of the can is about 10 cm, which leads the aperture and wavelength term to cancel. So the estimated spatial resolution without SAR is the range to the target. This prevents us from imaging with the real aperture radar, as the resolution is far too low to create a meaningful image. Compared to the value for a SAR antenna, which gives a resolution of about 5 cm, which is high enough resolution to meaningfully image larger objects.

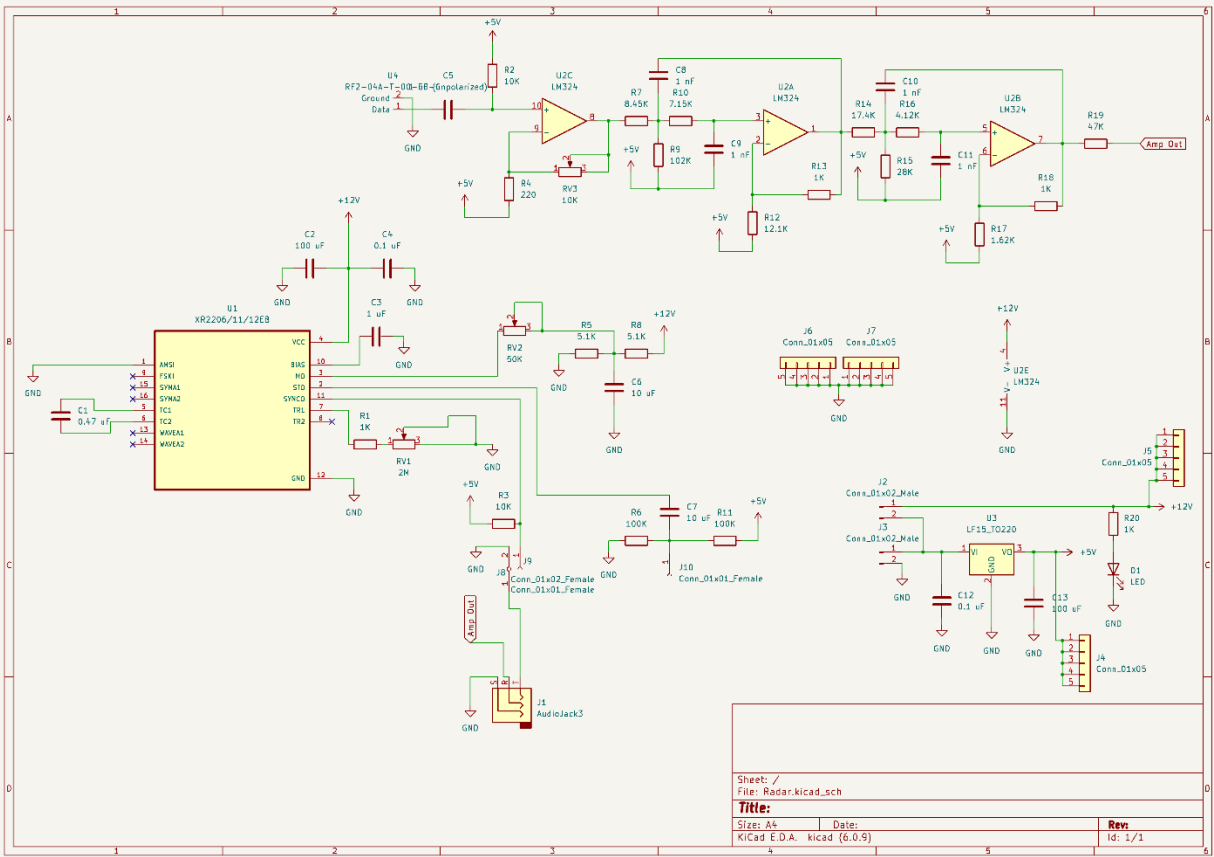
Appendix B



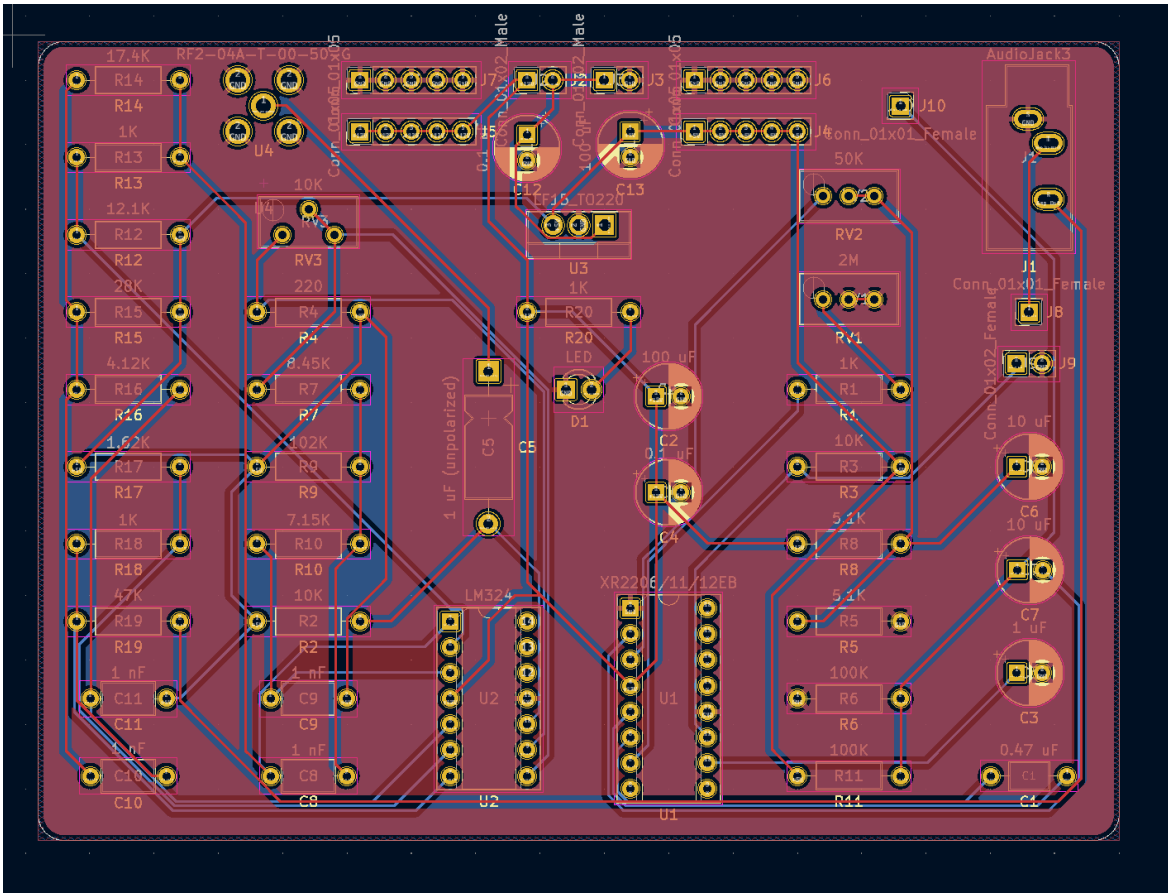
Experimental VCO output frequency vs tuning voltage. The slope is shown in black and is roughly constant over the voltage range.



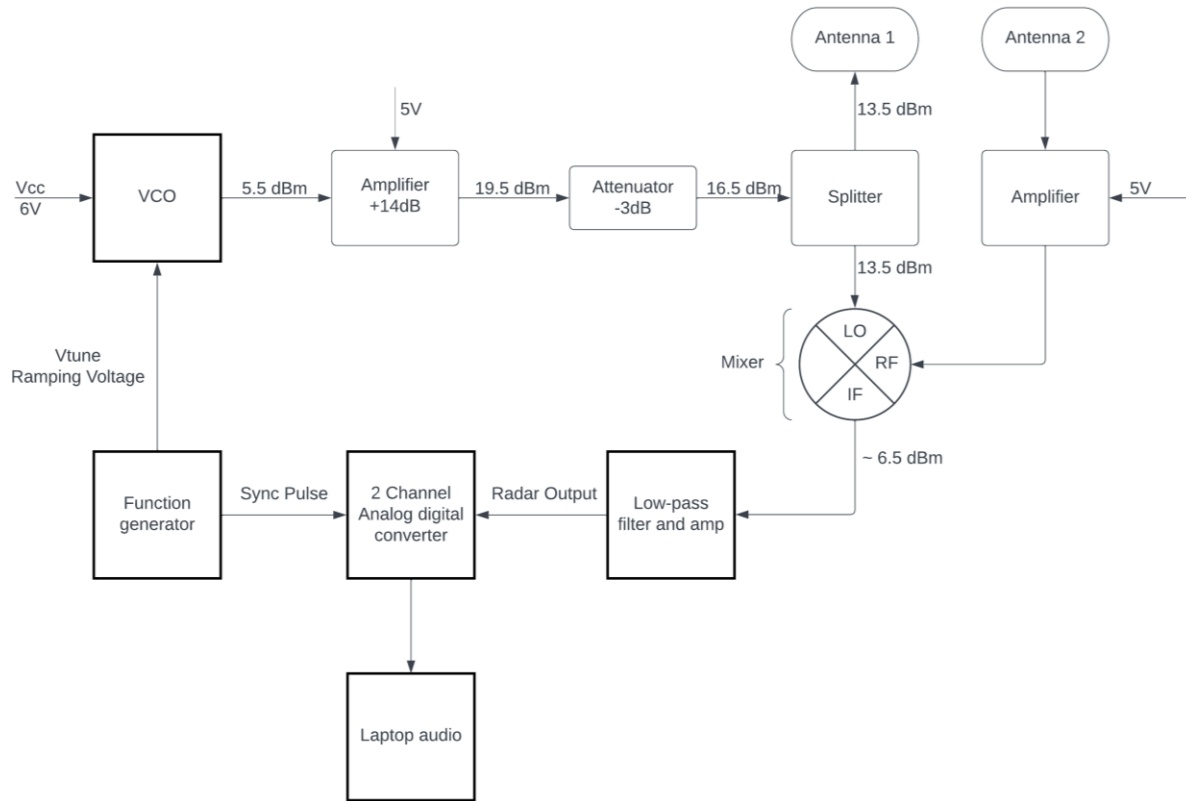
Relevant physical variables. First it taken from Synthetic Aperture Radar Systems and Signal Processing (1991).



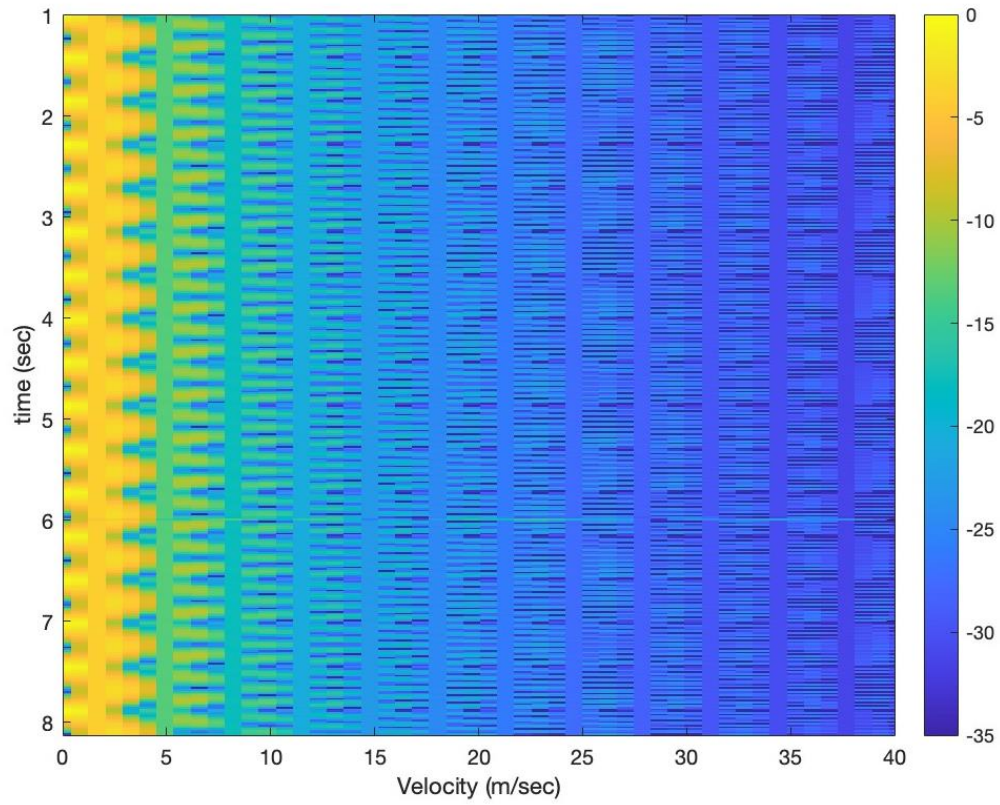
Circuit Diagram



PCB diagram.



RF circuit diagram with power outputs labeled



Example of output where the sync pulse and radar channels are swapped.

6.2 - Lab Handout

Synthetic Aperture Radar

Lab Guide

Lab Introduction

The following lab consists of using a homemade radar system to perform three different measurements: a velocity measurement using the doppler effect, a ranging vs time measurement, and creating a 2D image.

Background

The concept of a doppler shift should be familiar, but we will briefly go over it here. When a wave is transmitted from a moving source, observers will measure the frequency of the wave differently depending on the relative velocity between them. By transmitting at a known frequency and comparing it to the frequency of the wave bounced off an object, the relative velocity of the object can be determined. The experimental setup lacks the ability to measure the received frequency, but instead measures the difference between the transmitted and received frequency. It is not difficult to convert the standard doppler shift formula into one that contains the frequency shift instead of the received frequency.

Radar ranging and imaging are likely less familiar concepts. Ranging is fairly simple, an antenna transmits a constantly changing frequency and then by analyzing what frequencies are returned and the phase of the returned frequencies we can determine how far away objects are. A non-moving radar, what is referred to as a real aperture radar (RAR) is effective at detecting objects and measuring their distance but cannot produce high quality 2D or 3D images without a using a huge antenna, which is not possible in many circumstances. To increase the resolution without increasing the antenna size we exploit the fact that many radar systems are in motion. This allows the radar to act as if it has a much larger aperture, hence the name synthetic aperture radar (SAR). Using SAR allows us to take a RAR system with a spatial resolution in the order of 10s of meters to a system with a resolution in the order of centimeters.

Radar Design

The radar system consists of four main components: a function generator, a low-pass filter, a mixer, and a voltage-controlled oscillator (VCO). The function generator has two outputs, a triangle wave and a square wave, each of which are adjusted by two of the potentiometers in the circuit. One of the potentiometers (RV2) controls the height of the peak of the triangle wave, while the other controls the period of both waves (RV1).

The triangle wave is fed into the VCO and varies the frequency of the transmitted radio wave. The square wave, or sync pulse is connected directly to the audio output of the circuit and is used when analyzing the output to discern what the transmitted frequency at each time was.

The low-pass filter circuit also serves two purposes for the radar. First, it amplifies the output from the RF mixer. The degree of amplification is controlled by the final potentiometer (RV3). This potentiometer should be adjusted so that the gain is as high as possible without clipping. This should not be an issue unless measuring something very close to the antenna. Second, it acts as a low-pass filter that filters out frequencies higher than $\approx 20\text{kHz}$. This is done to remove the summed frequency from the mixer (this is explained below) which would cause aliasing in the recording.

The VCO has two inputs, only one of which is required. The VCO requires a steady 6 volt input to generate a signal, which is received on the Vcc port. With only this input the VCO outputs a single frequency. This configuration is used for doppler shift measurements. The second input, V-tune, accepts a wide range of voltages (0-15 V) and increases the output frequency linearly as the voltage increases.

The mixer is the other key RF component. A mixer's basic purpose is to take two inputs and compare their frequencies. The standard notation is to label the reference wave LO, the experimental or measured wave RF and the output IF. For an ideal mixer the output (f_{IF}) is composed of two frequencies, which are related to the frequency of the reference wave (f_{LO}) and the frequency of the experimental wave (f_{RF}) by the relation below:

$$f_{IF} = f_{LO} \pm f_{RF}$$

However, the low pass filter eliminates the summed frequency leaving only the difference between them. This frequency will be in the range of 0~15kHz, which is in the range that can be measured by the analog-digital converter (ADC).

The mixer only operates within a small range of powers, so the amplifier and attenuator ensure that the mixer receives the correct amount of power. Additionally, the mixer incurs a large power loss, typically 6-8 dB (75%-85%) of the LO power, which constitutes the need for an amplifier before it is read by the ADC.

The output from the circuit is two RCA connections, one carrying the filtered output from the mixer and the other carrying the sync pulse. This is fed to an ADC to digitize the signal as most laptops do not have the capacity to record two channel input. The channel with the radar signal is

very quiet, and when recording will appear to be completely empty. The matlab files are by default configured to read the sync pulse on the first channel and the radar on the second.

Velocity Measurement Using Doppler Shift

Measuring the velocity doesn't need a ramping voltage or the sync pulse, but only the ramping voltage needs to be disconnected. To take the measurement:

- With the ramp function disconnected, record the output of the radar as an audio file.
- Adjust the parameters in the matlab script to match the experimental setup and run the script.

While the measurement does not need the sync pulse, the matlab script still calls for and uses the sync pulse time. Try adjusting the sync pulse time to see how it changes the output, then examine the script and see how the sync pulse time is used in the analysis.

Consider how the ramping voltage would affect the doppler measurement by doing the following calculation. What would be the frequency difference due to the ramp function for a stationary object 20 meters away. What velocity does this correspond to and would it show up in the results.

Ranging Experiments

To take either ranging or SAR measurements two specifications from the radar are needed. Those are the length of a sync pulse and the bandwidth of the frequency sweep, which is calculated from the peak voltage of the ramp function. Both can be measured easily with an oscilloscope and are adjusted using two of the potentiometers in the circuit. Generally, the pulse length should be about 20 ms and the ramp height of 6 V. To make a measurement:

- After measuring the pulse length and ramp height, position the radar and begin recording audio
- Adjust the audio file name, sync pulse time and frequency start/stop in the matlab script

SAR Imaging

Imaging with SAR is similar to taking ranging measurements from multiple locations. To make measurements a measuring tape/measuring stick is needed to space the measurement points out equally. Generally, the measurements should be spaced by about 5 cm and go over a distance of 3 meters. To save time measurements can be taken over larger increments or shorter distance, but image quality will be affected by this. The analysis code looks for spaces in the audio file where there is no sync pulse to identify movement, so the sync pulse needs to be disconnected before every movement. The analysis also needs an approximate distance to the target, so ensure to measure/approximate this. To make a measurement:

- Measure the ramp height and sync pulse length
- Set up the tape measure/measuring stick perpendicular to the direction of the target
- Measure/estimate the distance to the target
- With the radar at the first position, begin recording with both audio channels connected
 - The radar does not need to record for very long at each position

- Disconnect the sync pulse channel by unplugging the white cable from the ADC and move the radar by the designated increment amount
 - There needs to be at least 0.25 s without the sync pulse to identify a movement, this can be adjusted in the script if needed.
- After measuring over the whole range adjust the relevant variables in the script

Measuring Differences in Materials

We expect different materials to interact with the radio waves we send off. Measuring an object is reliant on reflected waves, so a perfectly absorbing body would be indistinguishable from free space. While we don't have access to a perfectly or close to perfectly absorbing surface, water acts as an insulator in the frequency range we are transmitting.

Try to measure the difference in absorption/reflection by testing how well similarly sized objects of different materials are detected at different distances. Alternatively, does placing a tub of water/a metal sheet prevent detection of objects behind it.

Similarly, how well can you image if you place a sheet of paper/other thin material in front of the antenna. This is similar to through wall imaging, where you could try to measure through drywall or a cinderblock.

Resolution Experiment

The resolution of any imaging system is an important specification that describes how close two objects can be before the system cannot distinguish them. The ranging resolution is easy to calculate theoretically, but it is much more difficult to calculate the spatial resolution when the system is used as a SAR.

Design an experiment to test the spatial or ranging resolution. The general idea here is to move two objects closer and closer until they can no longer be distinguished from each other. Then compare this result to the theoretical results, which can be calculated as shown below.

The ranging resolution relates inversely to the bandwidth the signal is transmitted over and is calculated as:

$$\delta R = \frac{c}{2B}$$

Where B is the frequency bandwidth swept over, R is the range at the closest point, and c is the speed of light. This result holds for both a stationary radar and for SAR. The spatial resolution is more complicated and is dependent on the algorithm used to combine the measurements, the shape of the antenna/aperture, the range from the target, and the frequency swept over, among other things. However, two values are commonly cited for the spatial resolution. The first is for “unfocused” SAR which does not include a change in phase of the received frequency in the analysis. The second approximates the resolution when fully considering the phase change, which the algorithm we are using does. However, the second also makes some assumptions that do not hold for this system, however, it will still yield a much better estimate than the first.

$$\delta x \approx \sqrt{\frac{\lambda R}{2}} \text{ Assuming no consideration of phase change.}$$

$$\delta x \geq \frac{L}{2} \text{ Considering phase change.}$$

The second is a function of L only, which is the length of the aperture, in our case the diameter of the can. Note that this implies that decreasing the size of the aperture would infinitely increase the resolution, which is not true. Eventually the area of the aperture becomes a limiting factor, but this approximation will give a reasonable accurate result.

6.3 - Doppler MATLAB Code

%Doppler shift velocity measurement

%Adapted from Gregory L. Charvat

clear all;

close all;

%read the raw data .wav file here

%the audio file is stored as a matrix Y

%FS stores the number of samples per second of the audio file

[Y,FS] = audioread('dopplernoaudio.wav');

%Setting radar parameters

Tp = 0.02; %(s) Sync pulse time

fc = 2290E6; %(Hz) Radar frequency

%radar frequency does not need to be exact, error is very small

%defining the speed of light

c = 3E8; %(m/s)

%Calculate the number of samples per sync pulse

N = round(Tp*FS);

%Calculating wavelength of signal

lambda=c/fc;

%the input appears to be inverted, the 2 calls the channel of the recording

%may need to be changed depending on which channel contains the sync pulse

s = -1*Y(:,2);

%Y is not needed past here, but can be used to understand the data

%clear Y;

%create doppler vs. time plot data set here

%ii breaks the data down into a block for each sync pulse

%This is the resolution of the data, if Tp is 20 ms a data point will be

%recorded ever 20 ms

for ii = 1:round(size(s,1)/N)-1

 sif(ii,:) = s(1+(ii-1)*N:ii*N);

end

%subtract the average DC term here, removing noise

sif = sif - mean(s);

% Calculate the resolution of the velocity

zpad = 4*N; %4N velocity points per sync pulse

%doppler vs. time plot:

%taking a inverse fourier transform of the data

v = dbv(iff(sif,zpad,2));

v = v(:,1:size(v,2)/2); %v is symmetric around the center column, dropping the second half

mmax = max(max(v)); %finding maximum velocity

%calculate velocity

delta_f = linspace(0, FS/2, size(v,2)); %(Hz)

velocity = delta_f*lambda/2;

%calculating the time associated with each data point

time = linspace(1,Tp*size(v,1),size(v,1)); %(sec)

%plot

imagesc(velocity,time,v-mmax,[-35, 0]);

```
colorbar;  
xlim([0 10]); %limit velocity axis  
xlabel('Velocity (m/sec)');  
ylabel('time (sec)');
```

6.4 - Ranging MATLAB Code

```
%Analyzing ranging vs time data
%Adapted from Gregory L. Charvat

clear all;
close all;

%read the raw data .wav file here
[Y,FS] = audioread(['rangingnear.wav']);

%Setting radar parameters
Tp = 20E-3; %(s) pulse time
N = Tp*FS; %# of samples per pulse
fstart = 2270E6; %(Hz) LFM start frequency for example
fstop = 2500E6; %(Hz) LFM stop frequency for example
BW = fstop-fstart; %(Hz) transmit bandwidth
f = linspace(fstart, fstop, N/2); %instantaneous transmit frequency

%defining the speed of light
c = 3E8;

%range resolution
rr = c/(2*BW);
%max_range = rr*N/2;
max_range = 20;

%Sync pulse is stored as trig and radar as s
%the input appears to be inverted
trig = -1*Y(:,1);
```

```

s = -1*Y(:,2);
clear Y;

%parse the data here by triggering off rising edge of sync pulse
count = 0;
thresh = 0;
start = (trig > thresh);
for ii = 100:(size(start,1)-N)
    if start(ii) == 1 & mean(start(ii-11:ii-1)) == 0
        %start2(ii) = 1;
        count = count + 1;
        sif(count,:) = s(ii:ii+N-1);
        time(count) = ii*1/FS;
    end
end

%check to see if triggering works
% plot(trig, 'b');
% hold on;
% plot(start2, 'r');
% hold off;
% grid on;

%subtract the average
ave = mean(sif,1);
for ii = 1:size(sif,1);
    sif(ii,:) = sif(ii,:) - ave;
end

zpad = 8*N/2;

```

```

%RTI plot
figure(10);
v = dbv(iff(sif,zpad,2));
S = v(:,1:size(v,2)/2);
m = max(max(v));
imagesc(linspace(0,max_range,zpad),time,S-m,[-80, 0]);
colorbar;
ylabel('time (s)');
xlabel('range (m)');
title('RTI without clutter rejection');

%2 pulse cancelor RTI plot
figure(20);
sif2 = sif(2:size(sif,1),:)-sif(1:size(sif,1)-1,:);
v = ifft(sif2,zpad,2);
S=v;
R = linspace(0,max_range,zpad);
for ii = 1:size(S,1)
    %S(ii,:) = S(ii,:).*R.^3/2; %Optional: magnitude scale to range
end
S = dbv(S(:,1:size(v,2)/2));
m = max(max(S));
imagesc(R,time,S-m,[-80, 0]);
colorbar;
ylabel('time (s)');
xlabel('range (m)');
title('RTI with 2-pulse cancelor clutter rejection');

% %2 pulse mag only cancelor

```

```

% figure(30);
% clear v;
% for ii = 1:size(sif,1)-1
%   v1 = abs(iff(sif(ii,:),zpad));
%   v2 = abs(iff(sif(ii+1,:),zpad));
%   v(ii,:) = v2-v1;
% end
% S=v;
% R = linspace(0,max_range,zpad);
% for ii = 1:size(S,1)
%   S(ii,:) = S(ii,:).*R.^(3/2); %Optional: magnitude scale to range
% end
% S = dbv(S(:,1:size(v,2)/2));
% m = max(max(S));
% imagesc(R,time,S-m,[-20, 0]);
% colorbar;
% ylabel('time (s)');
% xlabel('range (m)');
% title('RTI with 2-pulse mag only cancelor clutter rejection');

```

6.5 - Doppler MATLAB Code

```
%This RMA SAR algorithm was written by Gregory L. Charvat as part of his dissertation:  
%G. L. Charvat, "A Low-Power Radar Imaging System," Ph.D. dissertation,  
%Dept. of Electrical and Computer Engineering, Michigan State University, East Lansing, MI, 2007.  
%%  
%This algorithm was based on:  
%Range Migration Algorithm from ch 10 of Spotlight Synthetic Aperture Radar  
%Signal Processing Algorithms, Carrara, Goodman, and Majewski  
  
%a note on formatting, our convention is sif(Xa,t)  
  
clear all;  
load sif;  
  
%apply hanning window to data first  
N = size(sif,2);  
for ii = 1:N  
    H(ii) = 0.5 + 0.5*cos(2*pi*(ii-N/2)/N);  
end  
  
for ii = 1:size(sif,1)  
    sif_h(ii,:) = sif(ii,:).*H;  
end  
sif = sif_h;  
  
figcount = 1;  
close_as_you_go = 0;  
do_all_plots = 0;
```



```
set(0,'defaultaxesfontsize',13); %set font size on plots
```

```
%*****
```

```
if do_all_plots == 1,  
    figure(figcount);  
    S_image = angle(sif);  
    imagesc(Kr, Xa, S_image);  
    colormap(gray);  
    title('Phase Before Along Track FFT');  
    xlabel('K_r (rad/m)');  
    ylabel('Synthetic Aperture Position, Xa (m)');  
    cbar = colorbar;  
    set(get(cbar, 'Title'), 'String', 'radians','fontsize',13);  
    print(gcf, '-djpeg100', 'phase_before_along_track_fft.jpg');  
    if close_as_you_go == 1,  
        close(figcount);  
    end  
    figcount = figcount + 1;  
end
```

```
%along track FFT (in the slow time domain)
```

```
%first, symetrically cross range zero pad so that the radar can squint
```

```
zpad = 2048; %cross range symetrical zero pad
```

```
szeros = zeros(zpad, size(sif,2));
```

```
for ii = 1:size(sif,2)
```

```
    index = round((zpad - size(sif,1))/2);
```

```
    szeros(index+1:(index + size(sif,1)),ii) = sif(:,ii); %symetrical zero pad
```

```
end
```

```
sif = szeros;
```

```
clear ii index szeros;
```

```

S = fftshift(fft(sif, [], 1), 1);
clear sif;
Kx = linspace((-pi/delta_x), (pi/delta_x), (size(S,1)));

if do_all_plots == 1,
    figure(figcount);
    S_image = dbv(S);
    imagesc(Kr, Kx, S_image, [max(max(S_image))-40, max(max(S_image))]);
    colormap(gray);
    title('Magnitude After Along Track FFT');
    xlabel('K_r (rad/m)');
    ylabel('K_x (rad/m)');
    cbar = colorbar;
    set(get(cbar, 'Title'), 'String', 'dB', 'fontsize', 13);
    print(gcf, '-djpeg100', 'mag_after_along_track_fft.jpg');
    if close_as_you_go == 1,
        close(figcount);
    end
    figcount = figcount + 1;
end

if do_all_plots == 1,
    figure(figcount);
    S_image = angle(S);
    imagesc(Kr, Kx, S_image);
    colormap(gray);
    title('Phase After Along Track FFT');
    xlabel('K_r (rad/m)');

```

```

ylabel('K_x (rad/m)');
cbar = colorbar;
set(get(cbar, 'Title'), 'String', 'radians','fontsize',13);
print(gcf, '-djpeg100', 'phase_after_along_track_fft.jpg');
if close_as_you_go == 1,
    close(figcount);
end
figcount = figcount + 1;
end

if do_all_plots == 1,
    figure(figcount);
    S_image = dbv(fftshift(fft(S, [], 2), 2));
    imagesc(linspace(-0.5, 0.5, size(S, 2)), Kx, S_image, [max(max(S_image))-40, max(max(S_image))]);
    colormap(gray);
    title('Magnitude of 2-D FFT of Input Data');
    xlabel('R_{relative} (dimensionless)');
    ylabel('K_x (rad/m)');
    cbar = colorbar;
    set(get(cbar, 'Title'), 'String', 'dB','fontsize',13);
    print(gcf, '-djpeg100', 'mag_after_2D_fft.jpg');
    if close_as_you_go == 1,
        close(figcount);
    end
    figcount = figcount + 1;
end

%*****
%matched filter

```

```

%create the matched filter eq 10.8
for ii = 1:size(S,2) %step thru each time step row to find phi_if
    for jj = 1:size(S,1) %step through each cross range in the current time step row
        %phi_mf(jj,ii) = -Rs*Kr(ii) + Rs*sqrt((Kr(ii))^2 - (Kx(jj))^2);
        phi_mf(jj,ii) = Rs*sqrt((Kr(ii))^2 - (Kx(jj))^2);
        Krr(jj,ii) = Kr(ii); %generate 2d Kr for plotting purposes
        Kxx(jj,ii) = Kx(jj); %generate 2d Kx for plotting purposes
    end
end
smf = exp(j*phi_mf); %%%%%%%%%%%%%%

%note, we are in the Kx and Kr domain, thus our convention is S_mf(Kx,Kr)

%apply matched filter to S
S_mf = S.*smf;

clear smf phi_mf;

if do_all_plots == 1,
    figure(figcount);
    S_image = angle(S);
    imagesc(Kr, Kx, S_image);
    colormap(gray);
    title('Phase After Matched Filter');
    xlabel('K_r (rad/m)');
    ylabel('K_x (rad/m)');
    cbar = colorbar;
    set(get(cbar, 'Title'), 'String', 'radians','fontsize',13);
    print(gcf, '-djpeg100', 'phase_after_matched_filter.jpg');
end

```

```

if close_as_you_go == 1,
    close(figcount);
end
figcount = figcount + 1;
end

clear S;

if do_all_plots == 1,
    figure(figcount);
    S_image = dbv(fftshift(fft(S_mf, [], 2), 2));
    imagesc(linspace(-0.5, 0.5, size(S_mf, 2)), Kx, S_image, [max(max(S_image))-40, max(max(S_image))]);
    colormap(gray);
    title('Magnitude of 2-D FFT of Matched Filtered Data');
    xlabel('R_{relative} (dimensionless)');
    ylabel('K_x (rad/m)');
    cbar = colorbar;
    set(get(cbar, 'Title'), 'String', 'dB', 'fontsize', 13);
    print(gcf, '-djpeg100', 'mag_after_downrange_fft_of_matched_filtered_data.jpg');
    if close_as_you_go == 1,
        close(figcount);
    end
    figcount = figcount + 1;
end

```

```

%*****

```

```

%perform the Stolt interpolation

```

```

%FOR DATA ANALYSIS

kstart = 4*pi*(fc-BW/2)/c;
kstop = 4*pi*(fc+BW/2)/c;

Ky_even = linspace(kstart, kstop, 1024); %create evenly spaced Ky for interp for real data

clear Ky S_St;
%for ii = 1:size(Kx,2)
count = 0;
for ii = 1:zpad;
%for ii = round(.2*zpad):round((1-.2)*zpad)
    count = count + 1;
    Ky(count,:) = sqrt(Kr.^2 - Kx(ii)^2);
    %S_st(ii,:) = (interp1(Ky(ii,:), S_mf(ii,:), Ky_even)).*H;
    S_st(count,:) = (interp1(Ky(count,:), S_mf(ii,:), Ky_even));
end
S_st(find(isnan(S_st))) = 1E-30; %set all Nan values to 0
clear S_mf ii Ky;

if do_all_plots == 1,
    figure(figcount);
    S_image = angle(S_st);
    imagesc(Ky_even, Kx, S_image);
    %imagesc(S_image);
    colormap(gray);
    title('Phase After Stolt Interpolation');
    xlabel('K_y (rad/m)');
    ylabel('K_x (rad/m)');
    cbar = colorbar;
    set(get(cbar, 'Title'), 'String', 'radians','fontsize',13);

```

```

print(gcf, '-djpeg100', 'phase_after_stolt_interpolation.jpg');
if close_as_you_go == 1,
    close(figcount);
end
figcount = figcount + 1;
end

%apply hanning window to data, cleans up data ALOT
N = size(Ky_even,2);
for ii = 1:N
    H(ii) = 0.5 + 0.5*cos(2*pi*(ii-N/2)/N);
end

for ii = 1:size(S_st,1)
    S_sth(ii,:) = S_st(ii,:).*H;
end
%S_st = S_sth;

%*****

%perform the inverse FFT's
%new notation: v(x,y), where x is crossrange
%first in the range dimension
clear v Kr Krr Kxx Ky_even;
v = ifft2(S_st,(size(S_st,1)*4),(size(S_st,2)*4));

bw = 3E8*(kstop-kstart)/(4*pi);
max_range = (3E8*size(S_st,2)/(2*bw));
figure(figcount);
S_image = v; %edited to scale range to d^3/2
S_image = fliplr(rot90(S_image));

```

```

cr1 = -35; %(m)
cr2 = 35; %(m)
dr1 = 1 + Rs; %(m)
dr2 = 110 + Rs; %(m)
%data truncation
dr_index1 = round((dr1/max_range)*size(S_image,1));
dr_index2 = round((dr2/max_range)*size(S_image,1));
cr_index1 = round(((cr1+zpad*delta_x/2)/(zpad*delta_x))*size(S_image,2));
cr_index2 = round(((cr2+zpad*delta_x/2)/(zpad*delta_x))*size(S_image,2));
trunc_image = S_image(dr_index1:dr_index2,cr_index1:cr_index2);
downrange = linspace(-1*dr1,-1*dr2, size(trunc_image,1)) + Rs;
crossrange = linspace(cr1, cr2, size(trunc_image, 2));
%scale down range columns by range^(3/2)
clear ii;
for ii = 1:size(trunc_image,2)
    trunc_image(:,ii) = (trunc_image(:,ii)).*(abs(downrange)).^(3/2);
end
trunc_image = dbv(trunc_image); %added to scale to d^3/2
imagesc(crossrange, downrange, trunc_image, [max(max(trunc_image))-40, max(max(trunc_image))-0]);
colormap('default');
title('Final Image');
ylabel('Downrange (m)');
xlabel('Crossrange (m)');
axis equal;
cbar = colorbar;
set(get(cbar, 'Title'), 'String', 'dB','fontsize',13);
print(gcf, '-djpeg100', 'final_image.jpg');
%if close_as_you_go == 1,
% close(figcount);

```



```
%end
```

```
figcount = figcount + 1;
```

6.6 - Doppler Additional MATLAB Code

```
%This file processes the raw data and auto runs the analysis code

% MIT IAP Radar Course 2011
%Resource: Build a Small Radar System Capable of Sensing Range, Doppler,
%and Synthetic Aperture Radar Imaging
%
%Created by Gregory L. Charvat
%SAR algorithm from:
%Range Migration Algorithm from ch 10 of Spotlight Synthetic Aperture Radar
%Signal Processing Algorithms, Carrara, Goodman, and Majewski

%Process raw data here

clear all;
close all;

%read the raw data .wave file here
[Y,FS] = audioread('towardswarehouse.wav');

%Setting radar parameters
Tp = 20E-3; %(s) sync pulse time
Trp = 0.25; %(s) minimum time to identify a movement
fstart = 2260E6; %(Hz) minimum frequency
fstop = 2590E6; %(Hz) maximum frequency

%constants
c = 3E8; %(m/s) speed of light
```

```

%Calculating important constants
BW = fstop-fstart; %(Hz) transmit bandwidth
N = Tp*FS; %# of samples per pulse
f = linspace(fstart, fstop, N/2); %instantaneous transmit frequency
fc = (fstop-fstart)/2+fstart; %(Hz) center radar frequency
cr = BW/20E-3; %(Hz/sec) chirp rate

%the input appears to be inverted, separate radar and trigger channels
trig = -1*Y(:,1);
s = -1*Y(:,2);
clear Y;

%parse data here by position (silence between recorded data)
%looking for lack of sync pulse to identify movement
rpstart = abs(trig)>mean(abs(trig));
count = 0;
Nrp = Trp*FS; %min # samples between range profiles

for ii = Nrp+1:size(rpstart,1)-Nrp
    if rpstart(ii) == 1 && sum(rpstart(ii-Nrp:ii-1)) == 0
        count = count + 1;
        RP(count,:) = s(ii:ii+Nrp-1);
        RPtrig(count,:) = trig(ii:ii+Nrp-1);
    end
end

%parse data by pulse
count = 0;
thresh = 0.08;
clear ii;

```

```

for jj = 1:size(RP,1)
    %clear SIF;
    SIF = zeros(N,1);
    start = (RPtrig(jj,:) > thresh);
    count = 0;
    jj;
    for ii = 12:(size(start,2)-2*N)
        [Y,I] = max(RPtrig(jj,ii:ii+2*N));
        if mean(start(ii-10:ii-2)) == 0 & I == 1
            count = count + 1;
            SIF = RP(jj,ii:ii+N-1)' + SIF;
        end
    end
end
%hilbert transform
q = ifft(SIF/count);
sif(jj,:) = fft(q(size(q,1)/2+1:size(q,1)));
end
sif(find(isnan(sif))) = 1E-30; %set all Nan values to 0

%SAR data should be ready here
clear s;
s = sif;
save sardatatransfer s; %for image data

%load IQ converted data here
load sardatatransfer s; %load variable sif %for image data

for ii = 1:size(s,1)
    s(ii,:) = s(ii,:) - mean(s,1);
end

```

```

sif = s;

clear s;

%*****

%radar parameters

%VERY IMPORTANT, change Rs to distance to cal target

%Rs = 3.5; %(m) y coordinate to scene center (down range), make this value equal to distance to cal
target

Rs = 3.5;

delta_x = 0.05; %(m) 5 cm spacing between measurement points

L = delta_x*(size(sif,1)); %(m) synthetic aperture length, spacing times number of points

Xa = linspace(-L/2, L/2, (L/delta_x)); %(m) cross range position of radar on aperture L

t = linspace(0, Tp, size(sif,2)); %(s) fast time, CHECK SAMPLE RATE

Kr = linspace(((4*pi/c)*(fc - BW/2)), ((4*pi/c)*(fc + BW/2)), (size(t,2)));

%Save background subtracted and callibrated data

save sif sif delta_x Rs Kr Xa BW fc c;

%clear all;

%run IFP

%SBAND_RMA_IFP_edit;

```

6.7 - Interview Questions

What waves/light topics do you cover in your physics course?

Do you currently have a demonstration for your waves course section?

What “real life” examples do you use to explain waves?

Do you think students would be interested in a demonstration like this?

Do you see a radar system such as this being beneficial in your current curriculum?

If your curriculum were changed a bit, would that change your last answer?

Would you change your curriculum to incorporate a demonstration like this?

Would your interest depend on if this were a finished product versus an unassembled kit?

What budget do you have to work with for classroom activities such as this?

Do you think \$500 is too expensive for something like this?

Have you applied for grants for projects/demonstrations similar to this before?

Do you use MATLAB or other software in your class?

What are some tricks to make a physics demo effective for students?

What are some guaranteed ways to lose a high schooler's attention when dealing with something complex such as this?

Are there any specific uses or features that would make this valuable in your classroom?

Is there something we didn't ask you that you want to talk about?