RF Imaging Array for Biomedical and Industrial Applications

Final Design Document

Team Number: *23*

Client and Adviser: *Mohammad Tayeb Al Qaseer*

Team Members:

- ***Denise Orege*** - RF Antenna Design Co-Lead
- ***Trent Moritz*** - RF Antenna Design Co-Lead
- ***Justin Pioquinto*** - Programming Lead
- ***Karthik Vempati*** - Data Processing and UI Lead
- ***Si Yuan Sim*** - RF PCB Design Lead
- ***Joe Paffrath*** - ADC PCB Lead
- ***Josh Montgomery*** - Technical Writing Lead

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Executive Summary

Summary of Requirements

This project involves the design and construction of an imaging array consisting of resonant antennas with radio frequency (RF) circuitry for generation and detection of signals that can provide a visual depiction of hidden structures, objects, or biomedical anomalies. The problem this project will solve is the need to identify objects that cannot be viewed at the surface level of various types of materials. The list of requirements for this project are as follows:

- Req. 1 - Computer Simulation Technology Modeling and Antenna Design (with Tuning)
- Req. 2 – RF Printed Circuit Board (PCB) Design
- Req. 3 – ADC PCB Design
- Req. 4 – Low Level Microcontroller Programming/Data Gathering
- Req. 5 – Data Processing and Display

Pages 46-52 below contain a comprehensive technical explanation of our design process/plan.

Applicable Courses from Iowa State University Curriculum

- EE 414 – Microwave Engineering
- EE 417 – Electromagnetic Radiation, Antennas, and Propagation
- EE 418 – High Speed System Engineering Measurement and Testing
- EE 230 – Electronic Circuits and Systems
- EE 224 – Signals and Systems I
- CprE 281 – Digital Logic
- CprE 288 – Embedded Systems I

New Skills/Knowledge Acquired that Were/Was not Taught in Courses

- Printed circuit board customization and ordering
- Resonant antenna design and simulation
- Interoperability design
- Construction of signal conditioning and acquisition circuitry for RF antennas

Development Standards & Practices Used

Multiple engineering standards related to RF antennas and circuitry were considered for this project. One such standard was ***P1128 - Recommended Practice for Radio-Frequency (RF) Absorber Evaluation in the Range of 30 MHz to 40 GHz***. It relates primarily to the following: "recommend realistic and repeatable criteria, as well as recommended test methods, to characterize the absorber characteristics applied to a metallic surface … [t]his recommended practice covers the parameters and test procedures for the evaluation of radio-frequency (RF) absorbers over the frequency range of 30 MHz to 40 GHz."

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List of Definitions

Definitions:

- RF – "RF" stands for "radio frequency" and is the primary engineering concept that our project centers around. Radio frequency (RF) is the oscillation rate of an alternating electric current or voltage or of a magnetic, electric, or electromagnetic field or mechanical system in the frequency range from around 20 kHz to around 300 GHz [2]. This is roughly between the upper limit of audio frequencies and the lower limit of infrared frequencies [2]. These are the frequencies at which energy from an oscillating current can radiate off a conductor into space as radio waves [2].

- Antenna array – The antenna array is the backbone of our project. It is a series of eight antennas that will propagate and receive signals from targets we intend to measure. These measurements will be passed to the RF PCB.

- RF PCB – "RF PCB" stands for "radio frequency printed circuit board." This component of our project sends commands to the antenna array. Commands are sent to the antenna array after receiving them from a user. Our system is configured to receive instructions through a user interface. These instructions are then interpreted by the microprocessor and sent to the RF PCB.

  The RF PCB houses many important components of our design. These components include phase locked loops for managing signal propagation and circuit designs for regulating power sources.

- ADC PCB – "ADC PCB" stands for "analog to digital printed circuit board." Our ADC PCB serves the essential function of passing analog data received from the antenna array back to the microprocessor for display to the user.

- Microprocessor – A microprocessor is any of a type of small electronic device that contains arithmetic, logic, and control circuitry necessary to perform the functions of a digital computer's central processing unit. Our microprocessor will control the various components of our system. It will receive commands from a user, send those commands to the RF PCB to control the antenna array, and eventually receive measurement data from the ADC PCB.

- Low-level programming – We use this term to refer to programming the microcontroller directly.

- High-level programming – We use this term to refer to programming the user interface display as well as the configuration of RF measurement results and data shown to a user.

1 Team

1.1 Team Members

- Justin Pioquinto (Computer Engineering), pioqujus@iastate.edu
- Denise Orege (Electrical Engineering), daorege@iastate.edu
- Trent Moritz (Electrical Engineering), tdmoritz@iastate.edu
- Si Yuan Sim (Electrical Engineering), simsy@iastate.edu
- Joseph Paffrath (Electrical Engineering), paffrath@iastate.edu
- Karthik Vempati (Electrical Engineering), vempati@iastate.edu
- Josh Montgomery (Electrical Engineering), jmonty@iastate.edu

1.2 Required Skill Sets for Project

- radio frequency (RF) circuitry
- resonant antenna design for imaging array
- signal detection
- CST studio (a high-performance 3D EM analysis software package for designing, analyzing and optimizing electromagnetic (EM) components and systems)
- HFFS (a 3D electromagnetic (EM) simulation software for designing and simulating high-frequency electronic products such as antennas, antenna arrays, RF or microwave components, high-speed interconnects, filters, connectors, IC packages and printed circuit boards)
- antenna construction and measurement for optimization
- design/construction of printed circuit board (PCB) for generating/routing signals to antenna array
- construction of signal conditioning and acquisition circuit (including amplifiers, buffers, ADCs)
- programming a microcontroller (e.g., FPGA, raspberry pi, other)
- writing software to transmit, process, and display the data
- technical writing for design documents
- organizational skills and professional discipline

1.3 Skill Sets Covered by the Team

- ***Justin Pioquinto*** – Justin will serve as the primary software and programming lead on the team. He will contribute primarily to programming a microcontroller and writing software to transmit, process, and display the data. Furthermore, he will provide supplemental assistance with all hardware related design aspects of the projects. He will also maintain a focus on organizational skills and professional discipline.

- ***Denise Orege*** – Denise will serve as one of three co-primary contacts with our professor/client. Denise will also aid with many of the hardware applications for the project: radio frequency circuitry, resonant antenna design, signal detection, EM analysis software utilization, antenna construction and measurement, design and construction of the PCB, and construction of signal conditioning and acquisition circuitry. She will also maintain a focus on organizational skills and professional discipline.

- ***Trent Moritz*** – Trent will serve as the second of three co-primary contacts with our professor/client. Trent will also aid with many of the hardware applications for the project: radio frequency circuitry, resonant antenna design, signal detection, EM analysis software utilization, antenna construction and measurement, design and construction of the PCB, and construction of signal conditioning and acquisition circuitry. He will also maintain a focus on organizational skills and professional discipline.

- ***Si Yuan Sim*** – Si Yuan will serve as the third of three co-primary contacts with our professor/client. Si Yuan will also aid with many of the hardware applications for the project: radio frequency circuitry, resonant antenna design, signal detection, EM analysis software utilization, antenna construction and measurement, design and construction of the PCB, and construction of signal conditioning and acquisition circuitry. He will also maintain a focus on organizational skills and professional discipline.

- ***Joseph Paffrath*** – Joe will aid with many of the hardware applications for the project: signal detection, EM analysis software utilization, antenna construction and measurement, design and construction of the PCB, and construction of signal conditioning and acquisition circuitry. He will also maintain a focus on organizational skills and professional discipline.

- ***Karthik Vempati*** – Karthik will aid with many of both the hardware and software applications for the project. Regarding hardware, Karthik will assist with the following: radio frequency circuitry, resonant antenna design, signal detection, EM analysis software utilization, antenna construction and measurement, design and construction of the PCB, and construction of signal conditioning and acquisition circuitry. Regarding software, Karthik will assist with the following: programming a microcontroller and writing software to transmit, process, and display the data. He will also maintain a focus on organizational skills and professional discipline.

- ***Josh Montgomery*** – Josh will serve as the primary technical writer for the project and will compose the first draft of all design documents. He will also provide supplemental assistance on both the hardware and software aspects of project design. Furthermore, he will coordinate with the leads for both hardware and software design elements while synthesizing the progress from each. He will also maintain a focus on organizational skills and professional discipline.

1.4 Project Management Style Adopted by the Team

We are likely to utilize a hybrid structure of both the Agile and Waterfall project management styles, as detailed in Figure 1.1 below. Our project will require completion of certain stages of the project before beginning other stages—this lends itself towards the Waterfall project management style. For example, we must complete the printed circuit board design before we can begin programming it. However, we will also work in parallel on many design stages—this lends itself to the Agile project management style. For example, we will design and measure the RF antenna while simultaneously designing the printed circuit board it will work in conjunction with.

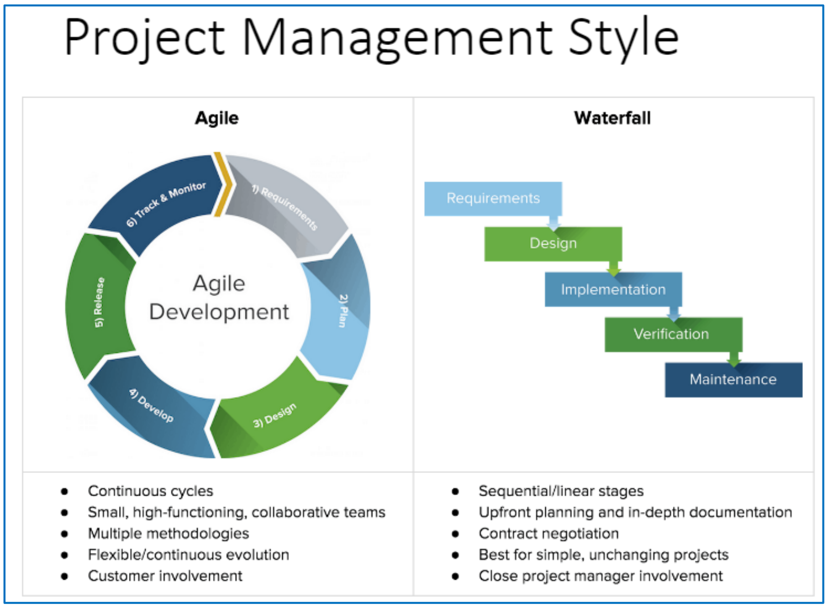

Figure 1.1 – Project Management Style Slide [3]

1.5 Initial Project Management Roles

1. **CST Modeling and antenna design**
    a. Trent
    b. Denise
2. **Antenna Tuning**
    a. Trent
    b. Denise
3. **RF PCB Design (PLL & Switches)**
    a. Si Yuan
    b. Karthik
4. **ADC PCB Design**
    a. Joe
    b. Si Yuan
5. **Low level programming (data gathering)**
    a. Justin
6. **Data Processing and Display**
    a. Justin
    b. Karthik
    c. Josh
7. **Technical Writing**
    a. Josh
    b. Karthik

2 Introduction

2.1 Problem Statement

This project involves the design and construction of an imaging array consisting of resonant antennas with radio frequency (RF) circuitry for generation and detection of signals that can provide a visual depiction of hidden structures, objects, or biomedical anomalies. The problem this project will solve is the need to identify objects that cannot be viewed at the surface level of various types of materials.

There are numerous industries and applications that face this generalized need. The two primary areas of need our project will address are as follows:

(1) **Imaging through walls or other structures** – This problem focus relates to, in essence, stud finding or identification of embedded cables and other objects in building structures. Large sums of money are spent retroactively repairing damaged utilities or improperly placed wall mounts because of the difficulty in identifying the objects behind drywall, plaster, or other common building materials. A proper solution will provide transparency for objects hidden behind solid or opaque structures.

(2) **Biomedical imaging** – The medical industry faces a constant need for means to identify tumors, blood clots, cancerous growths, tissue damage, and other medical anomalies that lie under the epidermis (outer skin layer). A solution to address this need will provide imaging of these concerning anomalies via a non-invasive, safe, effective method of rendering images of the anomalies or identifying inconsistencies in unseen tissue.

2.2 Requirements and Constraints

2.2.1 Requirements

Our RF imaging array project contains several concurrent and cross-compatible required deliverables. These requirements are enumerated and elaborated upon on the following pages:

1. Computer Simulation Technology Modeling and Antenna Design

The backbone of our project is the antenna array design. Eight RF antennas will be placed adjacent to one another in a one-dimensional array of antennas. These antennas emit radio frequencies in all directions and must be carefully designed, built, and tested for application appropriateness. Then, they must be assembled and calibrated in a stationary array, as shown in Figure 2.1 below. Assuring functionality requires use of numerical electromagnetic simulation tools (e.g., CST), as shown in Figure 2.2 below. The specific application we will use is CST Studio Suite. CST Studio Suite will enable us to determine whether our antenna array is tuned correctly, matched correctly, built correctly, and then how we can expect it to behave in real (i.e., physical) applications.

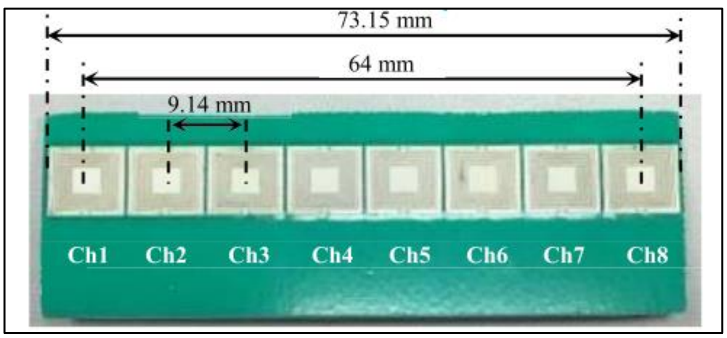

Figure 2.1 – One-Dimensional Antenna Array Example [4]

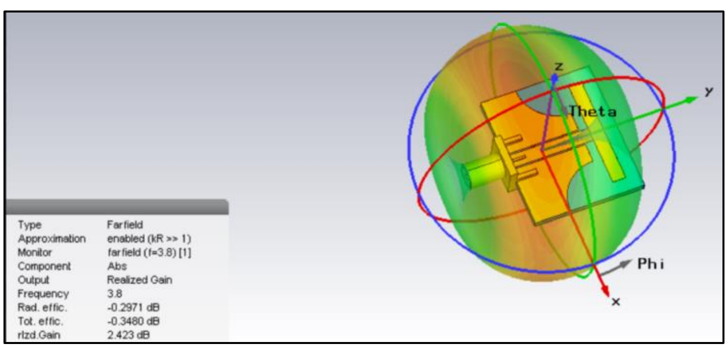

Figure 2.2 – CST Antenna Emission Rendering Example [5]

2. Antenna Tuning

Tuning our antenna array is an essential requirement of our project design. Each individual antenna of the eight-antenna array must be tuned to function properly on its own, and then all antennas must be re-tuned to function while stationed immediately adjacent to one another. Antennas emitting and receiving radio frequencies will inevitably interfere with each other. However, CST Studio Suite will again allow us to simulate these outcomes and design an array that is calibrated to minimize cross-interference between individual antennas. Ultimately, the antennas should be calibrated to optimize emission projection and reception.

Figure 2.3 below is a critically important representation of the optimality for RF antenna emissions: S11 (on the y-axis) represents the amount of power reflected back from the object that the antenna's outgoing RF emissions are directed towards. For an ideal antenna, all the power would be transmitted, so the magnitude of S11 should be zero. Using a logarithmic scale, zero is equal to negative infinity dB. However, since that is not possible, anything less than -20dB will be sufficient for our application.

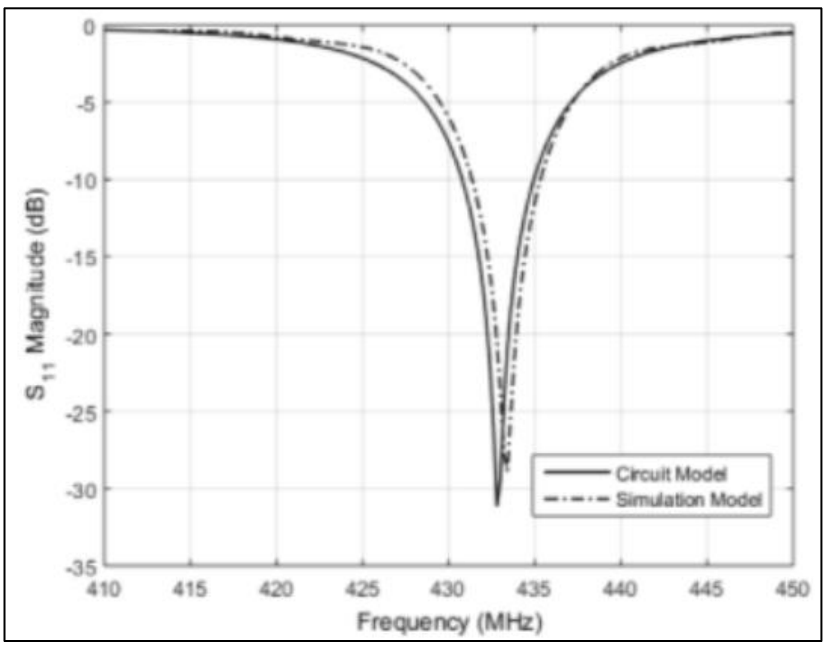

Figure 2.3 – Antenna Array Simulated Frequency Response Example [16]

3. RF PCB Design (PLL & Switches)

We will have to design two printed circuit boards (PCBs) for our project: the first is a PCB for the RF antenna array. This PCB will include a phase-locked loop and switches to operate the various antennas in the eight-antenna array. A phase-locked loop (PLL) is a control system used to generate an output signal with related output and input phases. This also correlates with enabling us to output a consistent output signal with constant frequency. This is crucial in an RF system as the system relies on a precise design frequency; changing this frequency would result in larger losses or a decrease in the expected power gain in the signal we are trying to send to the antenna to propagate out. Once the signal has been produced, we will use RF switches to selectively choose which antenna in our array we want to send the signal to which prevents interference and coupling between the many antennas.

Figure 2.4 below includes a red box around an exemplary image of what will eventually be our RF PCB design that includes both a PLL and switches. This RF PCB will interact with and control the RF antenna array while transmitting data to and from our software, analog-to-digital converter, and user-interface data display, all of which are explained on the subsequent pages.

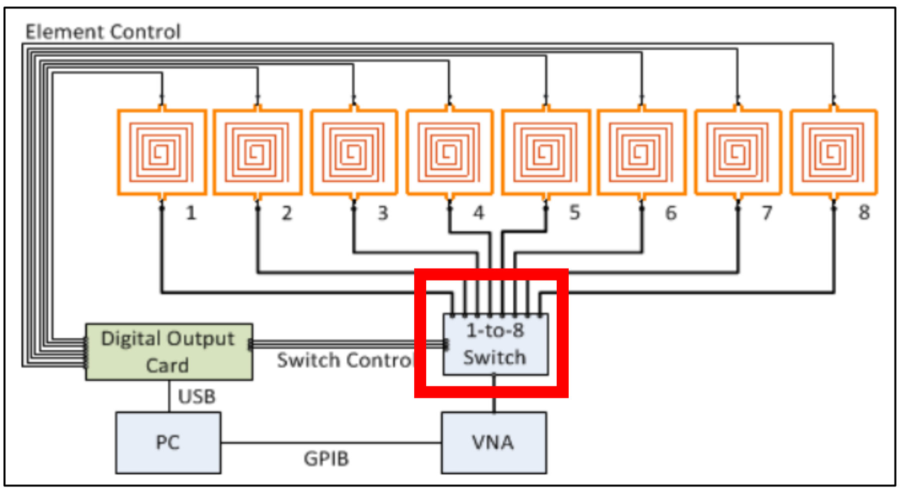

Figure 2.4 – Example of RF PCB Containing PLL and Switching Functionality [4]

4. ADC PCB Design

Our project design further requires a PCB layout of a subsystem utilizing an analog-to-digital (ADC) integrated circuit (IC) for interpretation of the data coming from the antenna array. An ADC is a system that takes real-time analog data and models it as digital data that is usable by the microcontroller governing our overall system. This will involve utilization of layout principles set forth in the documentation for the IC, as well as documenting what the output of this IC will look like to simplify the work of our microcontroller team.

5. Low Level Programming (Data Gathering)

A microprocessor must be programmed to control our hardware devices. We are likely to use a raspberry pi, but an FPGA or other microprocessor could also be used. This microprocessor will control several functions: (1) device commands and controls, (2) data gathering, (3) data display, and (4) user-interface communication and interaction.

The "low level" programming entails controlling devices and gathering data therefrom to provide information to the user. Specifically, data about the RF antenna emissions will be collected by the microprocessor. This data will be sent to the user interface thereby providing the user with information about emissions inconsistencies. Such inconsistencies include hidden structures in walls or biomedical anomalies that lie under the epidermis (outer layer of skin) and cannot be viewed by the human eye. An image of the raspberry pi we are considering for our microprocessor is displayed in Figure 2.5 below:

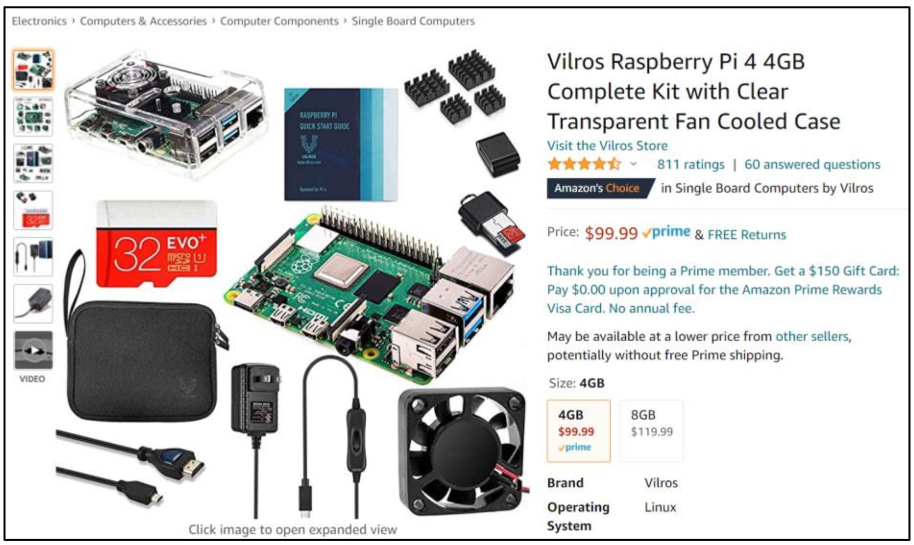

Figure 2.5 – Raspberry Pi Candidate for Microprocessor [6]

6. Data Processing and Display

The final requirement for our project involves microcontroller configuration (as in Figure 2.5 above) for data processing, coupled with a user interface for data display. Our hardware device will only be usable if we implement software that provides an easily understood visual or quantitative depiction of the information generated and collected by the antenna array working in conjunction with the other various components listed above. We plan to use Tornado (a Python web framework) to display the data on electronic devices like laptops or smartphones while a Python script will power the backend functionality.

2.2.2 Constraints

There are several constraints related to both the technical aspects of our project and our collective group resources.

1. **Budget** – We must purchase our project parts ourselves, and we are all still full-time students, so cost-consciousness is a significant factor. We may seek out funding assistance from corporate sponsors. Currently, we seek to keep our total spend below $300. This is a quantitative constraint.

2. **Number of Antennas in Array** – There will be eight antennas in our antenna array. This cap is necessary to reduce workload to reasonable levels, but more antennas could potentially increase performance. This is a quantitative constraint.

3. **Novel Concepts** – We are constructing a project at the cutting edge of RF antenna technology. This will challenge us conceptually and require that we educate ourselves on material we were previously unfamiliar with. The intrinsic constraint here is the limit of our collective technical knowledge and capabilities. This is a qualitative constraint.

4. **Appealing and Effective User Interface** – We must provide a display that a "casual user" of stud-finding or biomedical imaging technology can interpret. The casual user's knowledge of and experience with an imaging array for stud finding is a qualitative constraint.

2.3 Engineering Standards

STANDARD: P1128 - Recommended Practice for Radio-Frequency (RF) Absorber Evaluation in the Range of 30 MHz to 40 GHz [1]

ABSTRACT:

The purpose of this recommended practice is to recommend realistic and repeatable criteria, as well as recommended test methods, to characterize the absorber characteristics applied to a metallic surface. This recommended practice covers the parameters and test procedures for the evaluation of radio-frequency (RF) absorbers over the frequency range of 30 MHz to 40 GHz. Examples include those used for radiated emissions and immunity testing of electronic products or general antenna measurements. The evaluation measurements can be performed in frequency and/or time domain.

ENGINEERING STANDARD – APPLICATION TO OUR PROJECT:

This standard is related to our project in many respects. Specifically, we are going to use measurement techniques for the evaluation of RF antennas. We are also concerned with frequencies used for radiated emissions and general antenna measurements. However, we are not yet certain whether our RF antenna frequency range falls within the 30MHz to 40GHz range. Moreover, we do not expect to test our device on "metallic surfaces," which this standard is directed towards. Instead, we plan to focus on plywood, drywall, and (if time) human tissue. Therefore, as the parameters of our project become clearer, we will keep this standard in mind and reevaluate its future applicability to our project design requirements.

2.4 Intended Users and Uses

There are numerous industries and applications that constitute our use cases. The two primary use cases our project will address are listed below:

(1) **Imaging through walls or other structures** – This use case focus relates to, in essence, stud finding or identification of embedded cables and other objects in building structures. Large sums of money are spent retroactively repairing damaged utilities or improperly placed wall mounts because of the difficulty and identifying the objects behind drywall, plaster, or other common building materials. <u>The standard "user" is a homeowner, construction worker, foreman, maintenance employee, cable installer, electrician, and the like.</u> A proper solution will provide transparency for objects hidden behind solid or opaque structures.

(2) **Biomedical imaging** – The medical industry presents a unique use case for our project. Healthcare providers (such as doctors) maintain a constant need for means to identify tumors, blood clots, cancerous growths, tissue damage, and other medical anomalies that lie under the epidermis (outer skin layer). <u>The standard "user" is a radiologist, nurse, doctor, or other diagnostic healthcare worker.</u> A solution to address this need will provide imaging of concerning deep-tissue anomalies. The imaging will be presented through a non-invasive, safe, effective method of rendering images of the anomalies or identifying inconsistencies in unseen tissue.

3 Project Plan

3.1 Project Management/Tracking Procedures

MANAGEMENT STYLE:

Our group plans to use a **hybrid waterfall + agile project management style**. This fits most appropriately with our project goals. Our project will require completion of certain stages of the project before beginning other stages—this lends itself towards the waterfall project management style. For example, we must complete the RF and ADC printed circuit board (PCB) designs before we can begin programming our microprocessor to command operation of the PCBs.

However, we will also work in parallel on many design stages—this lends itself to the agile project management style. For example, we will design and measure the RF antenna while simultaneously designing the RF printed circuit board it will work in conjunction with. Figure 3.1 below displays a review of the two project management styles side-by-side.

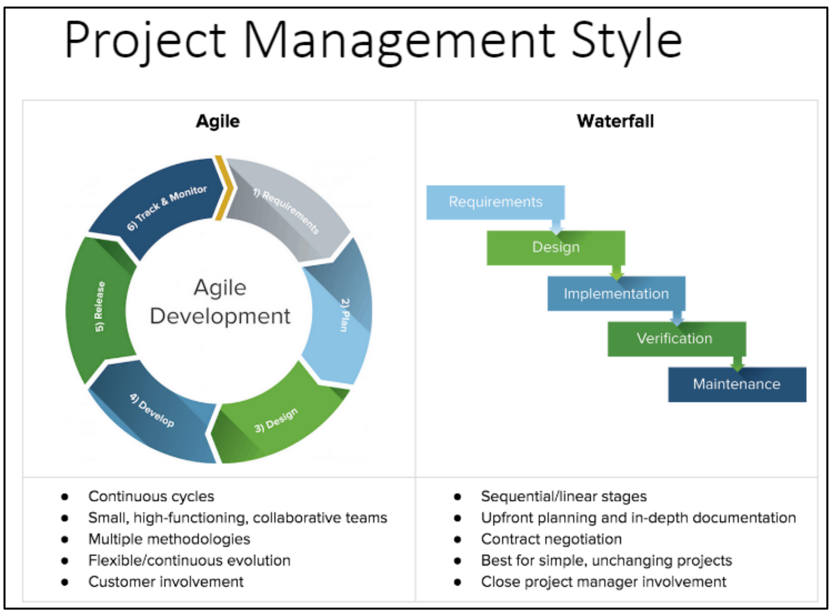

Figure 3.1 – Agile and Waterfall Project Management Styles [3]

PROGRESS TRACKING TOOLS:

Our group relies heavily on three primary tools for progress tracking and management: (1) Discord; (2) Google Drive; and (3) Google Calendar.

Discord: Every member of our group uses Discord daily for progress tracking and collaboration. It is our primary medium for collaboration and updating each other on our individual progress. It is also the primary medium we use to reach collective decisions, vote on contentious issues, and organize meetings. We discuss impending deadlines and long-term plans to accomplish goals and complete deliverables.

Google Calendar: We also utilize Google Calendar to schedule our many concurrent deadlines, obligations, and weekly meetings. Google Calendar is convenient for several reasons, but our primary use is to invite all group members to meetings without the need for constant manual reminders. Google Calendar allows us to create a single centralized recurring meeting and group invitation, and then it automatically reminds all of us when and where to attend. It also allows us to conveniently cancel a single meeting, if need be, without deleting the recurring meeting notice in the future.

Google Drive: Google Drive is where we house our shared work repository. It is also an effective means to monitor the progress of individual group member tasks. For example, several of our group members worked on a Bill of Materials concurrently, but they each had to research, select, and add their components for their respective project tasks independently. Google Drive allows us all to monitor the collective completion of a shared task such as composition of a Bill of Materials.

Future: We are likely to utilize GitHub when we enter the programming stage of our project. All members will have access to our GitHub repository at that time, and we will likely maintain sub-projects for the various programming tasks (low and high level/user interface display).

3.2 Task Decomposition

Our RF imaging array project contains several concurrent, interdependent, and cross-compatible tasks and subtasks. The primary tasks are enumerated and explained below:

3.2.1 Computer Simulation Technology Modeling and Antenna Design

The backbone of our project is the antenna array design. 8 RF antennas will be placed adjacent to one another in a one-dimensional array of antennas. These antennas emit radio frequencies in all directions and will be carefully designed, built, and tested for application appropriateness. Then, the antenna array will be assembled and calibrated in a stationary array, as shown in Figure 3.2 below. Assuring functionality requires use of numerical electromagnetic simulation tools (e.g., CST), as shown in Figure 3.3 below.[1] The specific application we will use is CST Studio Suite. CST Studio Suite will enable us to determine whether our antenna array is tuned correctly, matched correctly, built correctly, and then how we can expect it to behave in real (i.e., physical) applications.

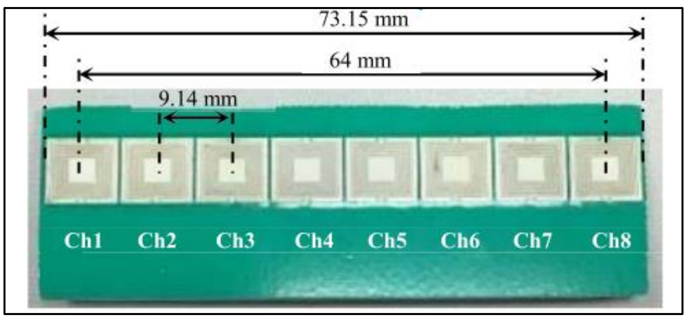

Figure 3.2 – One-Dimensional Antenna Array Example [4]

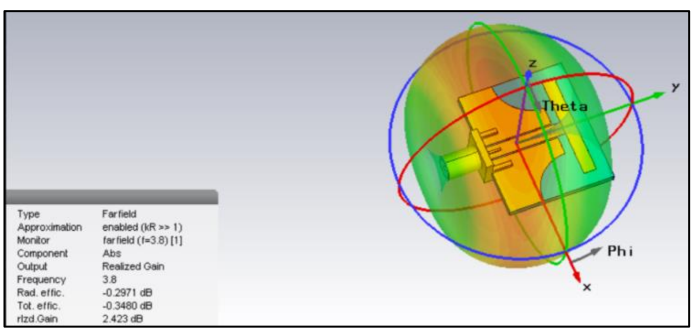

Figure 3.3 – CST Antenna Emission Rendering Example [5]

[1] Use of CST is a recurring sub-task we will utilize in multiple primary stages of our project including (1) antenna design, (2) antenna tuning, (3) RF PCB and switch design, and (4) microprocessor hardware-to-software programming synchronization.

Figure 3.4 below includes an image of our preliminary schematic. KiCad was used to produce the schematic [7]. The red box signifies where the antenna array will be positioned with respect to the other interdependent components.

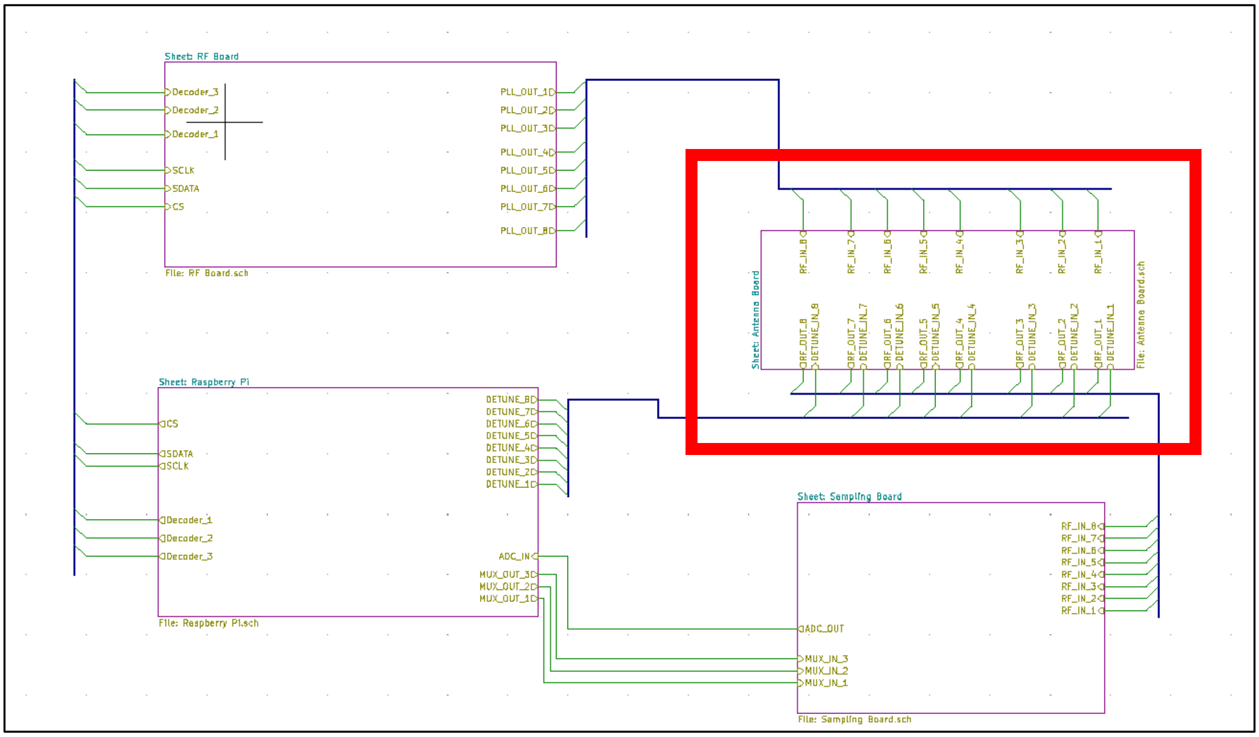

Figure 3.4 – Full Schematic (Antenna Array in Red)

3.2.2. Antenna Tuning

Tuning our antenna array is an essential primary task related to our project design. Each individual antenna of the eight-antenna array will be tuned to function properly on its own, and then all antennas will be re-tuned to function while stationed immediately adjacent to one another. Antennas emitting and receiving radio frequencies will inevitably interfere with each other. However, CST Studio Suite will again allow us to simulate these outcomes and design an array that is calibrated to minimize cross-interference between individual antennas. Ultimately, the antennas will be calibrated to optimize emission projection and reception.

Figure 3.5 below is a critically important representation of the optimality for RF antenna emissions: S11 (on the y-axis) represents the amount of power reflected back from the object that the antenna's outgoing RF emissions are directed towards. For an ideal antenna, all the power would be transmitted, so the magnitude of S11 should be zero. Using a logarithmic scale, zero is equal to negative infinity dB. However, we will aim for anything less than -20dB as that will be sufficient for our application.

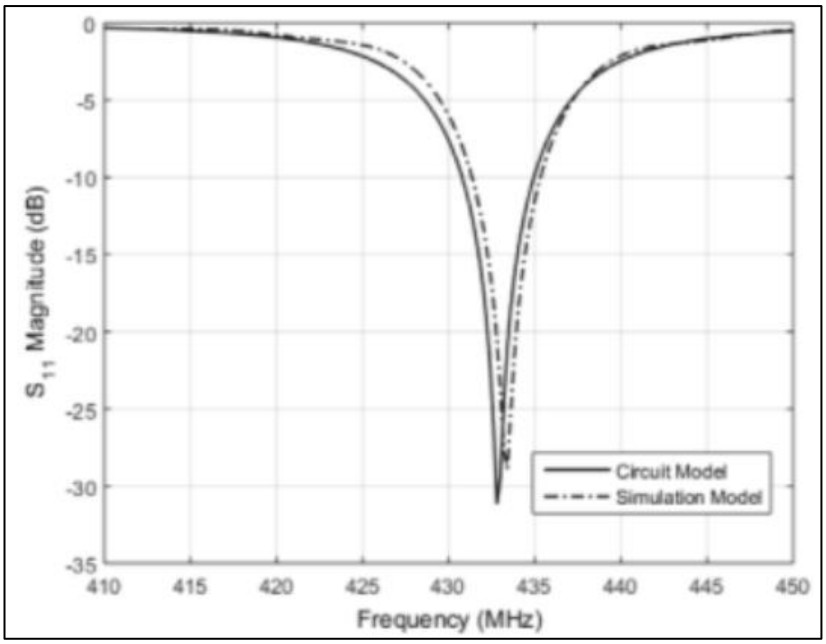

Figure 3.5 – Antenna Array Simulated Frequency Response Example [16]

3.2.3 RF PCB Design (PLL & Switches)

We will design two printed circuit boards (PCBs) for our project: **the first is a PCB for the RF antenna array**. This PCB is a primary task that will include a phase-locked loop[2] and switches to operate the various antennas in the eight-antenna array. This also correlates with enabling us to output a consistent output signal with constant frequency. This is crucial in an RF system as the system relies on a precise design frequency; changing this frequency would result in larger losses or a decrease in the expected power gain in the signal we are trying to send to the antenna to propagate out. Once the signal has been produced, we will use RF switches to selectively choose which antenna in our array we want to send the signal to which prevents interference and coupling between the many antennas.

Figure 3.6 below includes an image of our preliminary schematic.[3] The red box signifies where the RF PCB design will be positioned—this PCB will include both a PLL and switches. This RF PCB will interact with and control the RF antenna array while transmitting data to and from our software, analog-to-digital converter, and user-interface data display, all of which are explained on the subsequent pages.

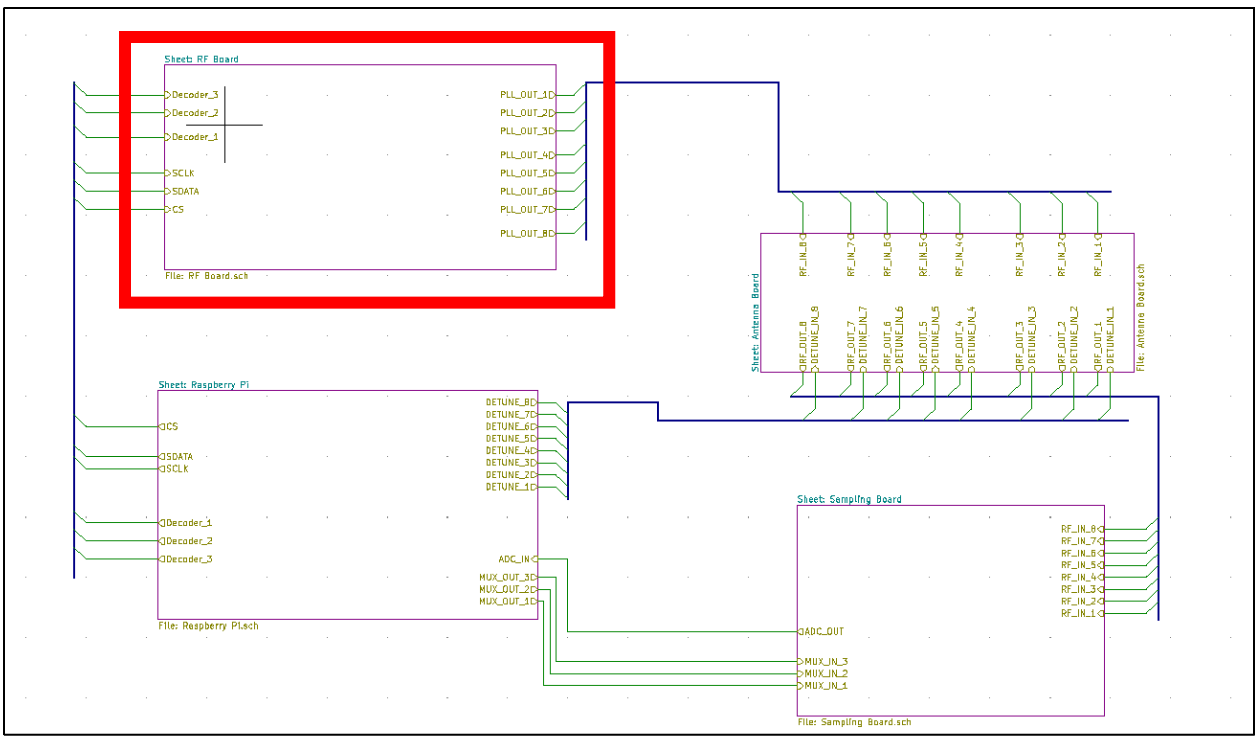

Figure 3.6 – Full Schematic (RF PCB in Red)

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[2] A phase-locked loop (PLL) is a control system that generates an output signal with related output and input phases.
[3] KiCad was used to produce the schematic [7].

3.2.4 ADC PCB Design

Another primary task will involve designing a second PCB incorporating the layout of a subsystem utilizing an analog-to-digital (ADC) integrated circuit (IC) for interpretation of the data coming from the antenna array. An ADC is a system that takes real-time analog data and models it as digital data that is usable by the microcontroller governing our overall system. This will involve utilization of layout principles set forth in the documentation for the IC, as well as documenting what the output of this IC will look like to simplify the work of our microcontroller team.

Figure 3.7 depicts our preliminary schematic. The red box demonstrates where the ADC PCB will be situated within the broader circuitry. The wires also demonstrate its connection to and interaction with the other interrelated system components.

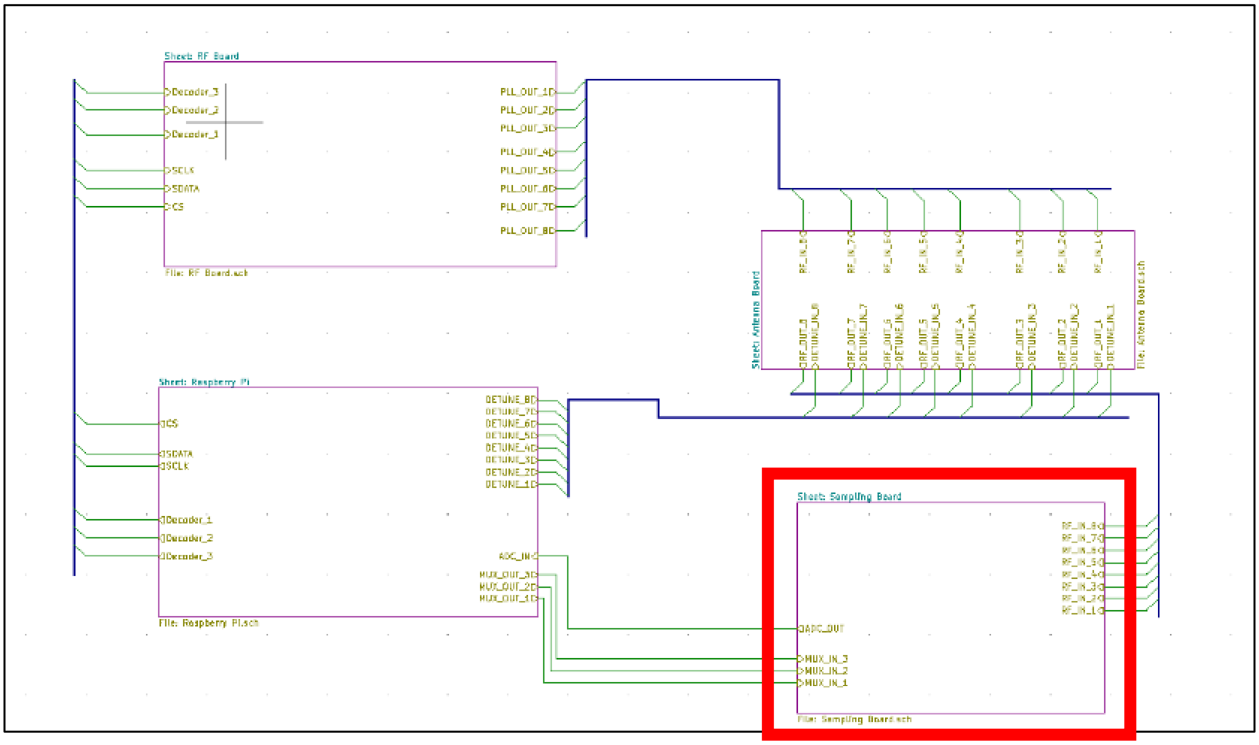

Figure 3.7 – Full Schematic (ADC PCB in Red)

3.2.5 Low Level Programming (Data Gathering)

A microprocessor will be programmed to control our hardware devices. We are likely to use a raspberry pi, but an FPGA or other microprocessor could also be used. This microprocessor will control several functions: (1) device commands and controls, (2) data gathering, (3) data display, and (4) user-interface communication and interaction.

The "low level" programming entails controlling devices and gathering data therefrom to provide information to the user. Specifically, data about the RF antenna emissions will be collected by the microprocessor. This data will be sent to a user interface thereby providing the user with information about emissions inconsistencies. Such inconsistencies include hidden structures in walls or biomedical anomalies that lie under the epidermis (outer layer of skin) and cannot be viewed by the human eye. An image of the raspberry pi we are considering for our microprocessor is displayed in Figure 3.8 below:

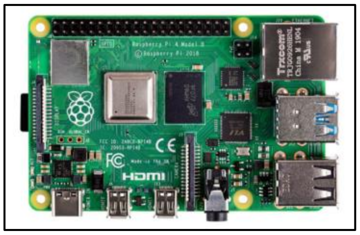

Figure 3.8 – Raspberry Pi Candidate for Microprocessor [8]

Figure 3.9 below depicts our preliminary schematic. The red box demonstrates where the microprocessor will be situated within the broader circuitry. The wires also demonstrate its connection to and interaction with the other interrelated system components. Notably, it will directly interact with the RF PCB and ADC PCB while sending commands and receiving information through those PCBs to and from the antenna array.

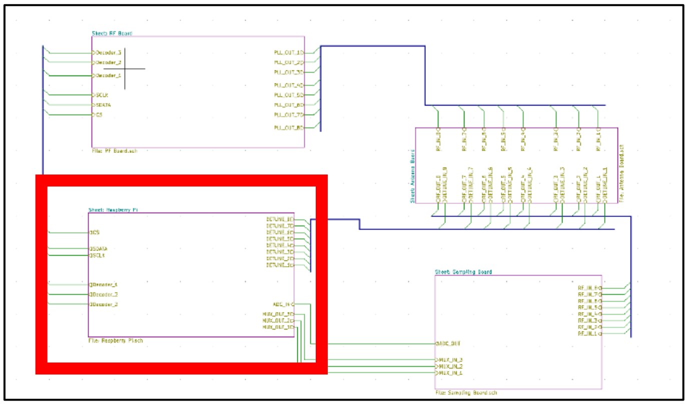

Figure 3.9 – Full Schematic (Microprocessor in Red)

3.2.6 Data Processing and Display

The final primary task for our project will involve microcontroller configuration (as in Figures 3.8 and 3.9 above) for data processing, coupled with a user interface for data display. Our hardware devices will be implemented with compatible software that provides an easily understood visual or quantitative depiction of the information generated and collected by the antenna array working in conjunction with the other various components listed above. We plan to use Tornado (a Python web framework) to display the data on electronic devices like laptops or smartphones while a Python script or other object-oriented programming language will power the backend functionality.

We are also considering displaying this information on an LCD screen with an HDMI port. Figure 3.10 below depicts an image of a candidate we are considering for our user interface display monitor—however, we may also use a wireless connection that enables use of any laptop as the display.

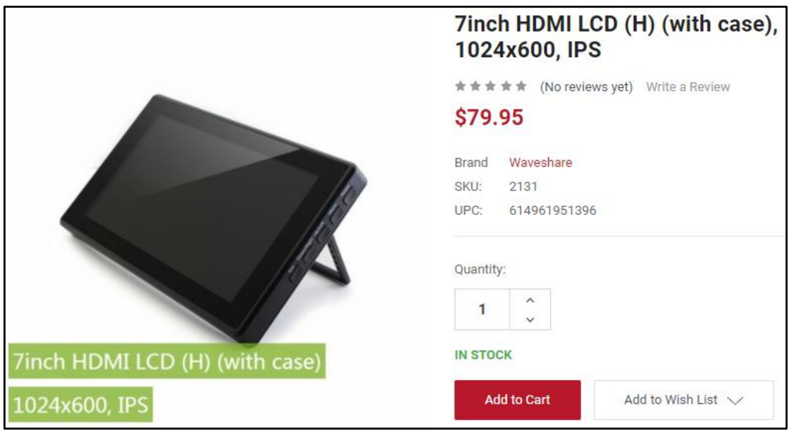

Figure 3.10 – User Interface Display Monitor Candidate [9]

3.3 Project Proposed Milestones, Metrics, and Evaluation Criteria

3.3.1 Milestones and Metrics: *Antenna CST Modeling, Design, and Tuning*

Milestones:

1. Design antenna without detuning or measuring circuity in CST; verify desired resonant frequency of 400 MHz with the antenna design
2. Design antenna with the detuning circuit along with variable capacitor on the matching network to allow for variation in components upon assembly and to tune the boards once they are fabricated
3. Place antenna design onto a PCB and have it manufactured to be tested with Vector Network Analyzer (VNA)[4] to confirm simulation parameters for components were accurate and design is valid
    a. Expect to see S11 magnitude to be around -20dB or less
    b. When compared to simulation, should see fairly close match but not exact due to manufacturing limitations of PCB and respective components
4. Using design from previous step, place 8 antennas in series and modify the tuning and detuning circuitry to achieve lowest possible interference among antennas
5. Design (and then fabricate) PCB with the antennas, matching network, and detuning circuitry on it and have it fabricated
6. With fabricated board, use VNA to tune all antennas individually and verify functionality at the design frequency; once again, seeking S11 magnitude of around -20dB or less

Metrics:

1. Overall S11 (reflections back to the source) of about -20dB or less if possible
2. Simulation to match real world within about 5%
3. Coupling between probes we want to be around -30dB represented by S21

[4] "VNA" stands for "Vector Network Analyzer." A VNA sends out signals and sees how they are reflected, or absorbed/transmitted.

3.3.2 Milestones and Metrics: *RF PCB Design (PLL & Switches)*

Milestones:

1. Identify viable components for vital integrated circuits (ICs) such as phase locked loop and RF switches
2. Simulate behavior of ICs in advanced design system (ADS) to ensure proper signal behavior such as the following:
    a. delivering sufficient power to the antenna as required
    b. Matching networks to ensure transmission line effects are minimized
3. Identify required supporting components (passive devices and other ICs)
4. Complete schematic design and PCB layout in CAD software
5. Create Bill of Materials (BOM) and purchase components for RF PCB
6. Solder components onto the board
7. Confirm (via testing) successful operation of board with expected results

Metrics:

1. PLL correctly produces a signal of 400MHz
2. Power transfer across the switches is at least 10dB
3. RF switches correctly turns on/off and sends the signal to the right destination

3.3.3 Milestones and Metrics: *ADC PCB Design*

Milestones:

1. Vital components for ADC PCB will be identified
2. Vital components for ADC PCB will be purchased
3. Supporting components for use of ADC IC will be identified and purchased
4. Total sub-BOM for ADC PCB assembled, with PCB layout identified
5. Layout for PCB used to order custom PCB from supplier
6. Components for ADC PCB hand-placed and visually verified
7. ADC PCB tested with a waveform generator and a digital oscilloscope
8. ADC PCB implemented and requirements verified within the top-level design

Metrics:

1. Sampling rate of ADC PCB will be verified to be 100kHz
2. Resolution of ADC PCB will be verified to be 16 bits

3.3.4 Milestones and Metrics: *Low Level Programming (Data Gathering)*

Milestones:

1. Code shell
2. Purchase of microcontroller
3. First draft of code for transmission and reception of all outgoing/incoming data
4. Testing phase
5. Consistent data transmission, reception, and interoperability

Metrics:

1. 80% accuracy for commands output to PCBs

3.3.5 Milestones and Metrics: *Data Processing and Display*

Milestones:

1. Code shell
2. Purchase of microcontroller
3. Interpretation of incoming data for transmission to user interface display
4. Incorporation of wireless data display tool (e.g., Tornado)
5. Consistent data transmission, reception, display, and interoperability

Metrics:

1. User satisfaction survey at 80%

3.4 Project Timeline/Schedule

Table 3.1 below displays a Gantt Chart. This chart sets forth the timeline for our project tasks and associated subtasks (developed in Section 2.2).

Table 3.1 – Gantt Chart for Team 23 Task Completion Schedule

TEAM 23 GANTT CHART - TASK COMPLETION SCHEDULE										
Task | Month	Aug ('21)	Sept ('21)	Oct ('21)	Nov ('21)	Dec ('21)	Jan ('22)	Feb ('22)	March ('22)	April ('22)	May ('22)
Antenna CST Modeling, Design, and Tuning										
RF PCB Design (PLL & Switches)										
ADC PCB Design										
Low Level Programming (Data Gathering)										
Data Processing and Display										
Full-System Integration Testing										
Technical Writing										

Table 3.1 makes clear that many of our primary and subtasks must be completed concurrently. However, some of the tasks are dependent on the completion or near-completion of others. For example, low level programming cannot begin until after antenna modeling, RF PCB design, and ADC PCB design are nearing well-established enough to begin producing representative data samples. Data processing and display is necessarily the last task we will complete; it is dependent on the completion and consistent functionality of all other technical tasks. Full-system integration testing will occur after all sub-systems are complete and connected to one another.

Technical writing will remain a consistent responsibility throughout the duration of the project. As such, its start date maps to the start of the class while its end date maps to the end of next semester's course. Finally, we have set ourselves an early deadline for completion of all technical aspects of the project. We intend to complete the project as quickly as possible to provide ample time for troubleshooting and presentation preparation.

3.5 Risks and Risk Management/Mitigation

1. **Risks and Risk Mitigation**: ***Antenna CST Modeling, Design, and Tuning***

Risk	~ %	Risk Mitigation Strategy
Rate of reflections back to source > -20dB	15%	
5% simulation-to-real world correlation tolerance	50%	Constant tuning and re-tuning
Destabilizing antenna crosstalk interference	70%	Error isolation and independent antenna tuning
Faulty probe coupling	30%	

2. **Risks and Risk Mitigation**: ***RF PCB Design (PLL & Switches)***

Risk	~ %	Risk Mitigation Strategy
PCB schematic design mistakes	40%	Meticulous schematic review
PLL failure to produce 400 MHz signal	20%	
< 10dB power transfer to antennae	25%	Switch re-design simplicity and energy conservation
Faulty automated RF on/off functionality	30%	

3. **Risks and Risk Mitigation**: ***ADC PCB Design***

Risk	~ %	Risk Mitigation Strategy
ADC PCB sampling rate < 100kHz	15%	
<< 16-bit ADC resolution	40%	FIR filters to filter out quantization noise

4. **Risks and Risk Mitigation**: ***Low Level Programming (Data Gathering)***

Risk	~ %	Risk Mitigation Strategy
< 80% accuracy for commands output to PCBs	50%	Careful quality control of PCB design; re-coding and constant quality assurance if necessary

5. **Risks and Risk Mitigation**: ***Data Processing and Display***

Risk	~ %	Risk Mitigation Strategy
Non-intuitive graphical display of data	25%	Objective user surveys for constructive feedback
Delay in processing of data	40%	Simple and efficient coding structure; careful calibration of hardware components

3.6 Personnel Effort Requirements

Table 3.2 below sets forth a detailed estimate of the projected effort per project task in total number of person-hours.

Table 3.2 – Team 23 Peron-Hour Effort Requirements (Per Task and Total)

Task	Person-hrs./wk. (est.)	~ # Wks.	Total
Antenna CST Modeling, Design, and Tuning	15 [*Trent/Denise*]	20	300
RF PCB Design (PLL & Switches)	10 [*Si Yuan*]	16	160
ADC PCB Design	12 [*Joe*]	12	144
Low Level Programming (Data Gathering)	12 [*Justin*]	14	168
Data Processing and Display	10 [*Karthik*]	16	160
Technical Writing	8 [*Josh*]	40	320
Total Person-Hour Effort Requirement			**1252**

The table above makes clear that some tasks will span a shorter calendar duration, but more time must be dedicated during the weeks where the task will be completed. For example, ADC PCB design will only run 12 weeks, but it will take more time during those weeks than programming to complete the data processing and display task.

Antenna CST Modeling, Design, and Tuning is the backbone of our project. RF PCB design is likely the second-most integral component of our RF imagining array. As such, they both require considerable commitments in time and calendar duration.

3.7 Other Resource Requirements

PARTS (BILL OF MATERIALS AS OF EARLY OCTOBER 2020):

Table 3.3 – Bill of Materials for Printed Circuit Boards

RF Circuit						
Part Number	**Description**	**Digikey Link**	**Quantity**	**Unit Price**	**Extended Price**	
ADF4360-7BCPZRL7	Voltage Controlled Oscillator	https://www.digikey.com/en/products/detail/analog-	3	7.74	23.22	
HMC253QS24	SP8T RF Switch	https://www.digikey.com/en/products/detail/analog-	2	17.39	34.78	
NXB0104PWJ	4-Channel Level Shifter	https://www.digikey.com/en/products/detail/nexperi	2	0.69	1.38	
AS213-92LF	SPDT RF Switch	https://www.digikey.com/en/products/detail/skywor	16	0.98	15.68	Second Option RF Switch
SN74LVC2GU04DBVR	2-Channel Inverter	https://www.digikey.com/en/products/detail/texas-i	16	0.41	6.56	
BGS18GA14E6327XTSA1	Cheaper RF Switch	https://www.digikey.com/en/products/detail/infineor	2			
ADC/Sampling						
Part Number	**Description**	**Digikey Link**	**Quantity**	**Unit Price**	**Extended Price**	
ADS8866IDGSR	IC ADC 16BIT SAR 10VSSOP	https://www.digikey.com/en/products/detail/texas-i	2	5.41	10.82	
MAX4020ESD+	IC OPAMP VFB 4 CIRCUIT 14SOIC	https://www.digikey.com/en/products/detail/MAX40	4	8.57	34.28	
	Raspberry Pi 4	https://www.amazon.com/Vilros-Raspberry-Compl	1	99.99	99.99	
ADG1606BRUZ	Multiplexer Switch ICs 2 Ron, +/-5V,	https://www.mouser.com/ProductDetail/Analog-De	2	8.83	17.66	datasheet

Table 3.4 – Bill of Materials for Antennas

Antenna					
Part Number	**Description**	**Digikey Link**	**Quantity**	**Unit Price**	**Extended Price**
TC74VHC238FK	3:8 Decoder	https://www.digikey.com/en/products/det	3	0.72	2.16
SMS7621-040LF	Shottky Diode	https://www.digikey.com/en/products/detail/sk	12	0.66	0.45
Still Needed:					
Op-amp					
Variable capacitor					

Table 3.5 – Bill of Materials for Diode Test Circuit

Part Number	Description	Digikey Link	Quantity	Unit Price	Extended Price
ADT1.5-122+	Balun		4		
SMS7621-040LF	Schottky diode	https://www.digikey.com/en/products	20	0.66	

TOOLS:

We require several tools and utilities—including both hardware and software—for completion of our project. These include at least the following:

- **KiCad** – for schematic design
- **CST Studio** – for simulation of RF antennas
- **Virtual Network Analyzer** – to facilitate antenna testing
- **Soldering** – to join different types of metals on PCBs together by melting solder
- **Python** – to project visual user interface display of data onto electronic devices
- **C Programming Language** – low level programming tool

FACILITIES:

We require use of the Applied Sciences lab at 1915 Scholl Road in Ames, Iowa. The facilities in lab will allow us to test our radio frequency antennas as well as solder components to our printed circuit boards. We will also be able to produce a 3D printed custom bracket to hold all the components of our RF antenna imaging array system, and we will likely finalize the construction in the applied sciences lab.

FUNDING SOURCES:

While there are specific monetary resources we need—and the instructions suggest we should not list those here—we also need to find ***sources*** for funding. We are exploring several avenues for corporate funding. We have considered and contacted several national and local companies.[5] We are in the process of corresponding with these potential corporate sponsors. We also have had success obtaining funding from the department with the approval of our client-adviser.

[5] The complete list of companies we have reached out to is as follows: MOSIS, TI, MICRON, Walmart, Costco, 3M, Verizon, Taco Bell, Coca-Cola, Google, Microsoft, Danfoss, Barilla, Mid-American Energy, MISO, John Deere, and Harman.

4 Design

4.1 Design Context

4.1.1 Broader Context

Design problem context: There is a considerable need in both the industrial and medical field to identify obstacles hidden behind opaque structures. Failure to do so can and does lead to avoidable damage or inaccurate diagnostic measurements.

Communities: The communities we are designing for include the construction industry, the electrician profession, the craftsman profession, and the health care industry. Each of these industries will be affected by our design because we aim to provide them with a tool that will ensure they are performing safe, well-informed work.

Societal Needs: The problem this project will solve is the need to identify objects that cannot be viewed at the surface level of various types of materials. Identifying such features is necessary to avoid damage to the hidden structures (in the construction industry) or to perform accurate diagnostic testing (in the healthcare industry).

Public Health Impact: In the healthcare context, lacking a diagnostic tool for imaging below the layer of tissue visible to the human eye can lead to missing concerning anomalies below the epidermis layer of the skin. In turn, this can result in avoidable complications and undesirable healthcare outcomes.

Global, Cultural, and Social Impact: Two primary industries are impacted by our product—construction and healthcare. Many professions make up these two broad industries. For construction, this includes construction workers, electricians, plumbers, craftsman, and the like. For healthcare, this includes x-ray technicians, nurses, doctors, and the like. It is likely that widespread adoption of our solution would lead to changes in these professionals' day-to-day activities, but it is unlikely to cause a significant cultural impact unless pricing structures only favor wealthy individuals.

Environmental: Fortunately, our product design does not require regular consumption of environmentally harmful goods. The components used in the product design and manufacture, however, may include plastics and precious metals. We will seek to source environmentally friendly parts, but there will be some waste during the testing and implementation stages.

Economic: This project has significant economic implications for the construction and healthcare industries. Untold damage and countless amounts of money are spent on retroactive repairs of utilities damaged during construction. This tool, taken to its logical implementation and adoption limit, could—for example—help avoid the costly necessity for proactive mapping of structures (because they can always be found later with our tool) as well as retroactive repair of damaged hidden structures.

4.1.2 User Needs

Industry #1 – Construction

User Groups: (1) construction workers, (2) electricians, (3) plumbers, (4) craftsmen

- Construction workers need a way to identify hidden building structures because they can damage these structures during construction with heavy machinery if they cannot see them.
- Electricians need a way to identify hidden utilities such as cables because utility cables are easily damaged if a clear understanding of the workspace is unavailable.
- Plumbers need a way to identify pipes hidden behind walls because they must repair and maintain these hidden pipes in a cost-effective manner.
- Craftsmen need a way to identify hidden structures in buildings because they often perform maintenance, remodeling, and repair and can lose money on their work if they cause damage to hidden structures.

Industry #2 – Healthcare

User Groups: (1) radiologists, (2) x-ray technicians, (3) nurses, (4) doctors, (5) medical imaging technicians

- Medical imaging technicians, radiologists, and x-ray technicians need a way to render images of tissue anomalies below the epidermis skin layer because their jobs require creation and interpretation of images that display bone, organ, and tissue damage, or abnormal growth below the outer skin layer.
- Doctors and nurses need a way to provide accurate diagnoses of concerning biomedical anomalies via imaging of such anomalies because they are required to properly identify underlying causes of illnesses and devise treatment plans accordingly.

4.1.3 Prior Work/Solutions

Similar products:

There are prior solutions, products, and work related to identifying hidden structures in buildings or providing biomedical imagining. To our knowledge, however, very few of these applications use radio frequency (RF) antennas to propagate and then receive signals. The existing market solutions are detailed below:

- **Stud finders [10]** – stud finders frequently use magnets or electricity to detect studs
  - ***Pros*** – this technology is well understood and has existed for a long time; stud finders are cheap
  - ***Cons*** – stud finders do not provide images of the items that are behind a wall; applications are limited application (specifically finding studs in walls)

- **Metal detectors [11]** – metal detectors work by transmitting an electromagnetic field from the search coil into the ground
  - ***Pros*** – long-standing technology that works well for what it does; easy-to-use with little to no learning curve
  - ***Cons*** – only works with metal objects; most do not provide clear 2D rendering of the object below the surface

There are also prior solutions, products, and work related to biomedical imaging. To our knowledge, however, none use radio frequency antennas to propagate signals and then receive distorted signals to image the source of the distortion. Pros and cons are omitted below because our system deliverable is less likely to properly function for this purpose by the end of our Senior Design class. However, it is worth noting how similar the functionality of an ultrasound machine is (using sound pulses instead of radio frequency signals). The existing market solutions for biomedical imaging are below:

- **X-ray machines [12]** – "Today's x-ray machines produce a stream of electromagnetic radiation that interacts with an anode in an x-ray tube. The x-rays made by this interaction are then directed toward the part of the body being examined."

- **Ultrasound machines [13]** – "The ultrasound machine transmits high-frequency … sound pulses into your body using a probe. … Some of the sound waves get reflected back to the probe, while some travel on further until they reach another boundary and get reflected. The reflected waves are picked up by the probe and relayed to the machine. The machine calculates the distance from the probe to the tissue or organ (boundaries) using the speed of sound in tissue … and the time of each echo's return... The machine displays the distances and intensities of the echoes on the screen, forming a 2D image."

- **CT scan machines [14]** – "A CT scanner emits a series of narrow beams through the human body as it moves through an arc. This is different from an X-ray machine, which sends just one radiation beam. The CT scan produces [more detail] than an X-ray image."

Related research:

We have conducted significant background research on the cutting-edge of RF antenna array imaging technology. The three primary references we are relying upon are listed below:

[15] A. Haryono, K. Aljaberi, M. Rahman, and M. A. Abou-Khousa, "High Resolution and Polarization Independent Microwave Near-Field Imaging Using Planar Resonator Probes," *IEEE Access*, vol. 8, pp. 191421–191432, Oct. 2020.

[4] M. A. Abou-Khousa and A. Haryono, "Array of Planar Resonator Probes for Rapid Near-Field Microwave Imaging," *IEEE Transactions on Instrumentation and Measurement*, vol. 69, no. 6, pp. 3838–3846, Jun. 2020.

[16] M. Abou-Khousa, K. T. M. Shafi, and X. Xingyu, "High-Resolution UHF Near-Field Imaging Probe," *IEEE Transactions on Instrumentation and Measurement*, vol. 67, no. 10, pp. 2353–2362, Oct. 2018.

4.1.4 Technical Complexity

Our design contains multiple components and subsystems that each utilize distinct engineering skills like circuit design, signal processing and propagation, antenna design, and programming. Furthermore, the scope of the problem we seek to solve contains multiple challenging requirements that match or exceed current solutions and industry standards.

A task list for this project—and the engineering principles implicated—are below:

- **Antenna CST Modeling, Design, and Tuning** – CAD modeling, VBA programming, signal transmission and processing
- **RF PCB Design (PLL & Switches)** – complex circuit design, signal reception and processing, circuit board customization, data transfer
- **ADC PCB Design** – programming, data sheet interpretation, data reception and transmission, printed circuit board design
- **Low Level Programming (Data Gathering)** – data reception, microprocessor programming, custom code infrastructure development
- **Data Processing and Display** – user interface design, data processing, data display, programming in Python

The list above makes clear that there are several distinct subsystems in our project. Each subsystem requires unique scientific, mathematic, and engineering principles.

4.2 Design Exploration

4.2.1 Design Decisions

We have faced several design dilemmas that have required calculated decisions.

1. **Microprocessor** – We had to carefully consider whether to use a Raspberry Pi, ESP32, or other microprocessor. Ultimately, we chose to use a Raspberry Pi because it has a much broader spectrum of potential functionality.

2. **User Interface Display** – We contemplated as a team whether to use a dedicated external display or design a way to project our user interface on most electronic devices. Ultimately, we decided to write a Python script that would allow us to present our data display on most electronic devices (like smartphones or laptops). This will likely take more work, but it will make our complete system more versatile.

3. **One Fixed Design vs. Two Designs with a Portable Version** – Initially, our client was considering requiring that we build two devices. The first device would be fixed in place like the imaging machines at airport TSA checkpoints. The second device would be handheld. However, after deliberating, we negotiated with the client to drop the second device requirement. This would have required an enormous secondary effort and recalibration of all other project subsystems. Nevertheless, the second version would have been interesting and useful in many distinct ways.

4.2.2 Ideation

Our microprocessor presents a strong example of many different potential options requiring one final decision. We engaged in structured ideation to reach a single conclusion. The options we considered were as follows:

- **Raspberry Pi [17]** – "The Raspberry Pi is a tiny and affordable computer that you can use to learn programming through fun, practical projects."
- **Teensy 4.0 [18]** – "The Teensy is a complete USB-based microcontroller development system, in a very small footprint, capable of implementing many types of projects."
- **ESP32 [19]** – "ESP32 is a feature-rich MCU with integrated Wi-Fi and Bluetooth connectivity for a wide-range of applications."
- **ESP8266 [20]** – "ESP8266 is a cost-effective and highly integrated Wi-Fi MCU for IoT applications."
- **Teensy 3.9 [18]** – "The Teensy is a complete USB-based microcontroller development system, in a very small footprint, capable of implementing many types of projects."
- **Arduino Mega [21]** – "The Arduino MEGA 2560 is designed for projects that require more I/O lines, more sketch memory and more RAM."

4.2.3 Decision-Making and Trade-Off

Ultimately, we settled on the Raspberry Pi because it was the strongest combination of features needed for our project. The factors we considered are below:

- **Simplicity –** It is generally understood that the Raspberry Pi is the easiest to use of all the microprocessor options. It is also the easiest to program for user interface data display.
- **Self-Contained –** With the Raspberry Pi, we do not have to create a breakout board for it unlike other MCUs.
- **Existing Libraries –** Many libraries already exist for Raspberry Pi so it will require less low-level programming.
- **GPIO Pins** – We wanted to maximize this factor, but the Raspberry Pi is actually not the industry leader in this regard.
- **Quad Core Capability** – Can run multiple processes in parallel, which is not just ideal, but crucial to the data gathering and post processing tasks of the project.

Table 4.1 – Microprocessor Decision Matrix

Option	Simplicity	Self-Contained?	Existing Libraries?	GPIO Pins?	Quad Core Capability
Raspberry Pi	Very Simple	Yes	Yes	Enough	Yes
Teensy 4.0	Moderate	Not as well	Limited	Many	None
ESP32	Challenging	Not as well	Limited	Some	None
ESP8266	Challenging	Not as well	Limited	Some	None
Teensy 3.9	Moderate	Not as well	Limited	Some	None
Arduino Mega	Simple	Yes	Yes, but less	Many	None

A variation of a decision matrix is provided above in Table 4.1. It pictographically depicts why the Raspberry Pi was our strongest choice for microprocessor.

4.3 Proposed Design

4.3.1 Design Visual and Description

Our project is a series of subsystems that comprise a complicated circuit. We have modeled this circuit, and our model layout is displayed in **Figure 4.1 below**.

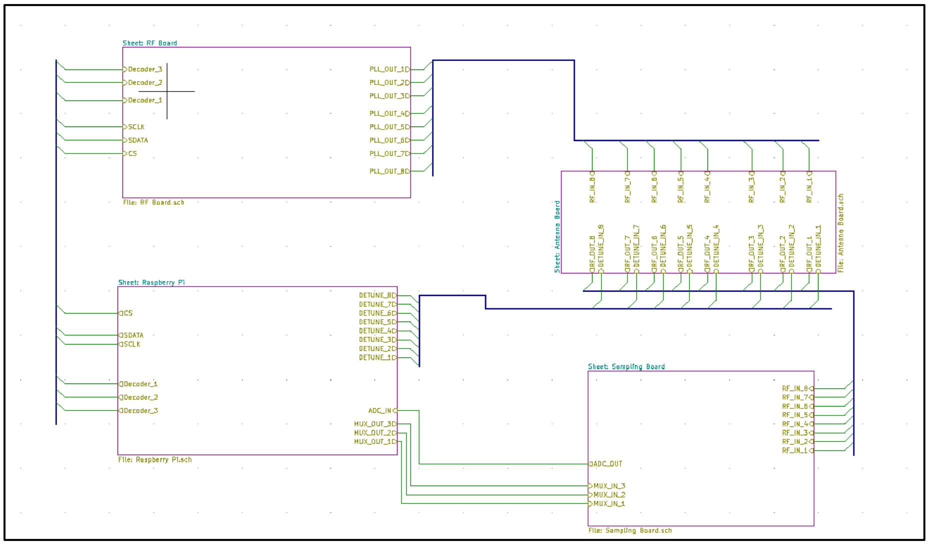

Figure 4.1 - Full System Circuit

The upper right quadrant of Figure 4.1 represents our RF antenna array. It includes eight I/O ports for each of the eight antennas.

The lower right quadrant of Figure 4.1 represents our ADC PCB. This will take signals from the RF antenna array and pass them to the microprocessor for processing and display.

The lower left quadrant of Figure 4.1 represents our microprocessor. It will send user-input commands to the RF PCB and receive data from the ADC PCB.

The upper left quadrant of Figure 4.1 represents the RF PCB. It will receive and transmit power, receive signals from the antenna array, send commands to the antenna array, and receive user-input commands from the microprocessor.

Figure 4.2 below displays the simulation and modeling step in the broader process of designing and ordering the antennas that will comprise our antenna array.

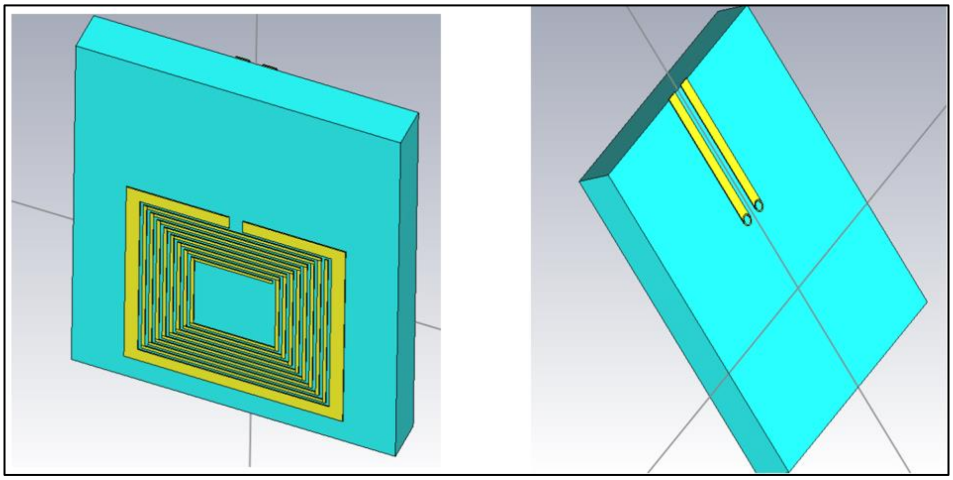

Figure 4.2 - Antenna Model and Simulation

The image at left in Figure 4.2 is the antenna side that will propagate signals into the medium we seek to measure. The image at right in Figure 4.2 is the "feed" side which will be connected to the RF PCB.

Figure 4.3 below displays an example of the CST simulations we are using to design the functional aspects of our antennas. We must place eight such simulated antennas in an array to predict and account for crosstalk and interference.

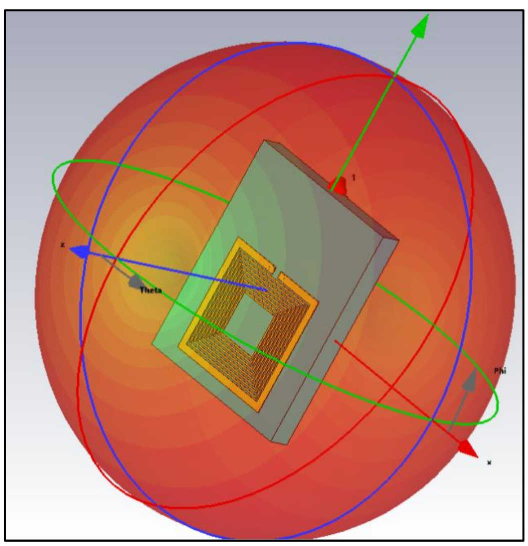

Figure 4.3 - Antenna Model CST Simulation

Figure 4.4 below displays the complete circuit diagram for our RF PCB.

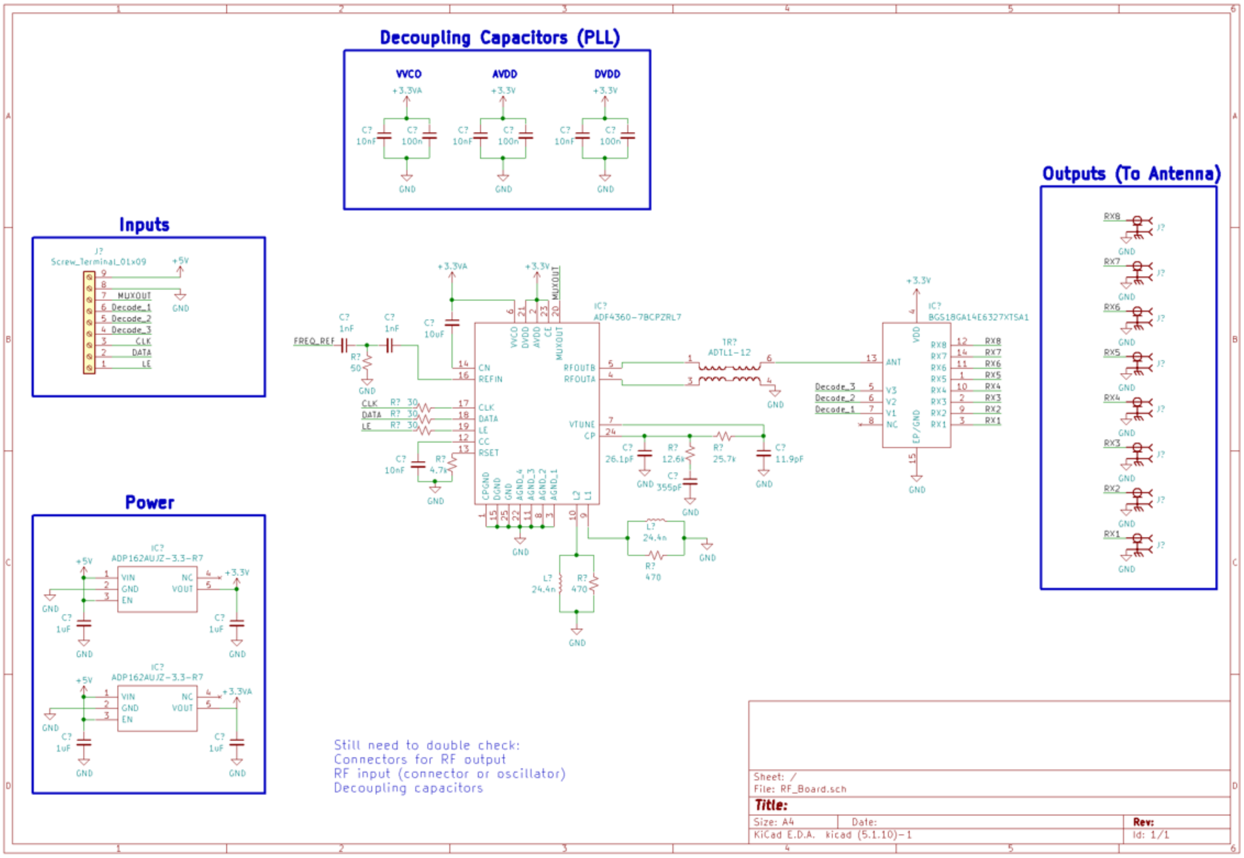

Figure 4.4 - RF PCB Schematic

The seemingly complicated circuit in Figure 4.4 severs several distinct—and conceptually elementary—purposes. The RF PCB's primary purpose is to control and measure the signals that the antennas propagate and receive. It will also maintain a baseline signal that our system will use as a constant to measure discontinuities in the mediums we are measuring.

4.3.2 Functionality

Our final design—and our completed system—will be usable and function in two ways.

The first functional use concept will take the form of a stationary device that objects are fed through or under. This design concept will be similar to the TSA scanners at airport checkpoints. Critically, TSA scanners at airports use radiation from x-rays to create images of luggage content. Of course, our system will use RF antenna propagation and measurement instead. Our system is likely also to be much smaller than the standard TSA checkpoint x-ray scanner. Figure 4.5 below displays the "feed through" functional concept we will implement as one possible use method for our complete system.

Figure 4.5 - TSA Checkpoint Machine Functional Use Example [22]

The second functional use concept will take the form of a handheld device that can be moved over the surface that our system is measuring through. This functional form of use will be like a stud finder. Figure 4.6 below displays the handheld stud finder use method that exemplifies the way a user will be able to use our complete system.

Figure 4.6 - Handheld Stud Finder Use Concept Example [23]

Functional Limitations and Non-Idealities:

Our complete project system will be mounted in a 3D printed thermoplastic bracket. It will necessarily be more unwieldy than a small and compact stud finder. Furthermore, it will be a fraction of the size of a TSA scanner, so it will not be able to scan through objects as large as a suitcase at one time like a TSA scanner. This is consequence of the necessity to create prototypes and a byproduct of our temporal limitations. Future iterations of the project would be smaller, more space efficient, and easier to use in a handheld capacity.

4.3.3 Areas of Concern and Development

Table 4.2 below displays our primary design concerns, our projected solutions for such concerns, and questions we have not yet solidified answers for.

Table 4.2 – Primary Design Concerns, Projected Solutions, and Lingering Questions

Design Concerns	Projected Solutions	Lingering Questions
Usability – design dimension uncertainty	We will minimize the size of the device while optimizing power and speed.	Final design dimensions? When will we know?
Using Python (a high level language) to handle high frequency ADC analog signals (a very low level process)	If we find that using python will slow down the functionality of our project, we will likely use C instead of python to handle the data gathering and post processing tasks.	When to use C vs. Python?
Over complexity – # of subsystems	Simplify processes or reduce functionality/speed to ensure min. viable functionality	How to find balance of consistent capability vs adding new features/functionality?
User interface interpretability	Conduct usability studies with intended end users for feedback on data visualization intuitiveness	What are the best usability studies to obtain effective feedback from end users?

4.4 Technology Considerations

Technology considerations played a central role in our project design. Essentially each phase of our design process required considering the strengths, weaknesses, and trade-offs of various technological alternatives.

LOW-LEVEL PROGRAMMING TECHNOLOGY CONSIDERATIONS

1. **Microprocessor** – We had to carefully consider whether to use a Raspberry Pi, ESP32, or another microprocessor. Ultimately, we chose to use a Raspberry Pi because it has a much broader spectrum of potential functionality.

HIGH-LEVEL PROGRAMMING TECHNOLOGY CONSIDERATIONS

2. **User Interface Display** – We contemplated as a team whether to use a dedicated external display or design a way to project our user interface on most electronic devices. Ultimately, we decided to write a Python script that would allow us to present our data display on most electronic devices (like smartphones or laptops). This will likely take more work, but it will make our complete system more versatile.

SYSTEM INTEGRATION TECHNOLOGY CONSIDERATIONS

3. **One Fixed Design vs. Two Designs with a Portable Version** – Initially, our client was considering requiring that we build two devices. The first device would be fixed in place like the imaging machines at airport TSA checkpoints. The second device would be handheld. However, after deliberating, we negotiated with the client to drop the second device requirement. This would have required an enormous secondary effort and recalibration of all other project subsystems. Nevertheless, the second version would have been interesting and useful in many distinct ways.

4.5 Design Analysis

Thus far, we have not encountered any significant issues with our proposed design from section 4.3 above. We are in the process of finalizing the construction of each of our four primary sub-systems: antenna array, RF PCB, ADC PCB, and microprocessor. It may become apparent later that we must make changes to our design in contrast with our design plan, but at present we have not deviated significantly from the proposed design set forth in Section 4.3 above.

Our relative design success to this point is largely due to meticulous planning of the various sub-systems in our overall design. Each team member was delegated a task that caters to their technical strengths, and this focused expertise has ensured a smooth transition from the design to construction, testing, and integration phases of our project.

4.6 Design Plan

In summary, we are utilizing the idea implemented in the paper *Array of Planar Resonator Probes for Rapid Near-Field Microwave Imaging* cited in Section 4.1.3 above. However, the novel implementation of our project is to use a mixer and Schottky diode to determine the magnitude with which microwave signals are being reflected back to our antennas. This enables us to modularize the system instead of needing to use a vector network analyzer (VNA) to send and read the microwave signals. This technological substitution avoids costlier design components and will help us realize a reduction in the overall size of our finished product.

Our design process thus far is further detailed in incremental steps below:

1) **Test board for Schottky diode –** We began by designing a test board to characterize the Schottky diode in our RF PCB to determine the power-to-voltage relationship which would allow us to process the data. Using this design strategy also enables us to determine the impedance of the mixer which will allow us to model it in our software to ensure that our antennas can resonate at the correct design frequency. The first two images below are schematic representations of the circuitry required for testing the power-to-voltage relationship (Figure 4.7) and the diode impedance (Figure 4.8), respectively. The third image (Figure 4.9) displays our actual test boards.

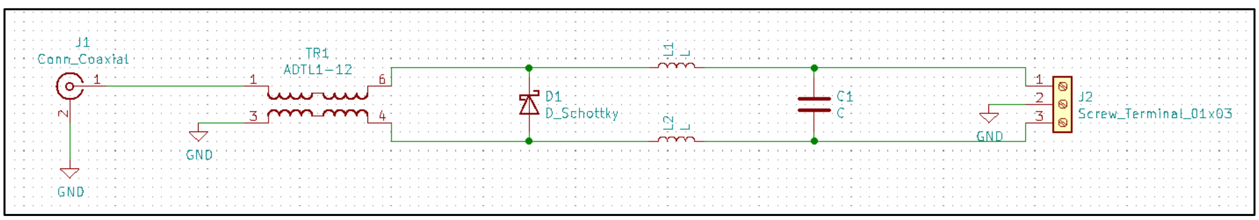

Figure 4.7 – Circuitry for Determining Power-to-Voltage Relationship

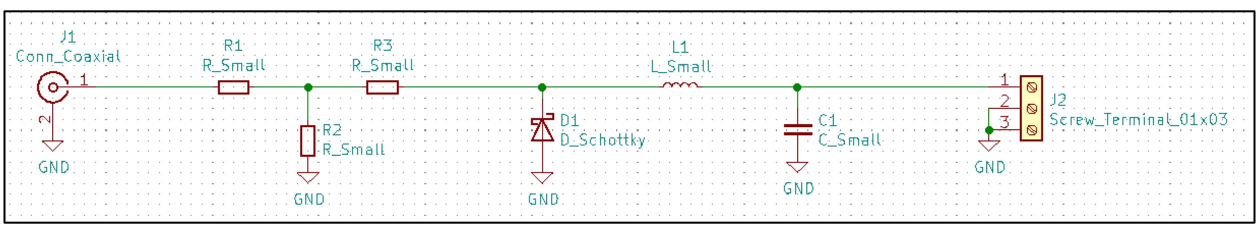

Figure 4.8 – Circuitry for Determining Diode Impedance

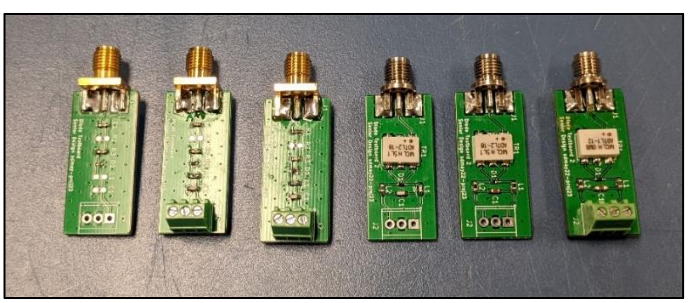

Figure 4.9 – Physical Test Boards

2) **Test bench to characterize the diode** – The next step in our design plan was to vary input power using a signal generator followed by reading the corresponding voltage output. We repeated this at different frequencies to obtain data that would allow us to characterize the diode and read accurate data during the testing stage. Similar correlations were identified between the measured data and data from the components' datasheets, but different readings were obtained at different frequencies which produced slightly different measurements than what our ideal simulation models predicted. We care most about the measurement at our design frequency of 400MHz. The two left-most charts below represent our measured power-to-voltage relationship (Figure 4.10) and the power-to-voltage relationship of the Schottky diode as provided in the diode component's datasheet (Figure 4.11). Figure 4.12 to the right is a picture of the measurement process.

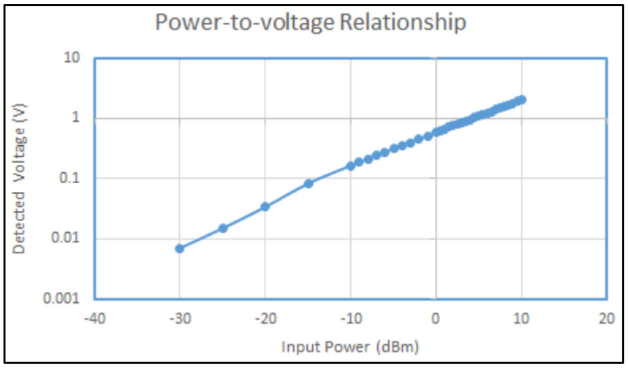

Figure 4.10 – Measured Power-to-Voltage Relationship of Schottky Diode

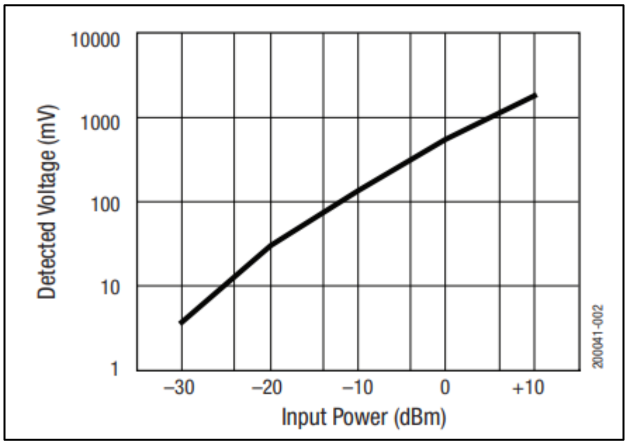

Figure 4.11 – Datasheet's Power-to-Voltage Relationship of Schottky Diode

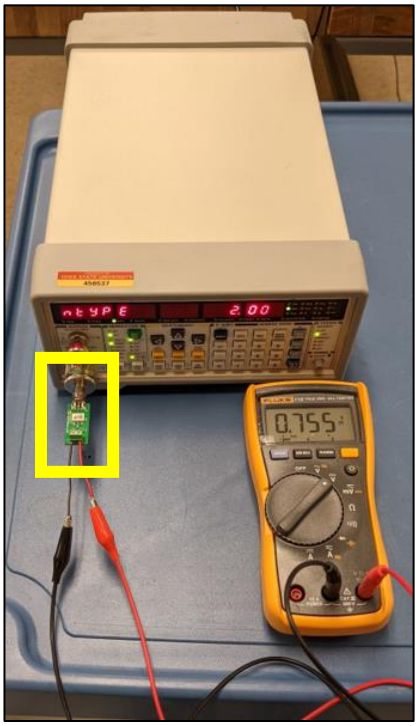

Figure 4.12 – Physical Test Board Measurements (Test Board Emphasized by Yellow Box)

3) **Vector Network Analyzer (VNA) for Measuring S11 Parameters of Diode –** The next step in our design plan was to use a VNA to measure S11 parameters of the diode. S11 diode parameters were described in Section 2.2.1. Using the VNA allowed us to obtain the input impedance of the diode. We performed these measurements twice: once with biasing for antenna detuning and once without where we read the voltage output. Graphic depictions of these two measurement results are displayed in Figures 4.13 and 4.14 below, respectively. Figure 4.15 depicts the physical test board VNA measurement.

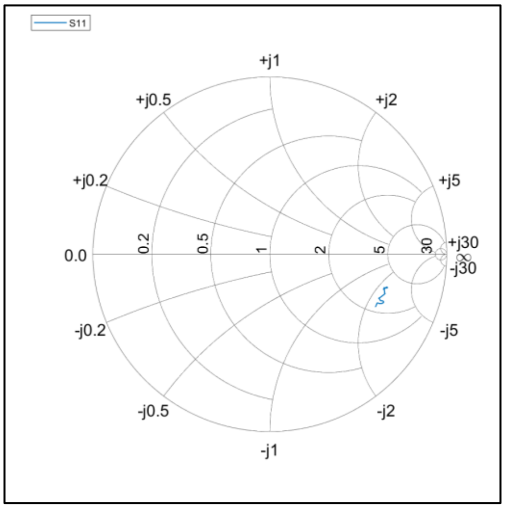

Figure 4.13 – VNA S11 Measurement of Diode with Biasing for Antenna Detuning (Impedance at 400MHz is 14-300jΩ)

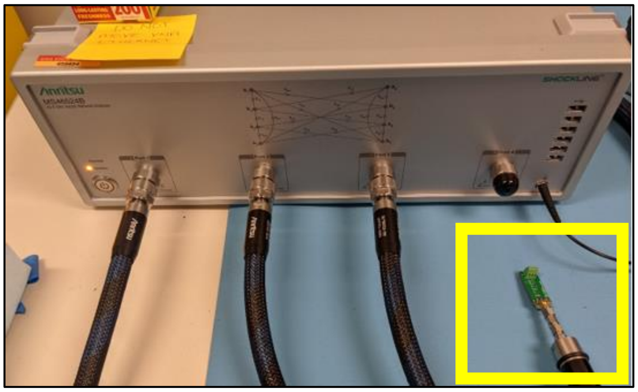

Figure 4.15 – Picture of Physical Test Board/VNA Measurement Process (Test Board Emphasized by Yellow Box)

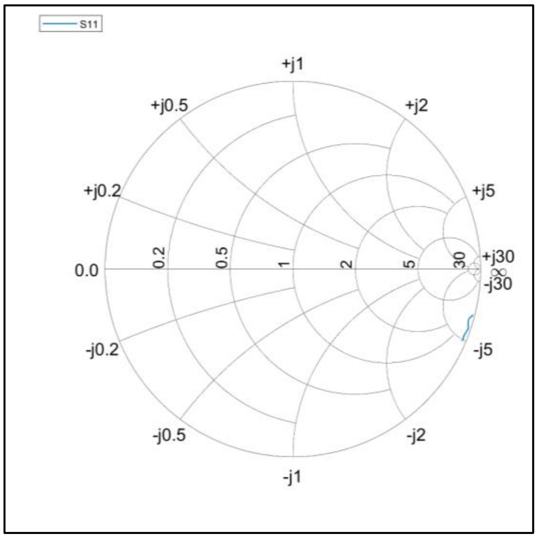

Figure 4.14 – VNA Measurement of Diode w/o Biasing for Obtaining Voltage Output (Impedance at 400MHz is 133-119jΩ)

4) **Antenna Model Design and Simulation –** We then proceeded to design a model of an RF antenna for use as a simulation test case. We aimed to simulate the resonant behavior of a single antenna while incorporating diode impedance. ***Figure 4.16 below*** depicts a front and rear view of our simulated RF antenna model. ***Figure 4.17 below*** depicts an isometric view of our simulated RF antenna model.

   Figure 4.18 on the next page depicts our self-generated S11 parameter plot ***before*** a matching network has been implemented to optimize antenna operability. ***Figure 4.19 on the next page*** depicts our self-generated S11 parameter plot ***after*** a matching network has been implemented to optimize antenna operability—this plot mirrors the example plot (e.g., Figure 3.5 detailed in Section 3.2 above) and demonstrates that our simulated antennas are tuned correctly and functioning as desired.

   Two other critical parameters of interest for antenna tuning and implementation are **radiation efficiency** and **impedance measurement**. A radiation efficiency plot—which we are still in the process of generating—shows how well the antenna is radiating its energy outward. If it is less than zero, then the antenna is not radiating well and is wasting energy. An impedance plot will show how the impedance (real and imaginary) changes as frequency is varied. To use a capacitor-based matching network, the imaginary component must be positive at our desired frequency (400 MHz). This is because capacitors introduce "negative" impedance.[6]

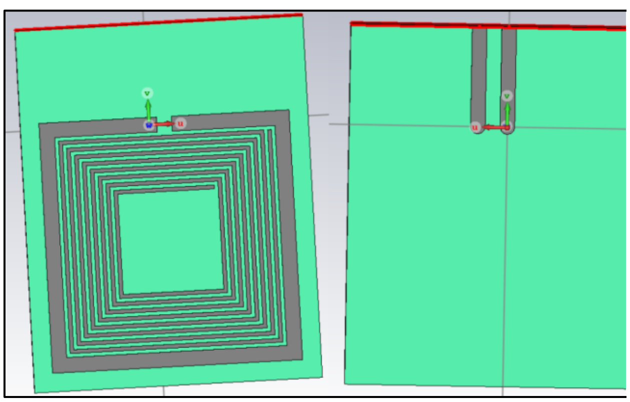

Figure 4.16 – Front (Left) and Rear (Right) View of Simulated RF Antenna Model

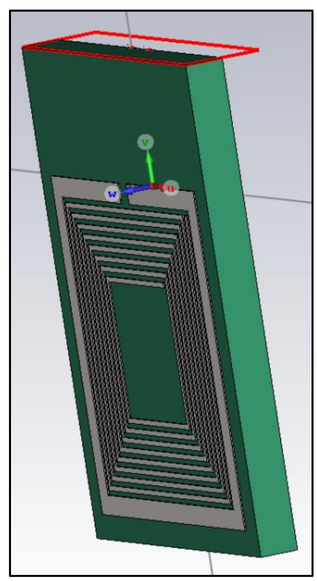

Figure 4.17 – Isometric View of Simulated RF Antenna Model

[6] Technically, the impedance introduced by a capacitor is not negative. However, a positive reactance is inductive, so the capacitance can be used to cancel it out and get the desired input impedance (100 ohms).

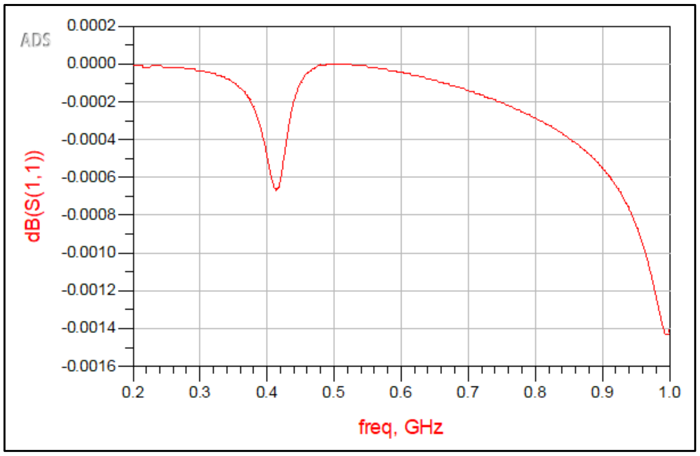

Figure 4.18 – S11 Parameter Plot *BEFORE* Matching Network is Implemented

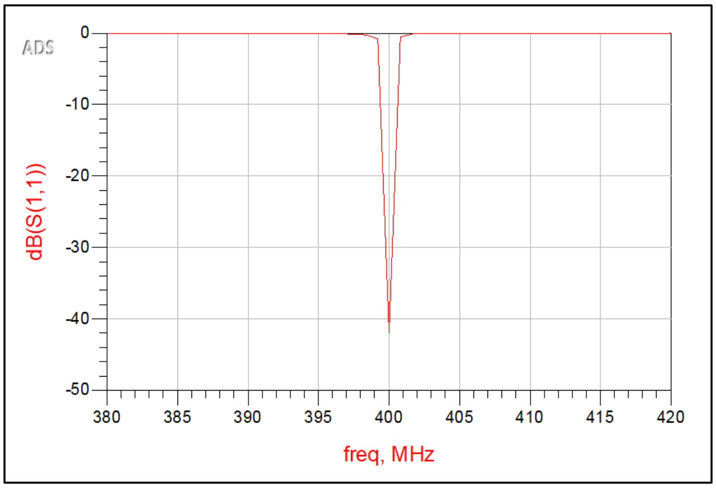

Figure 4.19 – S11 Parameter Plot *AFTER* Matching Network is Implemented

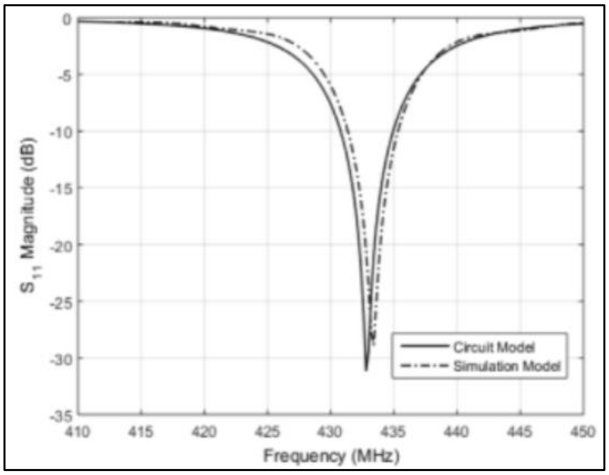

Figure 3.5 *(Duplicate for Referential Comparison)* **– Optimal S11 Parameter Plot Example**

5) **[Forthcoming] Test Measurements of Physical Antennas** – Our custom RF antennas will be ordered by mid-December 2021. Once we receive the physical antennas, we will be able to proceed to measuring the antennas. We will begin by measuring the resonance behavior of a single antenna before incorporating them in our 2D array of antennas.

6) **RF and ADC PCB Design** – We have completed the design schematics of our RF and ADC PCB boards, and they are prepped for ordering pending our adviser's approval (as of late November 2021). Figure 4.20 below depicts our finalized RF PCB layout schematic. Figure 4.21 on the following page depicts our finalized ADC PCB schematic. Once we have received the custom PCBs, we will begin to integrate the various sub-systems into one complete system including the RF antenna array, RF PCB, ADC PCB, microcontroller, and user interface display.

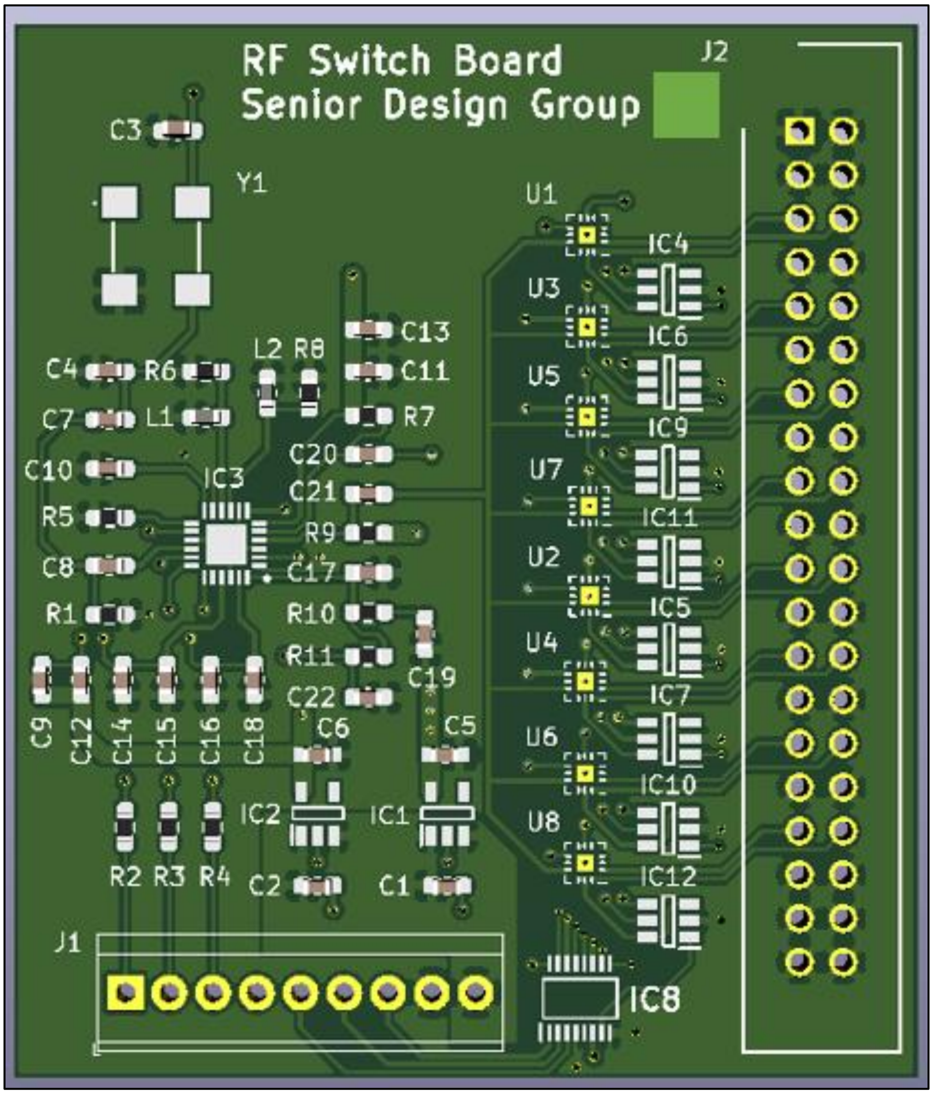

Figure 4.20 – Finalized RF PCB Layout Schematic

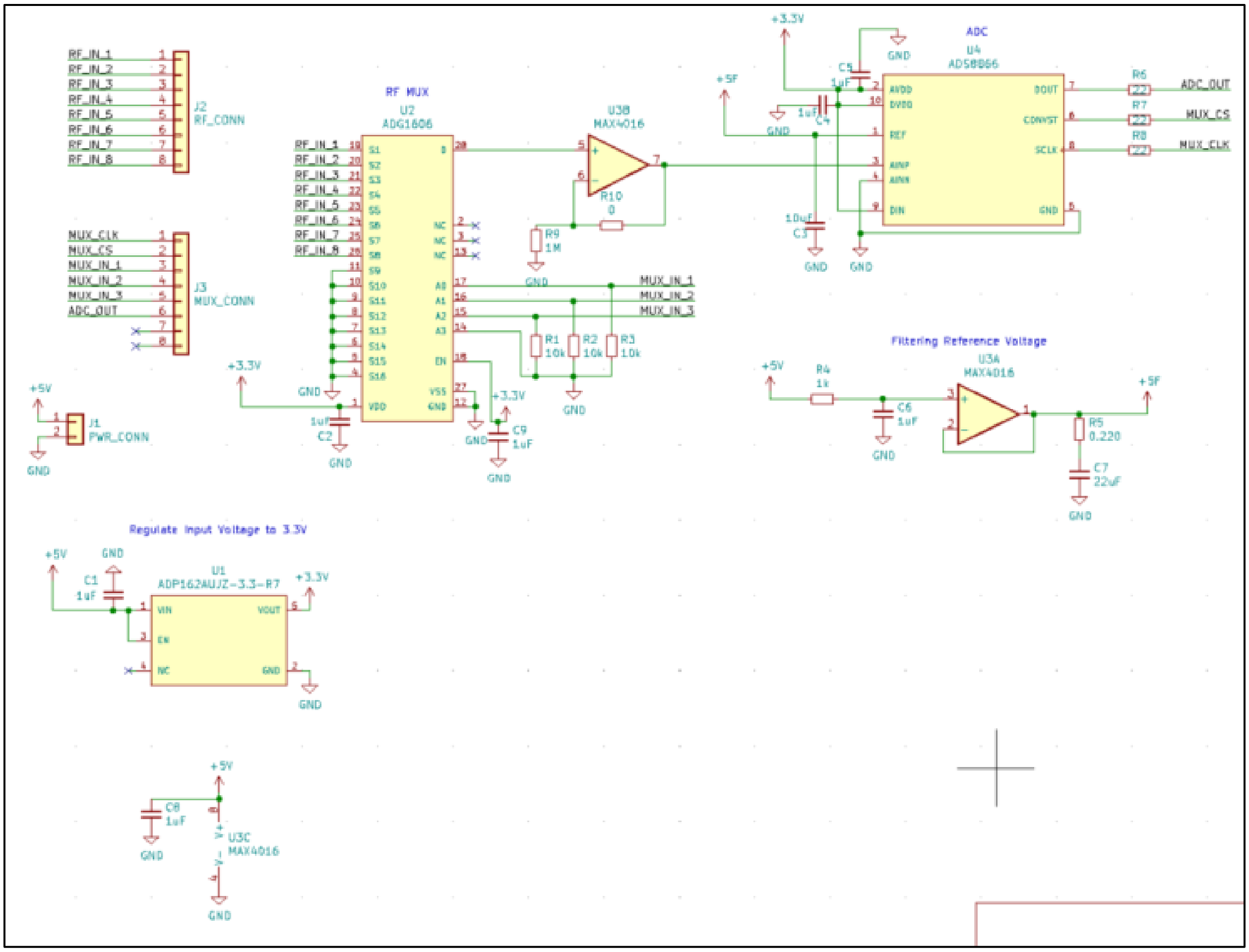

Figure 4.21 – ADC PCB Schematic

7) **[Forthcoming] Software development** – The last step in our design plan is software development. We must wait for the hardware to be tested and integrated before programming the microcontroller to control the hardware. Eventually, we will program both a user interface (high level programming) and the microcontroller to command the hardware (low level programming). The user interface will be coded with Python while the microcontroller will be coded with the C programming language.

5 Testing

5.1 Unit Testing

Every subsystem in our design requires standalone unit testing. This includes the RF PCB, ADC PCB, microprocessor (both low and high level programming), and antennas.

1) Antenna Array Unit Testing

The primary unit of measure (and testing) in our complete system is **Frequency Response**.

Figure 5.1 below is a critically important representation of the optimality for RF antenna emissions: S11 (on the y-axis) represents the amount of power reflected back from the object that the antenna's outgoing RF emissions are directed towards. For an ideal antenna, all the power would be transmitted, so the magnitude of S11 should be zero. Using a logarithmic scale, zero is equal to negative infinity dB. However, since that is not possible, anything less than -20dB will be sufficient for our application.

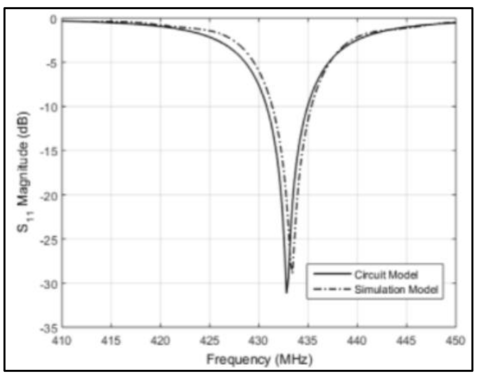

Figure 5.1 – Antenna Array Simulated Frequency Response Example [16]

Frequency response is a product of antenna tuning. To determine whether an antenna is tuned correctly, we will use a directional coupler and spectrum analyzer.

2) RF PCB Unit Testing

Like the antenna array unit testing, we will utilize frequency response measurement and testing to show the RF PCB is emitting proper signal frequencies. This will be like the antenna frequency response unit testing except instead of attenuation, we will see a positive frequency response since we expect (and require) power actually being delivered to the antennas.

3) ADC PCB Unit Testing

Regarding unit testing for the ADC PCB, we will transmit the ADC PCB a known voltage. We will then read it through to the microprocessor (MCU) while concurrently converting the known voltage manually. If the two values—read through and manual—are a match, we will be able to confirm that the ADC PCB passed its respective unit testing phase.

4) Microprocessor Unit Testing

The microprocessor is integrated with the entirety of rest of the system (i.e., all sub-systems). Therefore, while viewing the microprocessor as a standalone "unit" system, we will be able to unit test the microprocessor by merely checking that all the microprocessor's drivers are functioning individually with one system at a time. Restated, we will perform MCU testing by ensuring that the MCU should be communicating only with the RF PCB or only with the ADC PCB when such commands are exclusively specified by the operator.

5.2 Interface Testing

There are multiple interfaces in our complete system—these interfaces connect the various sub-systems to one another. A list of our interfaces is below.

Complete system interfaces:

- ***Antenna array to RF PCB*** (and RF PCB to antenna array)
- ***Antenna array to ADC PCB*** (and ADC PCB to antenna array)
- ***RF PCB to microprocessor*** (and microprocessor to RF PCB)
- ***ADC PCB to microprocessor*** (and microprocessor to ADC PCB)
- ***Microprocessor to user interface display*** (and UI display to microprocessor)

We will use several different tools to test these various interfacing sub-systems. For example, **to test the microprocess-to-UI-display interface**, we will examine the user interface display output and manually compare it to the data that our low-level software is receiving from the ADC and RF PCBs, respectively. We will then be able to determine the accuracy of our user interface display.

As another example, we will use a system of observation and measurement to test the **RF-PCB-to-antenna-array interface**. This is perhaps the most important sub-system interface in our overall system. The RF PCB should enable an operator to switch between individual antennas in the array by sending commands from RF PCB that controls the antenna array accordingly. It will be obvious whether the RF PCB is correctly controlling antenna switching, because it will either turn off 7 of 8 antennas while leaving the intended antenna on to propagate RF signals, or it will fail to turn off 7 of 8 antennas while leaving the intended antenna on to propagate RF signals.

5.3 Integration Testing

Our overall system is heavily reliant on complete sub-system integration functionality. **Figure 5.2 below depicts the interdependent sub-systems of our overall system.** The schematic below demonstrates the total reliance on—and criticality of—functional sub-system integration.

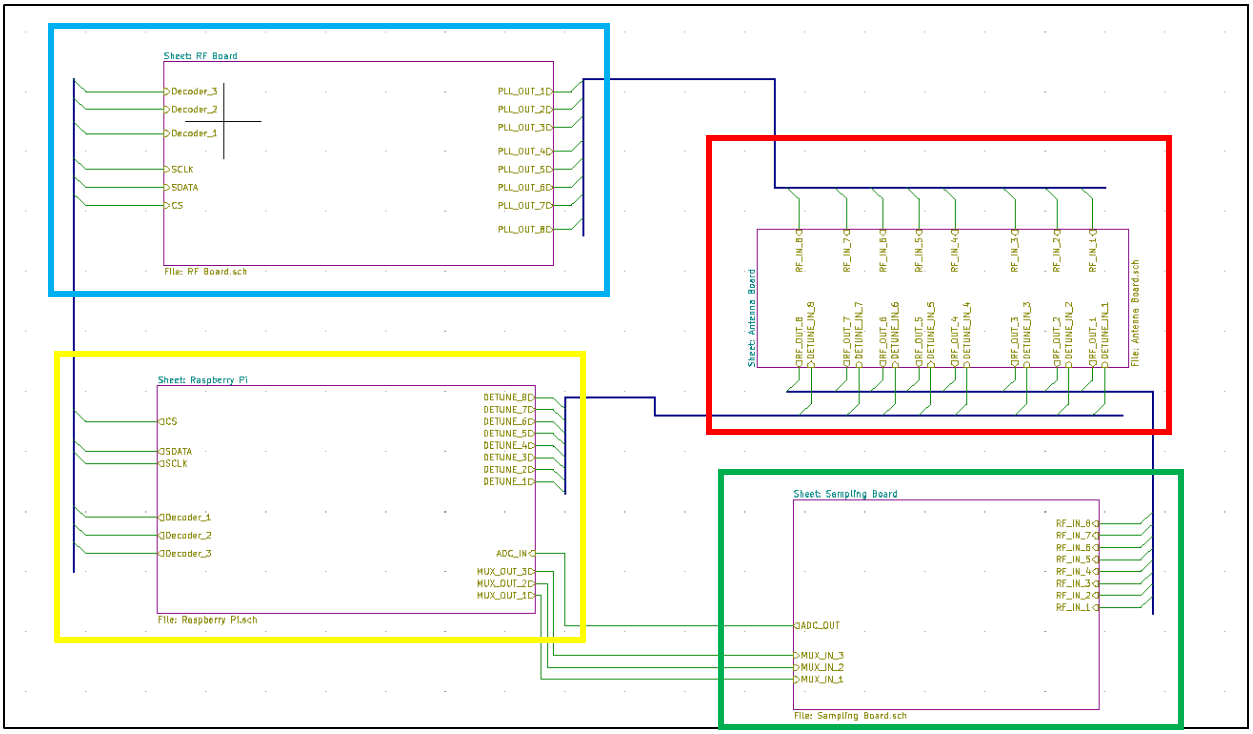

Figure 5.2 - Full System Circuit

The upper right quadrant of Figure 5.2 (red box) represents our **RF antenna array**. It includes eight I/O ports for each of the eight antennas. Complete RF antenna array integration requires that we tune, test, re-tune, and detune each antenna individually and in conjunction with the others. It also requires that we measure the analog signals being sent to the ADC from the antenna array. Finally, it requires that we check with switch and signal propagation functionality that comprise the relationship between the RF PCB and the antenna array.

The lower right quadrant of Figure 5.2 (green box) represents our **ADC PCB**. The ADC PCB will take signals from the RF antenna array and pass them to the microprocessor for processing and display. Complete ADC PCB integration requires that we test the accuracy of analog signals sent from the antenna array to the ADC PCB which are then passed to the microprocessor in the form of digital signals and data.

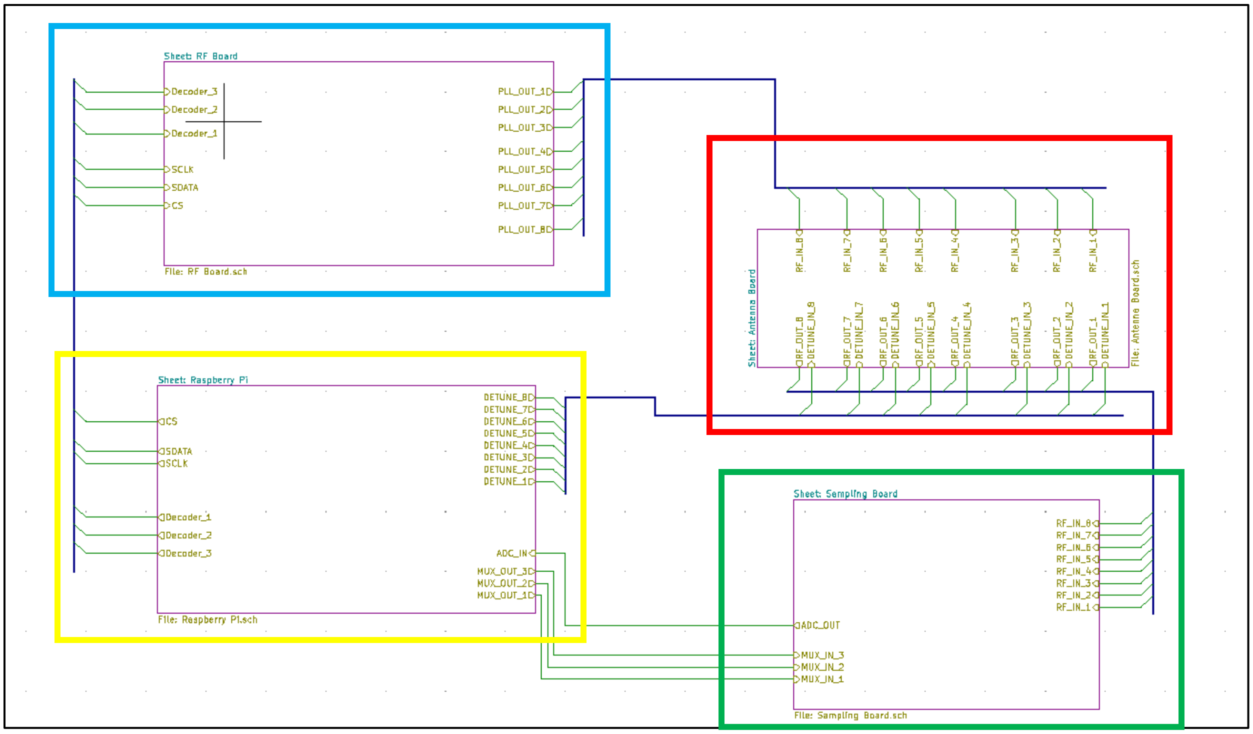

Figure 5.2 - Full System Circuit *(Duplicated for Reference)*

The lower left quadrant of Figure 5.2 (yellow box) represents our **microprocessor**. It will send user-input commands to the RF PCB and receive data from the ADC PCB. The microprocessor will house a considerable amount of software, so it will require standard software testing processes. However, it will also have to interface with the RF and ADC PCBs, and this will require manual testing of the signals and commands being sent to and from those sub-systems, respectively.

The upper left quadrant of Figure 5.2 (blue box) represents the **RF PCB**. It will receive and transmit power, receive signals from the antenna array, send commands to the antenna array, and receive user-input commands from the microprocessor. There are numerous tests we must run on the RF PCB, because it performs many different functions. One of the most important tests for the RF PCB is measuring the intended signal output against the actual signal output. This test will determine whether the "heart" of our project (the RF PCB) is accurately calibrated and properly controlling the "backbone" of our project (the antenna array).

5.4 System Testing

Our overall system requires functionality of several sub-systems that relate directly to our design requirements. The design requirements—are their respective system testing requirements—are summarized below:

1) **Antenna CST Modeling, Design, and Tuning**
    a. Testing for interoperability with RF PCB
    b. Testing for interoperability with ADC PCB
    c. Vector Network Analyzer used to test whether physical parts and assembly satisfy simulation parameters
    d. Test coupling between probes to ensure -30dB represented by S21

2) **RF PCB Design (PLL & Switches)**
    a. Testing for interoperability with antenna array
    b. Testing for interoperability with microprocessor
    c. Testing to ensure phase locked loop (PLL) produces 400MHz signal
    d. Testing to ensure power transfer across switches is at least 10dB
    e. "Smoke testing"[7] to ensure RF switches correctly turn on/off
    f. Smoke testing to ensure RF switches send signals to correct destination

3) **ADC PCB Design**
    a. Testing for interoperability with antenna array (accurate reception and conversion of analog signals)
    b. Testing for interoperability with microprocessor (accurate transmission of digital signals for processing)
    c. Testing to ensure ADC PCB sampling rate is 100kHz
    d. Testing to ensure ADC PCB resolution is 16 bits (or clear enough to be interpreted by microprocessor)

4) **Low Level Programming (Data Gathering)**
    a. Testing for interoperability with user ADC PCB (receiving digital signals)
    b. Testing for interoperability with RF PCB (sending operator commands)

5) **Data Processing and Display**
    a. Testing for sufficient user satisfaction and intuitiveness (~80%)

[7] "A quick test performed to ensure that the software works at the most basic level and doesn't crash when it's started. Its name originates from the hardware testing where you just plug the device and see if smoke comes out." [24]

5.5 Regression Testing

Regression Testing in Antenna Array

The clearest example of the need for regression testing in our overall system is in the addition of each individual antenna comprising our antenna array. There will be eight individual antennas in our 1x8 array of antennas, as shown in **Figure 5.3 below**. Each antenna must be able to function on its own, but it must also be tuned and re-tuned to account for the addition of adjacent antennas. This incremental tuning, re-tuning, and calibration process necessitates constant regression testing.

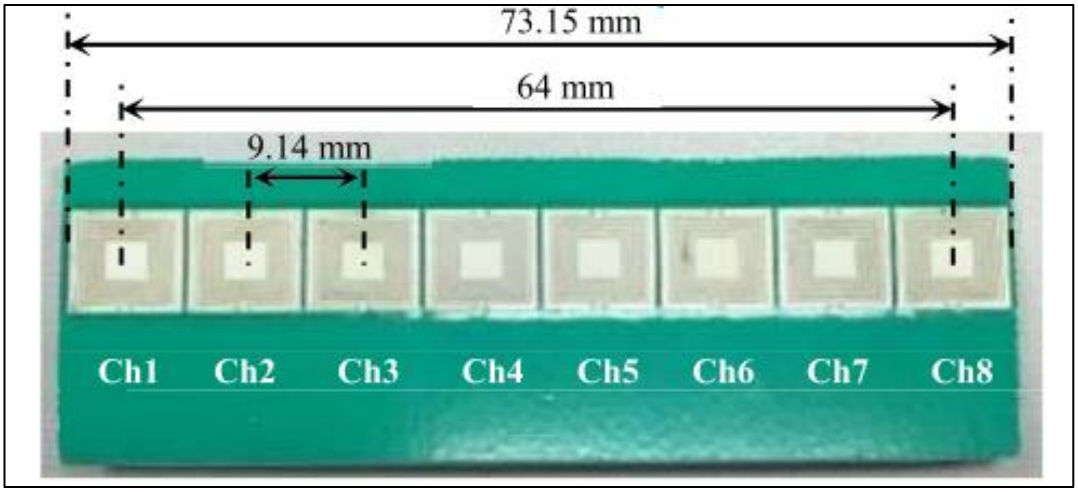

Figure 5.3 – One-Dimensional Antenna Array Example [4]

Regression Testing in Sub-System Integration

Regression testing will also be essential during the sub-system integration stage. As stated several times previously, our project comprises many complicated sub-systems working interdependently. If any of these sub-systems fail, our entire system will fail to meet our design requirements. As such, each sub-system will be introduced slowly and tested incrementally to stave off regression during any and all integration phases.

5.6 Acceptance Testing

Ultimately, our project will be designed to "image" objects that are hidden behind opaque structures. Testing system functionality is relatively straightforward:

1. **Manual object measurement** – We will measure a test object by hand as a base reference.

2. **Obscurement of object** – We will then hide the object behind a uniformly consistent surface (like drywall).

3. **Antenna array signal propagation and reception** – Our sub-systems—working in conjunction—will enable the RF antenna array to send signals and receive distorted signals in response that correlate with the object hidden under the opaque surface.

4. **User interface display output generation** – Our user interface display—controlled by our microprocessor—will generate a 2D image that is representative of the object behind the opaque surface.

5. **Comparison: UI-output-to-manual-measurement** – This is the final and most important step. We will compare our initial manual measurement results to measurement results gleaned from the system-generated user interface 2D image.

We will discuss an acceptable level of measurement error tolerance with our client. Preliminarily, we would like to produce imaging measurements with no more than approximately 20% measurement error. Of course, one of our primary design goals is to drive this measurement error percentage as low as possible. We will also test our system on several different sizes and shapes of objects, and on several different surfaces comprised of varying materials and thicknesses.

5.7 Results

Antenna Array – Frequency Response Results

Figure 5.1 was previously displayed in section 5.1 above, and it is displayed again below due to its critically important nature. The results of our design testing will confirm that we have achieved the optimality for our RF antenna emissions: S11 (on the y-axis) represents the amount of power reflected back from the object that the antenna's outgoing RF emissions are directed towards. Our results will allow us to recreate this graph with our own data and demonstrate that we are achieving our target result of less than -20dB for our application.

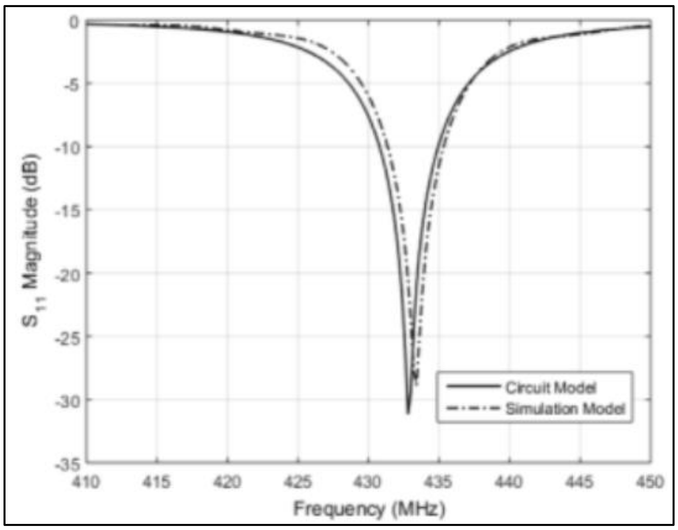

Figure 5.1 – Antenna Array Simulated Frequency Response [16] *(Duplicated for Reference)*

System and Acceptance Testing Results

As stated in section 5.6 above, the results of our system and acceptance testing will demonstrate that we are imaging objects hidden by opaque structures with repeatable accuracy. We will confirm this by comparing our user interface output measurements to manual physical measurements of the hidden objects during the testing phase. The result of this trial-and-error testing will lead to consistent measurement results that indicate our system is ready for production.

6 Implementation

All design plan stages were delineated in Section 4.6 above. Many of our design plans have already been implemented. The steps we have yet to complete were marked "[Forthcoming]" in in Section 4.6 above. The steps we have already implemented—and the steps we have yet to implement—are briefly reiterated below.

1) **Test board for Schottky diode –** We began our implementation phase by designing a test board to characterize the Schottky diode in our RF PCB to determine the power-to-voltage relationship which would allow us to process the data. Using this design strategy also enabled us to determine the impedance of the mixer which will allow us to model it in our software to ensure that our antennas can resonate at the correct design frequency.

2) **Test bench to characterize the diode** – The next step in our design plan implementation was to vary input power using a signal generator followed by reading the corresponding voltage output. We repeated this at different frequencies to characterize the diode accurately. Relatively similar correlations were identified between the measured data and data from the components' datasheets. We care most about the measurement at our design frequency of 400MHz.

3) **Vector Network Analyzer (VNA) for Measuring S11 Parameters of Diode –** The next step in our design plan was to use a VNA to measure S11 parameters of the diode. S11 diode parameters were described in Section 2.2.1. VNA use helped identify the input impedance of the diode. We performed these measurements with and without biasing.

4) **Antenna Model Design and Simulation –** We then proceeded to design a model of an RF antenna for use as a simulation test case. We aimed to simulate the resonant behavior of a single antenna while incorporating diode impedance.

5) **[Forthcoming] Test Measurements of Physical Antennas** – Our custom RF antennas will be ordered by mid-December 2021. Once we receive the physical antennas, we will be able to proceed to measuring the antennas. We will begin by measuring the resonance behavior of a single antenna before incorporating them in our 2D array of antennas.

6) **RF and ADC PCB Design** – We have completed the design schematics of our RF and ADC PCB boards, and they are prepped for ordering pending our adviser's approval (as of late November 2021). Once received, we integrate the various sub-systems into one complete system.

7) **[Forthcoming] Software development** – The last step in our design plan is software development. Eventually, we will program both a user interface (high level programming) and the microcontroller to command the hardware (low level programming). The user interface will be coded with Python while the microcontroller will be coded with the C programming language.

7 Professionalism

7.1 Areas of Responsibility

Table 7.1 below includes (1) a reprint of the International Journal of Engineering Education (NSPE) code of ethics, (2) a reprint of the IEEE Code of Ethics, and (3) two added columns to the right comparing, contrasting, and analyzing the "area of responsibility" as described in the IJEE-NSPE and IEEE Codes of Ethics.

Table 7.1 – NSPE Table 1 + IEEE Comparisons and Contrasts

AREA OF RESPONSIBILITY	NSPE Definition	NSPE Canon	Respective IEEE Canon(s)	IEEE Comparisons and Contrasts
Work Competence	Perform work of high quality, integrity, timeliness, and professional competence.	Perform services only in areas of their competence. Avoid deceptive acts.	"6. to maintain and improve our technical competence and to undertake technological tasks for others only if qualified by training or experience, or after full disclosure of pertinent limitations;" "9. to avoid injuring others, their property, reputation, or employment by false or malicious action;" "10. to assist colleagues and co-workers in their professional development and to support them in following this code of ethics."	The IJEE definition and canon are rather precise, whereas the IEEE code of ethics elaborates on falsification and malicious action. The IEEE code of ethics also lists a responsibility to mentoring coworkers to aid in their professional development, and this is not discussed in the IJEE table.
Financial Responsibility	Deliver products and services of realizable value and at reasonable costs.	Act for each employer or client as faithful agents or Trustees.	"2. to avoid real or perceived conflicts of interest whenever possible, and to disclose them to affected parties when they do exist;" "4. to reject bribery in all its forms;"	The IEEE code of ethics specifically lists conflicts of interest—which are often financial in nature—whereas the NSPE definition and canon are a bit more vague.
Communication Honesty	Report work truthfully, without deception, and understandable to stakeholders.	Issue public statements only in an objective and truthful manner. Avoid deceptive acts.	"3. to be honest and realistic in stating claims or estimates based on available data;"	The IEEE and NSPE statements related to communication honesty are quite similar in meaning and content.
Health, Safety, Well-Being	Minimize risks to safety, health, and well-being of stakeholders.	Hold paramount the safety, health, and welfare of the public.	"1. to accept responsibility in making decisions consistent with the safety, health,	Both the IEEE and NSPE codes of ethics use nearly identical language ("safety, health, and welfare")

			and welfare of the public, and to disclose promptly factors that might endanger the public or the environment;"	in these delineated code sections. However, the IEEE code of ethics elaborates a bit more.
Property Ownership	Respect property, ideas, and information of clients and others.	Act for each employer or client as faithful agents or Trustees.	"7. to seek, accept, and offer honest criticism of technical work, to acknowledge and correct errors, and to credit properly the contributions of others;"	"Property ownership" did not have a clear analogue in the IEEE code; however, both of these code sections from both papers appear to describe ideas as property (i.e., intellectual property).
Sustainability	Protect environment and natural resources locally and globally.	(None provided)	"1. to accept responsibility in making decisions consistent with the safety, health, and welfare of the public, and to disclose promptly factors that might endanger the public or the environment;"	Both codes of ethics (IEEE and NSPE) clearly state that engineers have a responsibility to preserving the welfare of the environment. The IEEE code does not explicitly list the necessity to preserve natural resources.
Social Responsibility	Produce products and services that benefit society and communities.	Conduct themselves honorably, responsibly, ethically, and lawfully so as to enhance the honor, reputation, and usefulness of the profession.	"5. to improve the understanding of technology; its appropriate application, and potential consequences;" "8. to treat fairly all persons and to not engage in acts of discrimination based on race, religion, gender, disability, age, national origin, sexual orientation, gender identity, or gender expression;"	Interestingly, the NSPE code does not touch on the need to avoid discrimination based on various societal categorizations, like in #8 of the IEEE code. This is a stark and surprising contrast (via omission on the part of the NSPE) that lends credibility to the IEEE code over the NSPE code.

7.2 Project-Specific Professional Responsibility Areas

- **Work Competence** – Work competence is likely one of the highest-priority areas of professional responsibility for our project. Due to the independent nature of the various sub-systems in our project, each of our group members must complete their responsibilities to the best of their ability. Failure to do so creates risk of jeopardizing the functionality of our overall system with little recourse for remedial measures by other group members. In short, we count on timely contributions from all group members.

- **Financial Responsibility** – Financial responsibility does not have a paramount role in our project, because our budget is relatively small (~$300-500). Nevertheless, it is important to the extent that the proper parts are identified and purchased. Moreover, a failure to secure funding pushed back our design and construction phases by a matter of weeks, so we witnessed the repercussions of lax financial responsibility firsthand.

- **Communication Honesty** – Communication honesty is important in our project for two primary reasons: (1) we need to present our progress and ideas in our written reports in a way that accurately conveys our status to our instructors and (2) we need to communicate our progress accurately to each other (the other members of our group) so each group member knows when to begin the various stages of sub-system design. Misrepresenting one's progress through inaccurate communication could stifle progress on all fronts.

- **Health, Safety, Well-Being** – One of the main applications of our project is biomedical imaging in the healthcare industry, so ensuring a functioning product is—in essence—pertinent to delivering quality healthcare solutions. Our second application is in the construction industry, and a functioning product that was designed with professional principles in mind will help prevent workplace hazards, wasted expenses, and delays.

- **Property Ownership** – This professional responsibility area is not particularly relevant to our project, because we are not responsible for confidential information of a client or property that does not belong to us as a group. That said, we have a responsibility to one another to deliver the highest quality finished product we can with the physical resources at our disposal.

- **Sustainability** – Again, sustainability is not a particularly pressing area of professional responsibility in our project, in part, because we do not perceive mass production or environmental waste as a necessary consequence of our system design. Yet, there are certain conversancy implications in our project, including the potential waste at construction sites if our product does not accurately identify hidden structures as it is intended to.

- **Social Responsibility** – Social responsibility is important in our project for many of the reasons stated above: construction and healthcare industry members will rely on our solution to enhance the efficiency and security of their jobs. We must keep their needs in mind while designing our system and implementing quality control measures.

7.3 Most Applicable Professional Responsibility Area

Work Competence

As stated in the section above, work competence is likely our highest-priority area of professional responsibility for our project. To ensure that we "perform work of high quality, integrity, timeliness, and professional competence," we have chosen a project that in a broad sense meets not only the interests of all the team members but also the skill level and areas of specialization of all the team members. More importantly, while considering the importance of specialization in effective teamwork, we divvied up the subsystems of the project and the respective tasks that come along with those subsystems among the team members based on their areas of competence. By doing this we save lots of time and effort as we ensure that a team member is not assigned to a subsystem that requires knowledge that they have no exposure to.

What the Professional Responsibility of "Work Competence" Means to Our Project

Due to the independent nature of the various sub-systems in our project, each of our group members must complete their assigned responsibilities to the best of their ability. In short, we are counting on all our group members to complete their unique tasks competently and in a timely manner. This ensures that all time and effort is used effectively and as a result as a team we produce high quality work.

Specific Impacts of Work Competence on our Project that we have Observed

Failure to maintain a competent level of work jeopardizes the functionality of our overall system with little recourse for remedial measures by other group members. Since we were careful and deliberate with how we assigned tasks, we have yet to face any major difficulty with the progress of the overall project. As with any project, obstacles are to be expected but by divvying up the tasks based on the team members' areas of competence, we ensure that we can minimize the overall risk to project because of such obstacles.

8 Closing Materials

8.1 Discussion

The list of requirements for this project are as follows:

- Req. 1 - Computer Simulation Technology Modeling and Antenna Design (with Tuning)
- Req. 2 – RF Printed Circuit Board (PCB) Design
- Req. 3 – ADC PCB Design
- Req. 4 – Low Level Microcontroller Programming/Data Gathering
- Req. 5 – Data Processing and Display

This semester, we have made significant progress on designing solutions to satisfy all five requirements. We have also began implementing Requirements 1-4.

Regarding Requirement 1 (*antenna array design and implementation*), we have completed all antenna simulations and have ordered our custom antennas. We plan to begin measurements of our physical antennas immediately after receiving the antennas in the mail. This essential sub-system of our project will lay the foundation for full-system integration. All other requirements and sub-systems depend on this critical design and implementation stage.

Regarding Requirement 2 (*RF PCB design and implementation*), we have completed schematic design and are nearing a point where we can order our custom RF PCB. The RF PCB severs several essential functions, including execution of user commands, powering the system, controlling antenna propagation, and measuring antenna resonance. This requirement is almost done, save for ordering and physical implementation within the broader interdependent system.

Regarding Requirement 3 (*ADC PCB design and implementation*), we have complete schematic design and are nearing a point where we can order our custom ADC PCB. The ADC PCB performs the essential task of translating analog data receiving through the RF antenna array and passing it to the microcontroller where it will eventually be presented to an end user. The ADC PCB is fully designed. Much like the RF PCB, we are merely awaiting ordering, shipment, and physical implementation within the broader overall interdependent system.

Regarding Requirement 4 (*low-level microcontroller programming design and implementation*), we have designed a code shell in the C programming language that provides an outline for the various sub-tasks the microcontroller must perform. We cannot begin implementation until requirements 1 through 3 are complete. This will be the last design and implementation phase we complete, and it will be finished in tandem with Requirement 5 below.

Regarding Requirement 5 (*high-level programming for data processing and user interface display design and implementation*), we have designed a code shell in Python that provides an outline for the user interface display that an operator can use to control our RF antenna array measurement system. We cannot begin until requirements 1 through 3 are complete.

8.2 Conclusion

Project Goals

As detailed at length above, this project involves the design and construction of an imaging array consisting of resonant antennas with radio frequency (RF) circuitry for generation and detection of signals that can provide a visual depiction of hidden structures, objects, or biomedical anomalies. The problem this project will solve is the need to identify objects that cannot be viewed at the surface level of various types of materials.

In summary, we are utilizing the idea implemented in the paper *Array of Planar Resonator Probes for Rapid Near-Field Microwave Imaging* cited in Section 4.1.3 above. However, the novel implementation of our project is to use a mixer and Schottky diode to determine the magnitude with which microwave signals are being reflected back to our antennas. This enables us to modularize the system instead of needing to use a vector network analyzer (VNA) to send and read the microwave signals. This technological substitution avoids costlier design components and will help us realize a reduction in the overall size of our finished product.

Current Progress

The result of our project will be a self-contained product consisting of five sub-systems: (1) RF antenna array, (2) RF PCB, (3) ADC PCB, (4) microcontroller, and (5) user interface display. We have completed the design of all five sub-systems, and we have begun implementation of (1), (2), and (3).

Future Project Milestones

We will eventually complete the implementation of all five primary sub-systems listed above: (1) RF antenna array, (2) RF PCB, (3) ADC PCB, (4) microcontroller, and (5) user interface display. We have not fully completed independent design and implementation of any of the five complex sub-systems, but we are very close to finalizing testing and implementation of sub-systems (1), (2), and (3). Implementation and testing of sub-systems (4) and (5)—microcontroller and UI programming, respectively—are dependent upon satisfactory completion of subsystems (1)-(3)—RF antenna array, RF PCB, and ADC PDB, respectively.

Currently, we are awaiting production and shipment of several custom components detailed in Section 4.6 above. We expect to receive these components within the next month and plan to begin full-system integration early next semester (Spring 2022). Once our system is fully integrated, we will begin testing interdependent sub-system functionality (e.g., ADC PCB to microcontroller data transmission). This will be the second-to-last project phase before we begin final testing of our complete fully integrated RF antenna array measurement system.

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8.4 Appendices

8.4.1 Team Contract

Team Name: SD22-23

Team Members:

1) Justin Pioquinto (Computer Engineering), pioqujus@iastate.edu
2) Denise Orege (Electrical Engineering), daorege@iastate.edu
3) Trent Moritz (Electrical Engineering), tdmoritz@iastate.edu
4) Si Yuan Sim (Electrical Engineering), simsy@iastate.edu
5) Joseph Paffrath (Electrical Engineering), paffrath@iastate.edu
6) Karthik Vempati (Electrical Engineering), vempati@iastate.edu
7) Josh Montgomery (Electrical Engineering), jmonty@iastate.edu

Team Procedures

1. **Day, time, and location (face-to-face or virtual) for regular team meetings:**

- **Mondays @ 10 a.m. on Google Meets** – weekly virtual (Google Meets) progress meetings with Professor/Client Tayeb Al Qaseer
- **Wednesdays @ 9 a.m. on Discord** – weekly virtual (Discord) progress meetings with TA Jacob Betsworth
- **Fridays, Weekends, and As Needed @ Applied Science II Lab** – in-person project design and construction work

2. **Preferred method of communication updates, reminders, issues, and scheduling (e.g., e-mail, phone, app, face-to-face):**

   Our team will meet through three primary mediums: Google Meet (virtual), Discord (virtual), and Face-to-Face. Progress will be reported through virtual meetings while project design and construction will occur in-person at the Applied Sciences II complex. Once the RF antenna and PCB are constructed the remainder of the design and construction will occur remotely and involve programming and testing.

3. **Decision-making policy (e.g., consensus, majority vote):**

   Our team will make decisions by majority vote if disagreements do arise. All team member opinions will be considered fairly and with equal weight—and all team members will be given equal time to speak—prior to votes contested issues.

4. **Procedures for record keeping (i.e., who will keep meeting minutes, how will minutes be shared/archived):**

   As the primary technical writers, Josh and Karthik will keep records of team meeting minutes. These records will be available to all team members through a shared doc drive.

Participation Expectations

1. **Expected individual attendance, punctuality, and participation at all team meetings:**

   Attendance is expected at all team meetings, but team members will be provided significant leniency if conflicting obligations arise. Our team mantra is essentially "all for one, and one for all," and we will do everything we can to ensure that team member schedules are considered. We will prioritize making the necessary accommodations to fully participate. We will operate on a "good faith effort" standard of contribution, attendance, punctuality, and participation.

2. **Expected level of responsibility for fulfilling team assignments, timelines, and deadlines:**

   Team members are expected to meet or exceed the responsibilities delegated to them in a timely manner. Team members are to notify the entire team via Discord message if it is not possible to complete their expected tasks in accord with internal deadlines.

3. **Expected level of communication with other team members:**

   Team communication will occur primarily through Discord, and team members are expected to communicate with one another "multiple" times throughout the week. "Multiple" in this context means a combination of commenting on Discord and attending team meetings. Three communications per week per team member is the desired team standard.

4. **Expected level of commitment to team decisions and tasks:**

   Team members are expected to remain aware of consensus team expectations. All team members are encouraged to weigh in on team decisions. All team members will be assigned to or volunteer for tasks proportional to their availability and skills. Team members are expected to commit as much as they are reasonably able to offer in completing their tasks in a timely fashion while maintaining a healthy work-life balance.

Leadership

1. **Leadership roles for each team member (e.g., team organization, client interaction, individual component design, testing, etc.):**

- **Professor/Client Liaisons** – Trent, Denise, Si Yuan
- **Technical Writing** – Josh, Justin, Karthik
- **Primary Group Coordinators** – Trent, Karthik, Josh
- **RF Antenna Hardware Experts** – Trent, Denise, Si Yuan
- **PCB Hardware Experts** – Joe, Karthik, Josh
- **Programming Leads** – Justin, Karthik, Joe
- **Simulation Software Leads** – Trent, Joe, Si Yuan, Denise, Justin

2. **Strategies for supporting and guiding the work of all team members:**

No team member will be solely responsible for a single essential responsibility. "Essential" in this context means a necessary requirement for completion of the project. This dual or multi-assignment responsibility structure will ensure all team members are supported and guided in completing internal tasks.

3. **Strategies for recognizing the contributions of all team members:**

The team will not prioritize delineating precisely who contributed to precise design aspects. However, the team's design documents will clarify which team members contributed on broader design stages like RF antenna design, measurement and testing, PCB design, simulations, and programming.

Collaboration and Inclusion

1. **Describe the skills, expertise, and unique perspectives each team member brings to the team.**

- ***Justin Pioquinto*** – Justin is a talented and accomplished computer engineering student. Justin will serve as the primary software and programming lead on the team. He will contribute primarily to programming a microcontroller and writing software to transmit, process, and display the data. Furthermore, he will provide supplemental assistance with all hardware related design aspects of the projects. He will also maintain a focus on organizational skills and professional discipline.

- ***Denise Orege*** – Denise has unique work experience related to non-destructive testing and evaluation. She also has an existing relationship with the Professor/Client Tayeb Al Qaseer. Denise will serve as one of three co-primary contacts with our professor/client. Denise will also aid with many of the hardware applications for the project: radio frequency circuitry, resonant antenna design, signal detection, EM analysis software utilization, antenna construction and measurement, design and construction of the PCB, and construction of signal conditioning and acquisition circuitry. She will also maintain a focus on organizational skills and professional discipline.

- ***Trent Moritz*** – Trent is a gifted student with a relentless work ethic. He is passionate about RF antenna software. He also has an existing relationship with the Professor/Client Tayeb Al Qaseer. Trent will serve as the second of three co-primary contacts with our professor/client. Trent will also aid with many of the hardware applications for the project: radio frequency circuitry, resonant antenna design, signal detection, EM analysis software utilization, antenna construction and measurement, design and construction of the PCB, and construction of signal conditioning and acquisition circuitry. He will also maintain a focus on organizational skills and professional discipline.

- ***Si Yuan Sim*** – Si Yuan is a gifted student with a relentless work ethic. He is passionate about RF antenna software. He also has an existing relationship with the Professor/Client Tayeb Al Qaseer. Si Yuan will serve as the third of three co-primary contacts with our professor/client. Si Yuan will also aid with many of the hardware applications for the project: radio frequency circuitry, resonant antenna design, signal detection, EM analysis software utilization, antenna construction and measurement, design and construction of the PCB, and construction of signal conditioning and acquisition circuitry. He will also maintain a focus on organizational skills and professional discipline.

- ***Joseph Paffrath*** – Joe possesses a creative mind and the ability to solve abstract, complex problems. Joe is a capable student and a pleasant teammate. Joe will aid with many of the hardware applications for the project: signal detection, EM analysis software utilization, antenna construction and measurement, design and construction of the PCB, and construction of signal conditioning and acquisition circuitry. He will also maintain a focus on organizational skills and professional discipline.

- ***Karthik Vempati*** **–** Karthik possesses world-class attention to detail and infectious ambition. Karthik also has invaluable industry experience at multiple engineering employers. Karthik will aid with many of both the hardware and software applications for the project. Regarding hardware, Karthik will assist with the following: radio frequency circuitry, resonant antenna design, signal detection, EM analysis software utilization, antenna construction and measurement, design and construction of the PCB, and construction of signal conditioning and acquisition circuitry. Regarding software, Karthik will assist with the following: programming a microcontroller and writing software to transmit, process, and display the data. He will also maintain a focus on organizational skills and professional discipline.

- ***Josh Montgomery*** – Josh is an experienced technical writer and engineering student. Josh will serve as the primary technical writer for the project and will compose the first draft of all design documents. He will also provide supplemental assistance on both the hardware and software aspects of project design. Furthermore, he will coordinate with the leads for both hardware and software design elements while synthesizing the progress from each. He will also maintain a focus on organizational skills and professional discipline.

2. Strategies for encouraging and support contributions and ideas from all team members:

Team members will ensure they are always supportive of one another and the group. When certain members have been less vocal than others for extended periods of time, those members will be politely encouraged to speak up and contribute to decision making and task completion. Differences in personalities will be accepted, accounted for, and embraced.

3. Procedures for identifying and resolving collaboration or inclusion issues (e.g., how will a team member inform the team that the team environment is obstructing their opportunity or ability to contribute?)

Team members will advocate for one another, and concerns about inclusivity and consideration will be treated with paramount importance. Any concerns are always welcome to be voiced, shared, discussed, and resolved. If a team member is uncomfortable bringing a concern to the group at large, they will reach out to their closest team contact who can bring the concern to the group.

Goal Setting, Planning, and Execution

1. **Team goals for this semester:**

- Design and build an incredible device
- Obtain an "A" grade for every team member
- Learn a considerable amount about the exciting multi-faceted project technologies
- Get ahead on the project to reduce the workload next semester
- Collaborate in a friendly and efficient manner

2. **Strategies for planning and assigning individual and team work:**

The team will discuss planning and individual assignments during the weekly client, TA, and team meetings. Tasks will be open for voluntarily contribution first—if tasks are not claimed they will be assigned by majority vote in accordance with scheduling accommodations and individual skills. All members will take a proactive role in task delegation and volunteering.

3. **Strategies for keeping on task:**

Team members appreciate that project progress is co-dependent. As such, certain members reliant on others to complete tasks will help the members remain focused until an essential task is completed. Individually, all team members will strive to complete tasks as soon as it is convenient in the spirit of accomplishing the team goals.

Consequences for Not Adhering to Team Contract

1. **How will you handle infractions of any of the obligations of this team contract?**

The nature of this team is not punitive. Members will not be publicly shamed or outwardly punished. Members will be supportively encouraged to continue to strive to do their best while any members who are struggling to accomplish tasks will be granted a partner member who will help complete the tasks in a mutually beneficial capacity.

2. **What will your team do if the infractions continue?**

The team will press onwards regardless of adversity, and no team member will be left behind. However, team member contributions will be highlighted during internal team meetings and in internal team discussions. It is expected that no team member will be blackballed in peer reviews and that all team members will be given equal weight for the value they contributed at the end of the project.

****

a) *I participated in formulating the standards, roles, and procedures as stated in this contract.*
b) *I understand that I am obligated to abide by these terms and conditions.*
c) *I understand that if I do not abide by these terms and conditions, I will suffer the consequences as stated in this contract.*

#	Signature	Date
1	/s/ Justin Pioquinto	9/13/2021
2	/s/ Denise Orege	9/13/2021
3	/s/ Karthik Vempati	9/13/2021
4	/s/ Josh Montgomery	9/13/2021
5	/s/ Si Yuan Sim	9/13/2021
6	/s/ Joseph Paffrath	9/13/2021
7	/s/ Trent Moritz	9/13/2021