VHF Antenna

ECE4872 Senior Design Project

VHF Antenna Team

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Executive Summary

The Low-Cost VHF Antenna is an antenna designed to be low-cost and low power. It is an antenna operating in the VHF band and will need to be self-deployable as well as be able to be easily integrated into an already existing frequency modulated continuous wave (FMCW) radar system. The antenna should be deployable as a series of fenceposts with little human installation.

The design will consist of an RF circuit and a signal processing component needed to extract relevant features from a received signal. The parameters of the antenna are modeled closely to an ideal imaginary antenna that is able to detect stealthy, low altitude, high speed targets, as per sponsor specification. The system will connect to a device generating the input signal, such as a function generator. The other end of the system will connect to a processing unit that will take in information, such as the target's doppler shift and time delay, which can then be used to calculate the range and speed of a target.

The design and simulation of the prototype will be done through the use of HFSS and MATLAB. Simulations will be run to determine if the parameters chosen for the design will meet the specifications given by the sponsor. Multiple simulations will be run to ensure reliability. This will all be done with an ideal environment; therefore, the actual results may vary from the simulations. This will be considered as further tests are carried out.

The estimated cost for materials for the antenna is estimated to be $276.09. This added with production, testing, packaging, and distribution cost will result in each antenna being sold for $3500.

The expected outcome of this project is a functional prototype and simulations proving the effectiveness of the design. Once the success of the prototype is achieved, the next steps

would be the approval for the actual construction of the VHF Antenna, incorporation into an RF circuit, and deployment in a real environment.

Nomenclature

- FMCW – Frequency Modulated Continuous Wave, a type of radar system
- ADC – Analog-to-Digital Converter, a system that converts an analog signal into a digital signal
- DAC – Digital-to-Analog Converter, a system that converts a digital signal into an analog signal
- HFSS – High Frequency Simulation Software, software used for simulation of antennas
- HPBW – Half Power Beamwidth, width of major lobe of an antenna with at least half power
- IEEE - Institute of Electrical and Electronics Engineers, the world's largest technical professional organization dedicated to advancing technology for the benefit of humanity
- I_{DD} – Symbol for supply current
-
- LNA – Low-Noise Amplifier, amplifier that amplifies signal without decreasing SNR
- NTIA – National Telecommunications and Information Administration, the Executive Branch agency that is principally responsible for advising the President on telecommunications and information policy issues

- Q-factor – Quality factor,
- RCS – Radar Cross-Section, measure of how large an object is to a radar
- RX – Received signal
- TX – Transmitted signal
- V_{DD} – Symbol for Voltage Drain Drain, indicates positive voltage
- VHF – Very High Frequency, a frequency band from 30 – 300 MHz
- S_{11} – The ratio of the voltage of signal reflected by the antenna to the voltage of the original signal sent to the antenna; It is often measured in dB as return loss (RL).

VHF Antenna

1. Introduction

The VHF Antenna team designed a low-cost antenna operating in the VHF band to be used as part of a frequency modulated continuous wave radar system. The team requested $400 of funding to develop a prototype for the designed low-cost VHF antenna.

1.1. Objective

The team designed and created a fabrication plan for a low-cost, low power antenna operating in the VHF band. This antenna will be incorporated into a radar system to detect objects with low radar cross-sections. As part of this project, the team selected an appropriate frequency within the VHF band, researched and decided on a particular antenna configuration, simulated the candidate designs, and determined the detectability of a target using the radar range equation.

1.2. Motivation

With the advancements in stealth technology, it has become increasingly difficult to detect and track objects with low radar cross-sections. Stealth aircraft absorb radar signals and reflect signals away from the source to reduce their cross-sections. These objects are optimized to avoid detection from radars using high frequencies around the X and Ku bands. However, if the frequency of the radar is decreased to a level where the wavelength becomes comparable to the size of the target, the effects of resonance take shape. Due to the larger values of the wavelength, the radiation-absorbent material surrounding a target is not as effective against the lower frequency causing the target to induce a larger return signal allowing for more effective detection.

1.3. **Background**

By selecting a frequency whose wavelength is approximately twice the size of the targets of interest, the team can design an antenna to take advantage of resonance and detect objects that would prove to be difficult at typical radar frequencies. For this project, the targets have radar cross-sections of around $1m^2$. The VHF band in the radio spectrum has wavelengths ranging from 1m to 10m, providing a desirable range of values for resonance.

Regardless of their type, implementation, and design, antennas consume energy and transmit it as a three-dimensional wave. This characteristic, which is common to all antennas, can be represented in the form of a radiation pattern. Radiation patterns include several auxiliary energy parameters, such as antenna gain and directivity. This, in turn determines the type of the antenna: omnidirectional, low directional or highly directional.

The other key characteristics which determine an antenna's design are directivity and gain. Although both of these values serve to describe similar concepts, and could be derived from the same principles, it is necessary to distinguish between them. Directivity measures the degree to which the radiation emitted is concentrated in a single direction (power density). While it does not consider losses presented in a system, the value which characterizes the directional properties of the antenna and takes into account its losses is called the gain. These dependences and concepts are further described in the "Design Approach" section of this document.

2. Project Description, Customer Requirements, and Goals

The goal of this project is to design a low-cost VHF antenna for radar applications. It should be capable of detecting fast, low altitude targets by transmitting an electromagnetic wave and then receiving the signal after it is reflected off the target. The antenna should be capable of detecting the range and speed of the target. It is intended to space these antennas on a collection of fence posts that are spaced a certain distance apart for coverage of a large area. The antennas should be easily installable in these fence posts. Additional components for the radar system will be incorporated as needed for the amplification and processing of the transmitted and received signals.

The design considerations were based on the requirements of the stakeholders (customers). The stakeholders are graphically displayed in the stakeholder chart in Figure 1 and the stakeholders are described in Table 1.

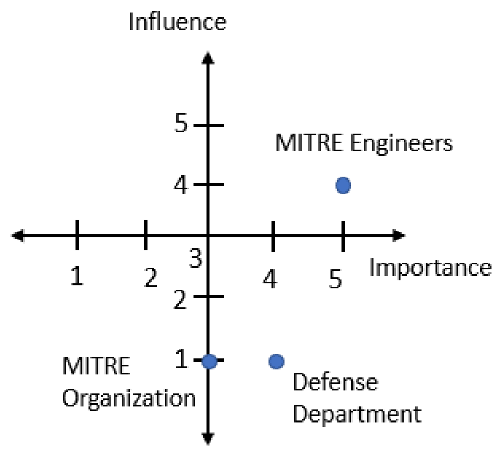


Figure 1. Stakeholder chart: Describes the importance and influence of the major stakeholders of the project.

Table 1. Stakeholders

Stakeholder	Interests	Impact/Effect	Importance	Influence
MITRE Engineers	Integrate low-cost VHF antenna design into radar fence posts	Will produce a new design option	5	4
MITRE Organization	Innovative technology in federally funded projects	Will increase value of the MITRE organization	3	1
Defense Department	Detect stealthy objects using antenna	Highly effective and less expensive radar detection capability	4	1

The MITRE engineers are the most important stakeholders; they created the project description and will determine whether the product meets the requirements of their application. They also have quantified several requirements in the project description such as the expected temperature range, the transmit power, and the expected radar cross section. The MITRE organization is another stakeholder because the completion of this project will support the mission of the organization. Finally, the Department of Defense is another stakeholder because this project will produce a low-cost VHF antenna for radar fence posts, thus improving the cost efficiency of their defense technology.

Figure 2 shows the Quality Function Deployment (QFD), which relates customer requirements to engineering requirements. The customer requirements were either directly stated or implied in the project description. For example, one requirement directly stated was that the antenna should operate with low power. Another requirement that was implied was the that the antenna should be accurate i.e. it can determine the range and speed of the antenna with minimal error.

The engineering requirements were chosen to address the customer requirements with quantifiable values that could in turn be used to determine suitable antenna parameters. For example, the qualitative *durability*, *long-range,* and *low-cost* requirements were quantified using the engineering requirements of *temperature resistance, transmit power*, and *cost*.

Column #	1	2	3	4	5	6	7	8	9
Direction of Improvement	▼	▼	▲	◇	◇	◇	◇	▼	▼
Customer Requirements (Explicit and Implicit) / Engineering Requirements	Cost	Transmit Power	Temperature Resistance	Target Cross Section	Target Speed	Target Altitude	Frequency of Operation	Target Location Error	Time to Learn Installation Process
Detectability	○	●		●	●	●	●	▽	
Durability	●		●						
Low Maintainance	○		○						
No Interference		○						○	
Easily Installable									●
Long Range	○	●		●	●	●	●	●	
Accurate	●	○		●	●	○	○	●	
Low Cost	●	●	○		●	●	▽	●	
Low Power	○	●				●		●	
Target	$1000-10000	.01-1 W	-63 to 50°C	0.001 m^2	400 m/s	200 to 10,000m	30 to 300 MHz	max(1%, 30 m)	10 min

Relationships		Direction of Improvement	
Strong	●	Maximize	▲
Moderate	○	Target	◇
Weak	▽	Minimize	▼

Figure 2. Quality Function Deployment (QFD) – displays the qualitative customer requirements and the quantified engineering requirements.

The target value for one engineering requirements was chosen based on a related standard. It was decided that the *target location error* should be less than 1% or 30 m, whichever is greater, based on the International Maritime Organization (IMO) radar standards [1]. Other target values, such as the transmit power, were directly given by the sponsor as 0.01 – 1W.

The antenna is also subject to several constraints that are listed in Table 2. These constraints are limits that must be followed in the design of the antenna.

Table 2. Constraints.

Constraint	Value	Justification	Source
Temperature Range	-63^0C to 50^0C	Must be able to endure locations with extreme climates	Sponsor
Operational Frequency	>30 MHz and <300 MHz	Antenna must operate in the VHF range	Sponsor
Cost	<$10,000	Antenna must be low-cost	Sponsor
Transmitted Signal Waveform	Continuous Wave	Eliminate Blind Spots	Sponsor
Transmitted Power	0.01 – 1 W	Low power means low energy cost	Sponsor

The functional analysis was developed based on the customer requirements and is shown in Figure 3. The block diagram essentially shows what the system must do. It will receive a modulated signal, will transmit the signal, receive the reflected signal, and return information about the target range and speed. The engineering requirements quantity how well the system should do it. For example, the system should be capable of determining the range and speed of the target with an error less than 1% or 30 m, whichever is greater.

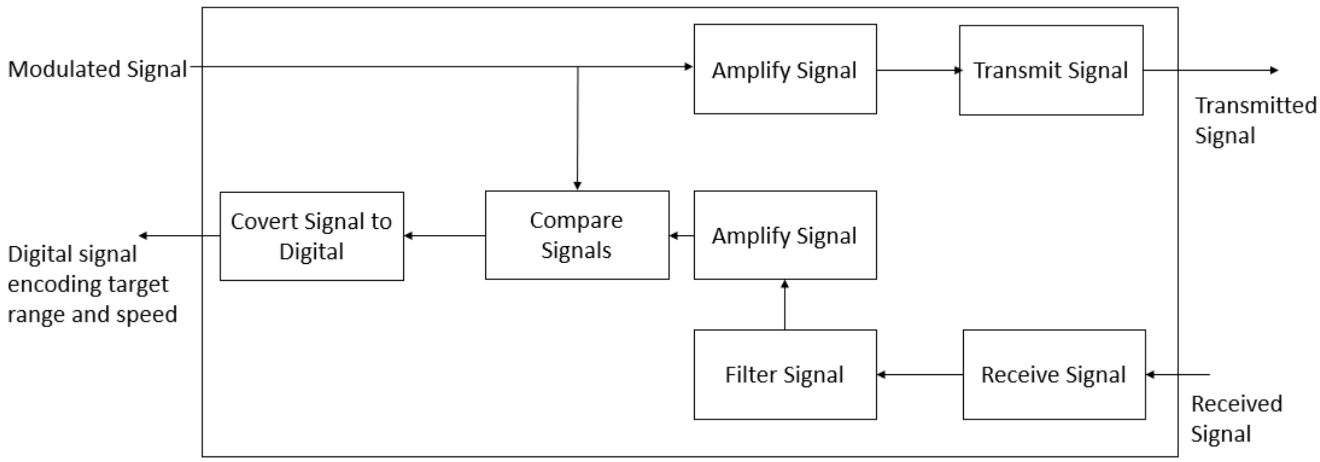


Figure 3. Functional Analysis: Shows the input and outputs of the system that will be designed as well as the key subsystems.

3. Technical Specifications

The sponsor has provided two sets of parameters for the antenna system. Table 3 contains information regarding the system's antenna properties.

Table 3. Antenna Specifications

Antenna Parameters	Specification
Transmit Power	0.01 – 1 W
Operating Frequency	30 – 300 MHz
Input Impedance	50 Ω
Operating Temperatures	-63 – 50 °C
Cost	$1,000 – $10,000

Table 4 contains information regarding the types of targets the antenna should be able to identify when used as part of a radar system.

Table 4. Target Specifications

Target Parameters	Specification
Radar Cross-Section	0.01 – 1 m^2
Altitude	200 – 10,000 m
Speed	400 m/s

Furthermore, there are several qualitative features that the antenna should adhere to.

Qualitative Specifications:

- Narrow-band
- Simple Deployment
- Low Maintenance
- Maximize Range

4. Design Approach and Details

The design approach outlined in Figure 4 begins by outlining a set of ideal parameters for an antenna before conducting research through reading literature and identifying existing antennas. This is then followed by multiple iterations of design and simulation.

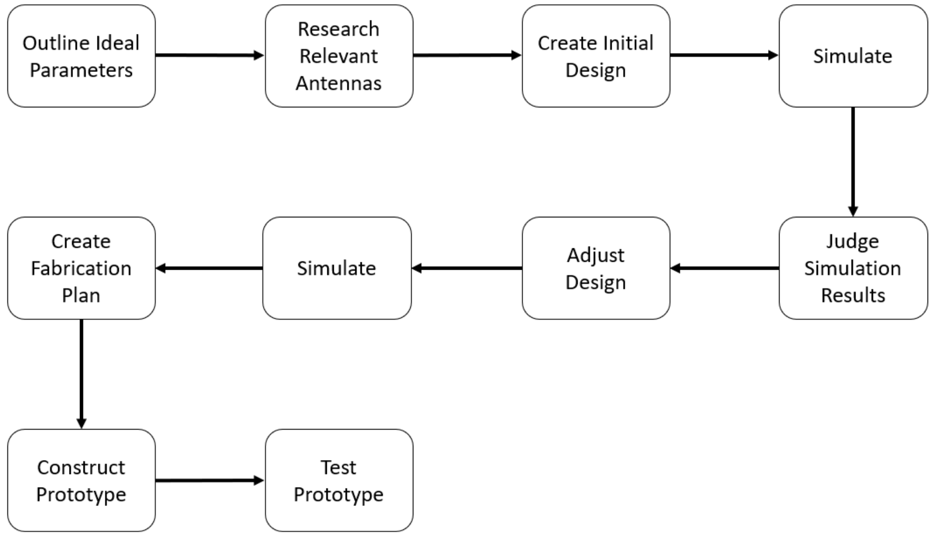


Figure 4. Summary of Design Approach

4.1 Design Concept Ideation, Constraints, Alternatives, and Tradeoffs

The primary function of the antenna is to identify fast-moving objects with low radar cross-sections with a narrow-band antenna operating in the VHF band. The VHF antenna consists of two subsystems: a radiating antenna and an amplification circuit that processes the received signal from the antenna.

Antenna

The antenna will sit near the ground, positioned so that targets fly near the antenna's zenith. This means it must have a radiation pattern allowing it to transmit and receive signals from objects as they fly while also avoiding any ground scatter from obstructions such as trees.

Half Power Beamwidth

The width of the antenna's beam dictates how adjacent systems can be placed to each other while being able to reliably identify target's flying at the minimum height. The smaller the beamwidth, the lower the elevation angle, and the more closely packed together the systems need to be. By increasing the beamwidth, the number of antennas required to cover a given perimeter decreases. However, an increase in beamwidth also sees the introduction of ground scatter from objects like trees.

Bandwidth

As the antenna is required to be narrowband, a smaller bandwidth is preferred. However, because the antenna will be utilized as a frequency modulated continuous wave radar, there needs to be room for the antenna to transmit and receive waves with varied frequencies in order to make calculations of distance and speed based on the shifts in frequencies.

Gain

The gain of the antenna will be decided by the value of the half power beamwidth. The narrower the antenna's beam, the higher the gain. However, the efficiency should be as high as possible so that the realized gain is as close as possible to the directivity. To do so, conductive, dielectric, and reflective losses need to be minimized.

Input Impedance

To further maximize the efficiency of the antenna, the input impedance needs to be matched to that of the transmission line it is connected to. By designing the antenna to be 50Ω, it will "match" the majority of standard transmission lines and reduce reflections.

RF Circuit

The RF circuit connects the end of the transmission line to a processing unit. The RF circuit has a low-noise amplifier that increases the low signal voltage received by the antenna to one that is digestible by a computer or microcontroller. The circuit needs to amplify the signal while also minimizing the noise that appears from various sources.

Signal Processing

In order to extract a target's relative velocity and range from the antenna, some signal processing needs to take place to extract data such as the doppler shift of the returned signal. To compare the received (RX) signal to the transmitted (TX) signal, a mixer is required. Furthermore, because a single antenna is used as a monostatic radar, there needs to be an isolation between the TX and RX signals which is achieved by utilizing a ferrite circulator that acts as a duplexer that separates the two. Once the RX signal has been isolated, it, along with the input signal, are fed to a mixer to extract their difference. The mixed signal is used to determine the target time delay and doppler shift which then determine target range and velocity respectively.

Computing and Hardware Integration

The antenna needs to be installed with little human interaction and be low maintenance. This means that the antenna should be designed to physically and electrically connect to the radar system with a minimal number of connections and be easily assimilated to the system.

For simulation and analysis of the antenna, HFSS and MATLAB are used to determine the effectiveness of the antenna in detecting a target.

4.2 Final Concept Selection and Justification

The team outlined an ideal set of specifications for the design of the antenna.

4.2.1 Resonant Frequency

First came the decision of choosing a resonant frequency. Knowing that the antenna had to operate within the VHF band, consulting the NTIA’s frequency allocation chart and located three resonant frequencies at 50 – 54 MHz, 146 – 148 MHz, and 222 – 225 MHz. The lower the resonant frequency, the higher the ratio between power received and power transmitted, however, the physical size of the antenna will also increase. Due to this, the group opted for a frequency towards the upper end of the VHF spectrum at 224 MHz.

4.2.2 Radiation Pattern

For the radiation pattern, the team needed an antenna that could perceive the vast majority of the sky above it. This meant that it needed to concentrate signals in the upper hemisphere. However, this comes with the caveat that the antenna should ignore any obstructions from objects such as trees. The ideal radiation pattern would be similar to cos(θ), where θ is the elevation angle.

4.2.3 Half Power Beamwidth

Similar to the reasoning for radiation pattern, the half power beamwidth needs to cover a large part of the sky while ignoring objects on or protruding from the ground. By assuming a separation distance of 3km and a minimum target height of 200m, the HPBW is approximately 165°.

$$HPBW = 180 - 2 \cdot \tan^{-1} \frac{h_{min}}{\frac{d_S}{2}} = 180 - 2 \cdot \tan^{-1}\left(\frac{200}{1500}\right) = 165° \qquad (1)$$

4.2.4 Bandwidth

The project requirement calls for a narrowband radar. However, the antenna's bandwidth also needs to accommodate shifted waves based on doppler shifts and frequency modulation from range. The bandwidth of the antenna can be decided by the desired distance resolution [2].

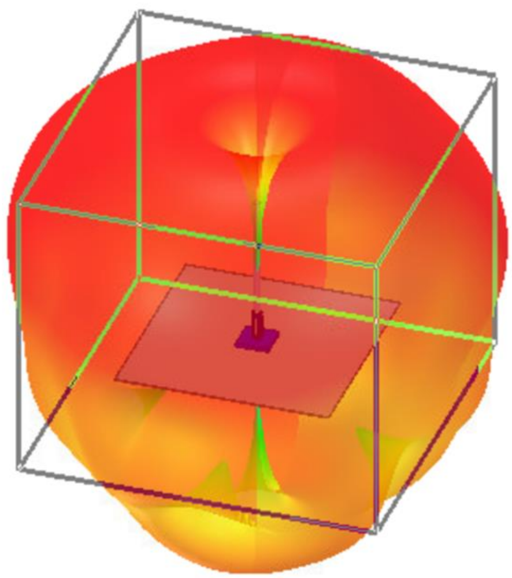
$$BW = \frac{c}{2 \cdot d_{res}} = \frac{3 \cdot 10^8 m/s}{2 \cdot 300m} = 500kHz \qquad (2)$$

For an antenna with a range of 3km, a bandwidth of 500kHz is ideal. A bandwidth of 500kHz, which can be applied through the bandpass filter on the RF circuit, results in a resolution of 300m. This allows for potentially ten distinct ranges across a 3km range.

4.2.5 Material

For a low-cost antenna with low maintenance, a cheap sturdy material is desired. Aluminum is a great option because it is very conductive, lightweight, and cheap relative to other options such as copper and silver. Aluminum also comes with benefits of having a very wide temperature resistance, in which the required operating temperature fits very comfortably in.

Figure 5 shows the antenna model and 3-D radiation plot obtained from an HFSS simulation. For the simulation, the ground plane and monopole rod geometries and materials were set to the desired values shown in Table 5. Additionally, the brace was accounted for in the simulation using a representative geometry and dielectric constant of 10% infill PLA as $\epsilon_{PLA,10\%}$= 1.19 ($\epsilon_{PLA,100\%} = 2.9$) [3]. Then the far-field radiation pattern at the resonant frequency (224 MHz) were obtained. Next, the S_{11} parameter was calculated by stepping through frequencies between 150 to 300 MHz. It was desired that the magnitude of the S_{11} parameter was minimized at the resonant frequency.



3D Gain Plot superimposed over Antenna Model

Figure 5. HFSS simulation 3-D radiation pattern

Table 5. Antenna Design Parameters

Parameter	**Specification**	
3/4 Wave Monopole	(λ)	(mm)
Rod Length	0.726	959
Rod Diameter	0.015	20
Ground Plane Side Length	0.91	1220
Ground Plane Thickness	0.0075	1
Rod Material	Aluminum-6061	
Ground Material	Aluminum-6061	
Brace Material	PLA	

The simulation results of the radiation pattern are shown in Figure 6. In the elevation plane, although the gain dips at 0^0 (pointing straight up), the gain rapidly rises above 0 dB within 15^0. The gain remains above 0 dB until about 78^0 from the zenith. This means that a single antenna has roughly 126^0 of visibility in the elevation plate (after removing the blind spot around 0^0). The 3-D representation of the radiation pattern shown in Figure 5 can be seen to match the 2-D polar plots. As seen in the image, the gain is high throughout a range of angles in the upper hemisphere, except for the blind spot at the zenith.

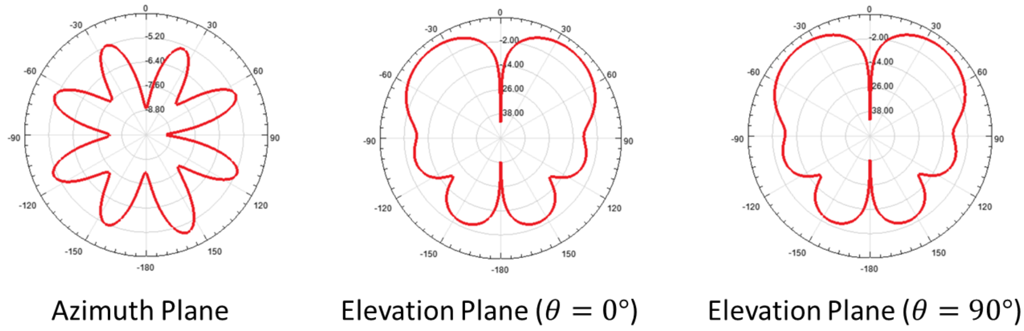


Figure 6. Simulated 3D Radiation Pattern for 3/4 wave monopole.

Table 6 summarizes the comparison of key parameters between the ideal and designed antenna. The gain is only slightly less than the ideal gain. The HPBW of the design is relatively close to the desired value but it should be noted that there is also a blind spot at the zenith. Additionally, the S_{11} exceeds the expectations of the desired value. The side lobe level is 7 dB above the desired level but is still reasonably low.

Table 6. Summary of Ideal and Designed Antenna Specifications

Antenna Parameters	**Designed Specification**	**Ideal Specification**
Gain	6 dB	8 dB
HPBW	156°	160°
S_{11}	-22.8 dB	-20 dB
SLL	-13 dB	-20 dB
Resonant Frequency	222.7 MHz	224 MHz
Bandwidth (-10 dB)	27.3 MHz	500 kHz

Input Impedance	56 – 4.8j Ω	50 Ω
Material	Aluminum-6061	Aluminum-6061
Operating Temperatures	-63 – 50 °C	-

Table 7. Summary of Amplifier Circuit Specifications

Amplifier Circuit Parameters	**Specification**
Minimum Detectable Signal	10^{-14} W
Noise Floor	$2 \cdot 10^{-15}$ W
SNR_{dB}	17 dB
V_{DD}	5 V
I_{DD}	53 mA

Figure 7 shows the RF circuit. The RF circuit is important because it takes input from the processing unit to generate and amplify a frequency modulated signal that can be transmitted by the antenna. It also amplifies the received signal and compares it to the transmitted signal to produce a signal that encodes the range and speed of the target. This received signal is converted to digital so that it can be processed by the CPU.

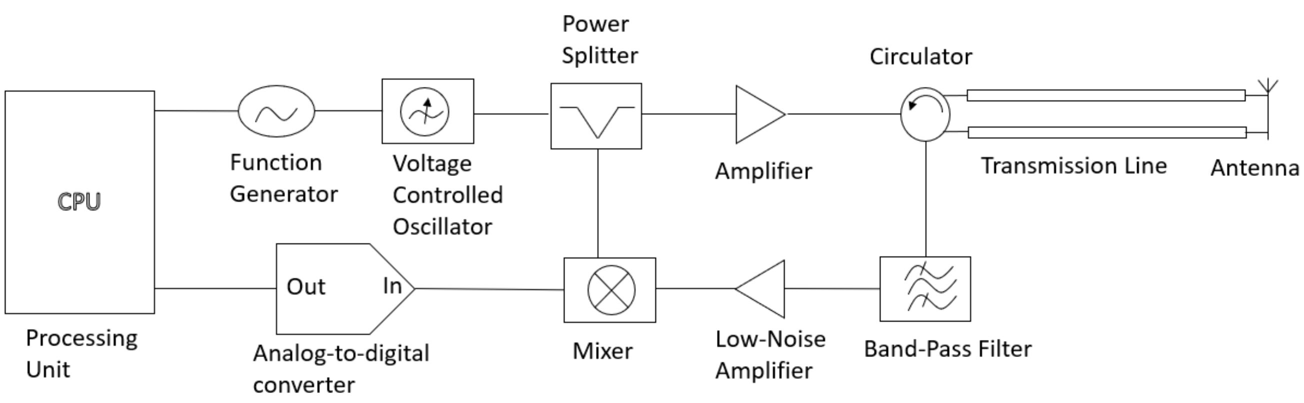


Figure 7. RF circuit for generation, modulation, amplification, transmission, reception, filtering, and conversion of signal.

Table 8 describes the components of the RF circuit.

Table 8. Components of RF Circuit

Component Name	Function
Processing Unit	Sends commands to the function generator to produce a signal. Also takes digital received signal and uses it to compute target range and speed.
Function Generator	Generates analog signal based on input from processing unit.
Voltage Controlled Oscillator (VCO)	Modulates the signal produced by the function generator.
Power Splitter	Half of the power of the input signal is extracted for comparison with the output signal.
Amplifier	Amplifies the generated signal for transmission.
Circulator	Element that outputs the received signal from the antenna to a different port from where the transmitted signal is an input, thus separating the input signal from the output signal.
Transmission Line	Serves to carry the transmitted signal from the RF circuit to the antenna and to carry the received signal from the antenna to the RF circuit. It must be matched to the antenna (50 Ω).
Band-Pass Filter	Selects the frequency of operation from the received signal to eliminate noise at other frequencies.
Low-Noise Amplifier	Amplifies the received signal without adding significant noise to it.
Mixer	Subtracts the transmitted signal from received signal to generate a new signal that encodes the target's range and speed.
Analog to Digital Converter	Converts analog signal to digital signal for further processing.

Table 9. Maximum Detection Range as a function of Radar Cross Section

Radar Cross Section (m^2)	Max Range (m)
1	3400
0.1	1911
0.01	1074

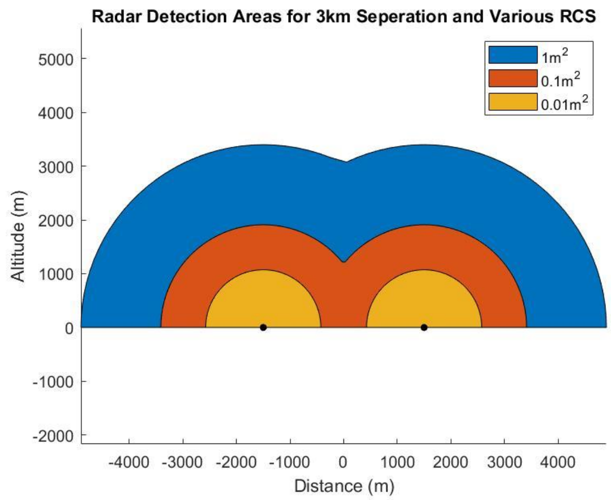


Figure 8. Detection regions for a pair or radars separated by 3km

By putting together the simulations of the antenna and the RF circuit, the team was able to determine the radar system's maximum range for various RCS. The team found that with a RCS of $1m^2$, the radar could detect systems as far away as 3.4km and discern the signal from the noise level.

4.3 Codes and Standards

Allocation of the Radio Spectrum by the National Telecommunications and Information Administration (NTIA). The allocation data influenced the team's design by limiting the operation frequencies of the antenna. The antenna needs to avoid interference, but also not inflict its own interference on other systems [4].

The input impedance of an antenna is typically 50Ω and transmissions line are built with that assumption. To maximize the antenna's radiated power and reduce mismatch losses, the antenna's input impedance should closely match 50Ω [5].

IEEE C95.1-2019 standard provide limits for the maximum electric and magnetic field. These limits are derived from potential health effects of human exposure to EM fields. The standards list exposure reference levels (ERLs) to avoid these effects. The IEEE defines two ERLS, one for persons permitted in restricted environments and a second for those in unrestricted environments [6].

IEEE 149-1977 provides test procedures for the measurement of antenna properties. This standard will guide the testing and measurement for radiation pattern, gain, antenna impedance, and power draw [7].

Cypress AN91445 describes various aspects of the antenna design and its RF layout. The guidelines include application notes on antenna-tuning procedure, antenna geometry, RF trace, power supply decoupling, PCB stackup, and choice of RF passive components [8].

4.4 Design Constraints

4.4.1 Radiation Resistance

One of the key parameters affecting antenna size constraints is radiation resistance, which is part of feed point resistance caused by electromagnetic waves. In order to achieve maximum efficiency, the antenna load value must be as close as possible to its radiation resistance [9]. As the dimensions of the antenna decrease, its radiation resistance decreases too. Such decrease leads to the increased difficulty of matching antenna with the rest of the system, from which it follows that the resistance of the antenna conductors must be reduced in proportion to the square of the length of the antenna. Small antennas made of thin wires would not be able to achieve high efficiency, while the use of thick conductors would result in losses due to the skin effect.

4.4.2 Overvoltage, Overcurrent and Q-Factor

The quality factor of a small antenna is inversely proportional to the volume occupied by its magnetoquasistatic field. The Q factor cannot be reduced by varying the design of the antenna, since in any case, with decreasing dimensions, the active radiation resistance decreases very quickly in relation to the reactive one [10].

At the same time a decrease in the size of the antenna leads to an increase in the field strength near it; according to the minimum estimate, the field strength is inversely proportional to the size of the antenna. Since fields are generated by voltages and currents, overvoltage and overcurrent are inevitable in small antennas [10].

5. Project Demonstration

Once the final design is completed and approved by the team, a fabrication plan was created. The final prototype is shown in Figure 9.

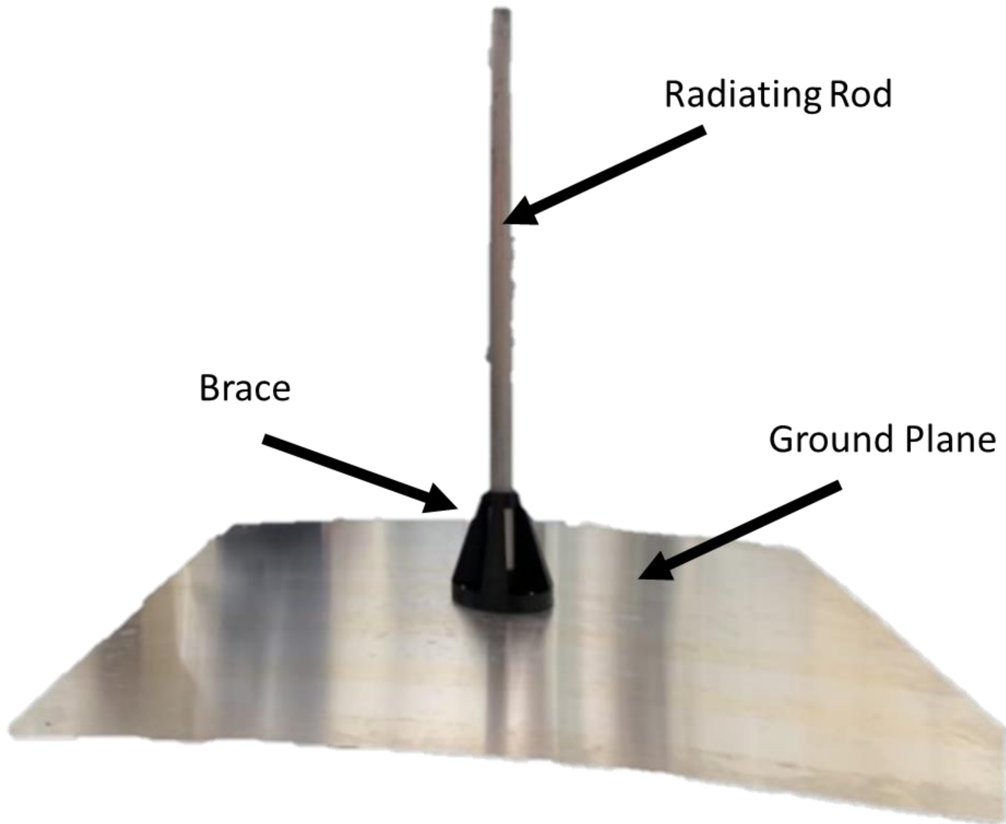


Figure 9. Final antenna prototype consisting of aluminum rod, aluminum ground plane, PLA brace, and SO239 (not shown).

In order to verify that design meets its requirements, a number of tests should be performed on the prototype. First, S_{11} testing was performed using a network analyzer. A low S_{11} at the resonant frequency would demonstrate that the antenna was radiating its energy rather than reflecting it. The setup of the test is shown in Figure 10.

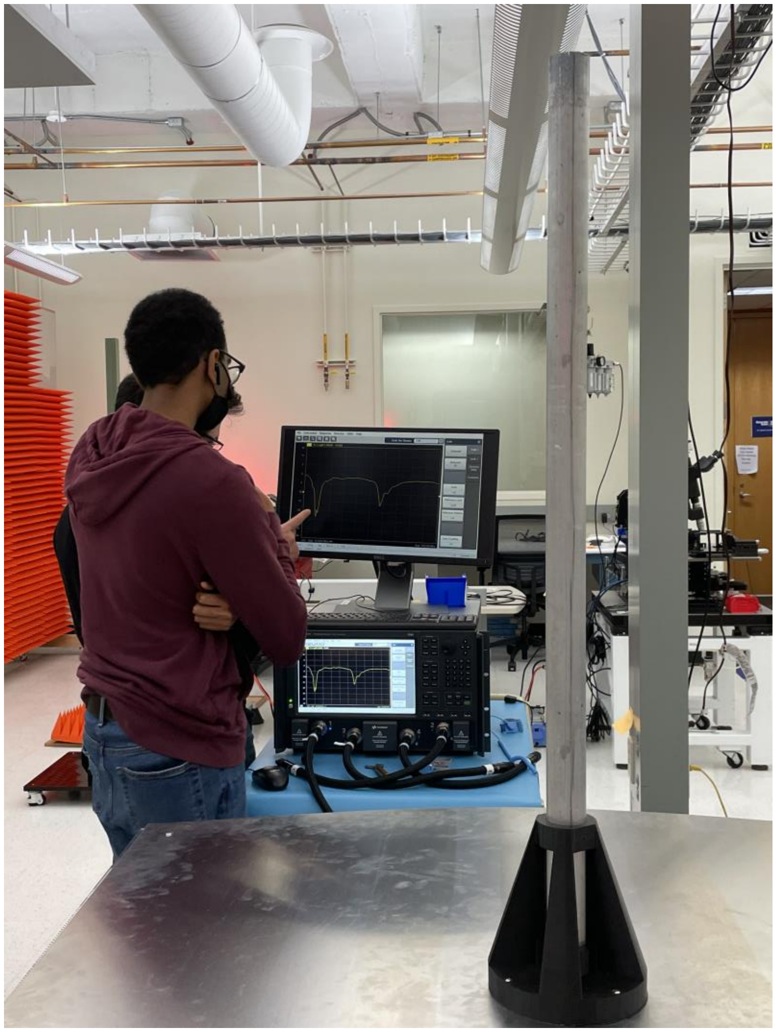


Figure 10. S_{11} testing being performed on antenna using a network analyzer.

The results of the Network Analyzer test produced the results shown in Figure 11. The first experiment, shown in red, had an S_{11} of -18.8 dB, the second experiment, shown in blue had an S_{11} of -31.9 dB, while the simulation, shown in yellow, had an S_{11} of -22.8 dB. In the first experiment, a wire soldered to the SO239 was inserted into a hole at the base of the monopole rod to create an electrical connection. However, this led to poor results for the S_{11}, likely because the soldered wire acted as an inductor. The wire was removed, improving the return loss but also shifting the resonant frequency to the left due to the increase in height of the monopole. Overall, the results show that the antenna is an efficient radiator.

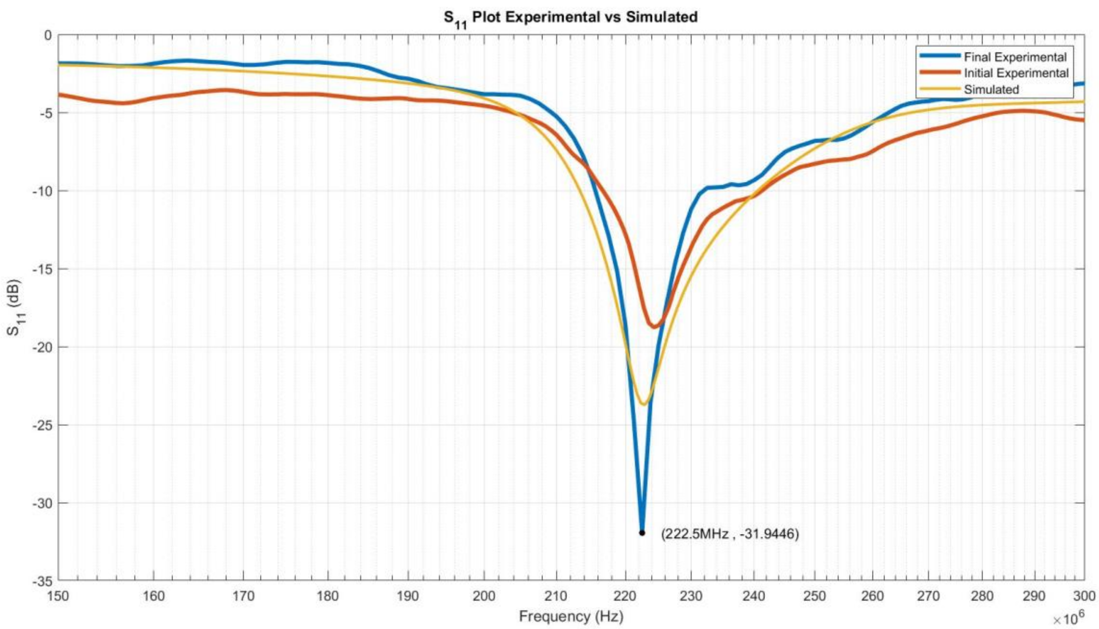


Figure 11. Results of S_{11} test performed using network analyzer.

The radiation pattern can be found by measuring the electric field when the antenna is placed in an anechoic chamber, which is shown in Figure 12. These facilities are provided by certain companies such as Northrop Grumman. Since access to these facilities difficult and expensive to obtain, radiation pattern testing was not performed for this project.

Figure 12. Anechoic chamber – used for antenna property measurements including radiation pattern and contours, gain, and side lobe level. [11]

6. Schedule, Tasks, and Milestones

All tasks in the project fall under one of six categories: documentation, design, simulation, fabrication, website, and the expo. Mohammed is in charge of documentation, and he is the team's design lead. Seidi is the team's simulation leader. Michael is the team's fabrication lead. Sanket is the team's expo coordinator. Lastly, Kenneth is in charge of website responsibilities.

Appendix A contains the Gantt chart for the team's schedule in the Fall of 2021. Appendix B is a Gantt chart of the team's schedule and tasks for the Spring of 2022 semester. Appendix C contains the Pert Chart which contains all the team's tasks for the full duration of the project.

The tasks with the greatest degree of difficulty are the design and simulation tasks. Based on the team's estimates for task durations and using project management tools, the calculated probability of finishing the project one week before the GT Capstone Expo was 93.03%.

7. Marketing and Cost Analysis

7.1 Marketing Analysis

VHF antennas are commonly used for FM radio broadcast, two-way land mobile radio systems, long-range data communication, and marine communications [12]. However, there are not many commercially available VHF antennas for radar use. Radars generally use a frequency range between 400 MHz to 36 GHz while the VHF antennas range between 30 MHz to 300 MHz [12,13]. The main market target for the Low-Cost VHF Antenna will be companies, like MITRE, that specialize in national defense. The Low-Cost VHF Antenna is not expected to be sold commercially, but rather through a contract with the Federal Government or similar companies to MITRE. The market demand for these VHF Antennas is not high, but each transaction is expected to sell several hundred antennas, depending on the size of the perimeter being covered. The Low-Cost VHF Antenna is designed to cover 3 kilometers each. This is a great alternative to using a single giant radar system that covers a much larger area.

7.2 Cost Analysis

The total material cost for a prototype of the VHF Antenna is approximately $276.09 as of April 2022. This will differ every month due to fluctuations in the price of the materials. Just the price of aluminum has risen by 36.66% from December 2020 to November 2021 [14]. Table 10 shows the breakdown of material cost for individual items per prototype.

Table 10. Total Material Costs

Product Description	Model/Supplier	Unit Cost	Count	Category	Cost
Aluminum-6061 Rod	Grainger	$ 78.20	0.5	Antenna	$ 39.10
Aluminum-6061 Base Plate	Grainger	$ 80.96	1	Antenna	$ 80.96
Polycarbonate Base Plate	McMaster-Carr	$ 145.88	1	Antenna	$ 145.88
SO-239	American Radio Supply	$ 2.98	1	Antenna	$ 2.98
PLA Brace	GT Invention Studio	$ 3.23	1	Antenna	$ 3.23
#6 Machine Screws	Home Depot	$ 0.25	8	Antenna	$ 2.00
#6 Nuts	Home Depot	$ 0.11	8	Antenna	$ 0.85
#4 Machine Screws and Nuts	Home Depot	$ 0.13	4	Antenna	$ 0.51
Nylon Washer	Home Depot	$ 0.58	1	Antenna	$ 0.58
Antenna Subtotal					**$ 276.09**
LNA	SKY67159-396LF	$ 4.38	2	Circuit	$ 8.76
Mixer	CSM2-10	$ 72.70	1	Circuit	$ 72.70
Power Splitter	VSP-2402	$ 6.23	1	Circuit	$ 6.23
Circulator	AM400-500CIR133	$ 455.00	1	Circuit	$ 455.00
Bandpass Filter	RBP-220+	$ 20.17	1	Circuit	$ 20.17
Circuit Subtotal					**$ 562.86**
Grand Total					**$ 838.95**

Table 10 shows the breakdown of the non-recurring costs for the initial prototype of the VHF Antenna. The cost is based on $70,000 yearly salary for the engineers and $50,000 yearly salary for the non-engineers, and includes licenses needed for testing. The total non-recurring cost is estimated to be approximately $172,631.67.

Table 11. Non-Recurring Costs

	Employees	**Number**	**Salary/year**	**Months**	**Cost**
Research	Engineers	5	$70,000	4	$116,666.67
MATLAB License	-	-	-	-	$215.00
HFSS License	-	-	-	-	$750.00
Production	Engineers	2	$70,000	1	$11,666.67
Production	Non-Engineers	2	$50,000	1	$8,333.33
Packaging	Non-Engineer	1	$50,000	1	$4,166.67
Marketing	Non-Engineer	1	$50,000	3	$12,500.00
Sales	Non-Engineer	1	$50,000	2	$8,333.33
Distribution	Non-Engineer	1	$50,000	1	$4,166.67
Support	Engineer	1	$70,000	1	$5,833.33
Total Non-Recurring Cost					**$172,631.67**

The total number of units sold over a 5-year period is estimated to be 3400 units in total. This estimation was made by dividing the total Atlantic coastline by the area covered by each VHF Antenna. The Atlantic Coastline is estimated to be 2069 miles or approximately 3330 kilometers [15]. The VHF Antenna is designed to cover an area of 3 kilometers. This would mean that approximately 1110 VHF Antennas will be needed to cover the entire Atlantic Coastline. However, realistically, it is not expected for the sales to be above 1000 units annually.

Appendix D shows the breakdown of annual costs, annual profits, number of units sold annually, and the total profit made over the 5-year period. The total non-recurring cost has an overhead of 200% and is adjusted to a per unit price of $152.63. Testing of the antenna is set to be approximately $800 per antenna, with one out of ten being tested at random. With the adjusted non-recurring cost plus the cost for the test, as well as the cost for producing, packaging, marketing, distribution, sales, and support, the unit price per antenna is set to be $3500.

The 5-year total profit is expected to be $3,192,419.50 with a total profit per unit of $938.95. If the overhead is maintained at 150% for the annual recurring costs and the units sold match the predictions in Appendix A, the percent total profit per unit is approximately 26.83%.

8. Conclusion

The VHF antenna team has completed the design, fabrication, and testing stages of the project. The design was a ¾ λ monopole with a radiation pattern, gain, resonant frequency, and other parameters suitable for the antenna’s requirements. Simulation was performed using HFSS to validate the design. The antenna was fabricated by purchasing and assembling the necessary parts. The testing on the S_{11} using a network analyzer shows that the prototype is able to closely match the results of the simulation. The team has completed 100% of the work required for the project and has presented it at the Capstone Expo.

9. Leadership Roles

Leadership Role	Responsibilities	Member
Documentation Coordinator	Maintain and ensure proper submission of documents Keep track of deadlines Communication with advisor and sponsors	MD
Design Team Lead	Determine ideal parameters for design Scope area of interest Delegate design literature to members	MD
Webmaster	Create “big picture” idea Decide on purpose and layout Delegate website tasks to members	KH
Simulation Team Lead	Overseeing simulation of design using software tools Judge efficacy of simulation based on parameter values Delegate simulation portions	SK
Fabrication Team Lead	Creation of fabrication plan Ordering and inventory of parts Overseeing and leading construction of prototype Delegate construction tasks to members	SL
Expo Coordinator	Outline necessary steps and components for expo Create timeline and roadmap for successful expo Ensure deadlines and steps are met Delegate expo tasks to members	SS

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Appendix A – Project Gantt Chart Fall 2021

See next page for Fall 2021 Gantt Chart

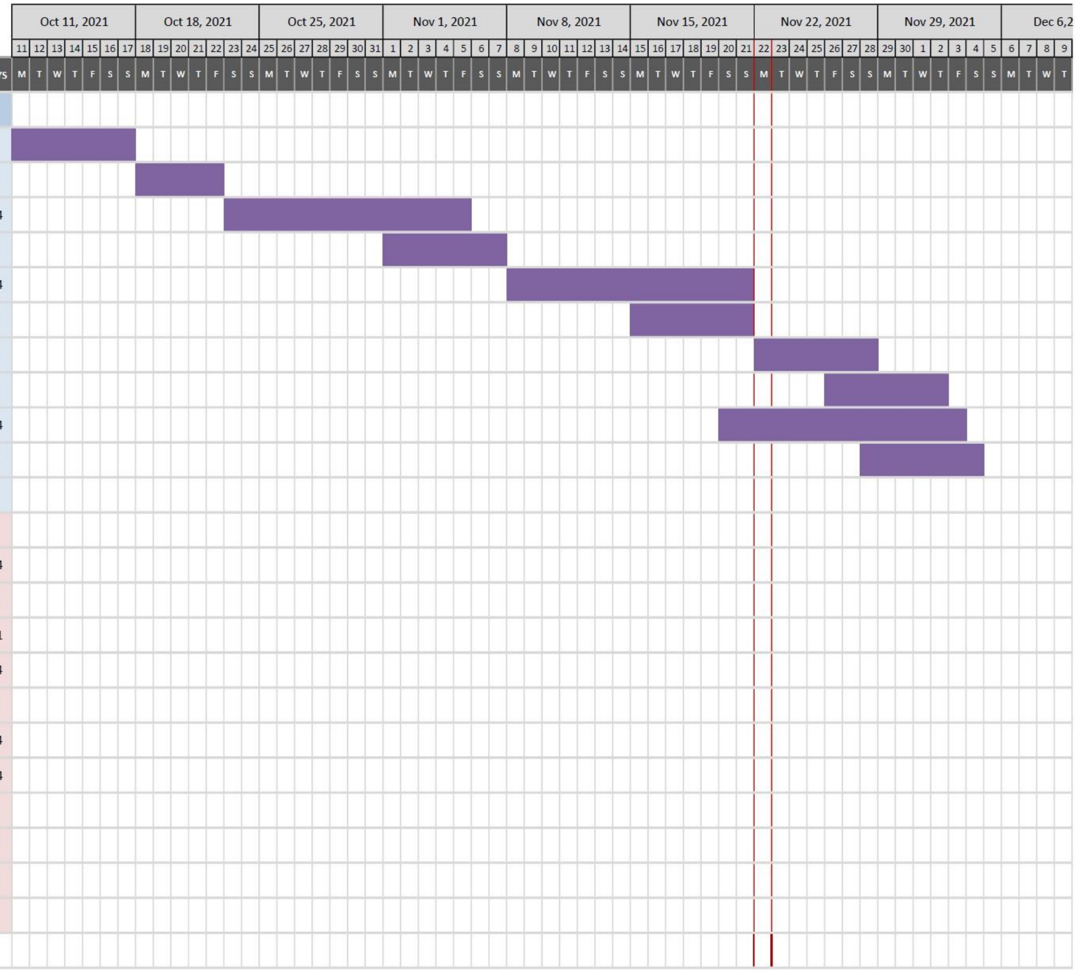
Low Cost VHF Antenna

ECE 4871 Special Topics
Mohammed Deafalla, Kenneth Holder, Seidi Kartal, Seunghwan Lee, Sanket Sane

Project Start: Mon, 10/11/2021

Display Week: 1

TASK	ASSIGNED Time in Weeks	PROGRESS	START	END	DAYS
Fall 2021 Semester					
Establish Baseline Antenna Propertie:	1	0%	10/11/21	10/17/21	7
Draft Project Summary	1	0%	10/18/21	10/22/21	5
Familizarization with Design Tool	2	0%	10/23/21	11/5/21	14
First Design	1	0%	11/1/21	11/7/21	7
First Simulation	2	0%	11/8/21	11/21/21	14
Project Proposal	1	0%	11/15/21	11/21/21	7
Second Design	0.5	0%	11/22/21	11/28/21	7
Second Simulation	1	0%	11/26/21	12/2/21	7
Create Fabrication Plan	2	0%	11/20/21	12/3/21	14
Order Parts	1	0%	11/28/21	12/4/21	7
Spring 2022 Semester					
Shipping Parts	2	0%	1/10/22	1/23/22	14
Oral Project Presentation	1	0%	1/10/22	1/16/22	7
Assemble Parts	3	0%	1/17/22	2/6/22	21
Antenna Testing 1	2	0%	2/7/22	2/20/22	14
Test Feedback	1	0%	2/21/22	2/27/22	7
Antenna Testing 2	2	0%	2/28/22	3/13/22	14
Senior Design Expo Preparation	2	0%	3/14/22	3/27/22	14
Website	1	0%	3/28/22	4/3/22	7
Expo	1	0%	4/22/22	4/28/22	7
Final Project Summary	1	0%	4/29/21	5/5/21	7



Appendix B – Project Gantt Chart Spring 2022

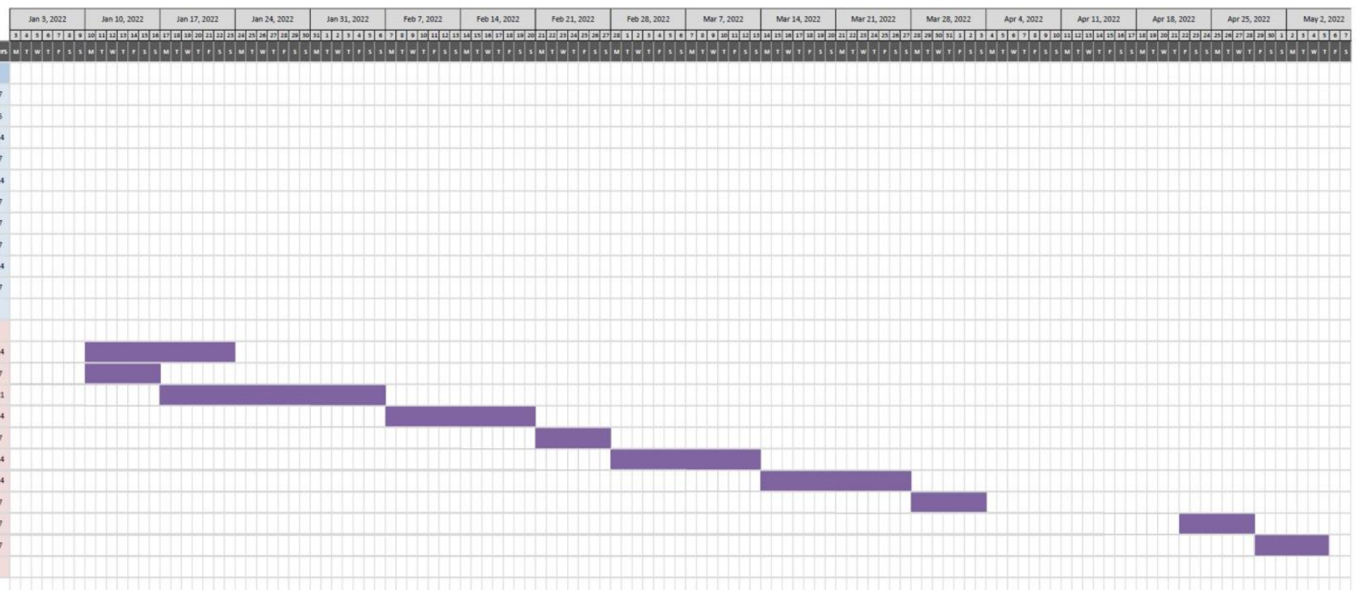
See next page for Spring 2022 Gantt Chart

Low Cost VHF Antenna

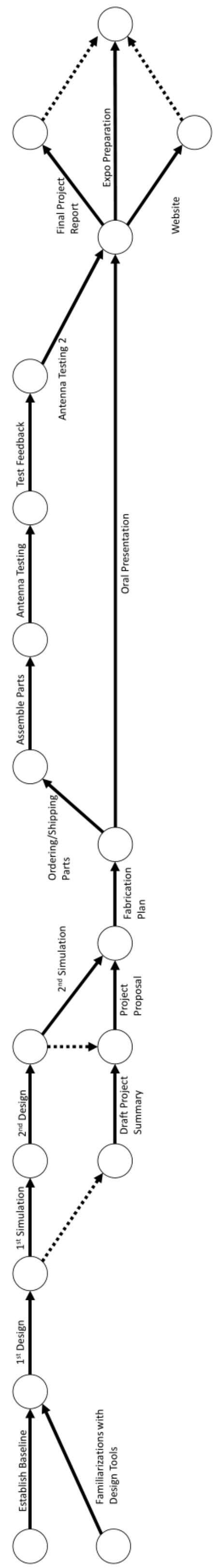
ECE 4871 Special Topics
Mohammed Deafalla, Kenneth Holder, Seidi Kartal, Seunghwan Lee, Sanket Sane

Project Start: Mon, 10/11/2021
Display Week: 1

TASK	ASSIGNED Time in Weeks	PROGRESS	START	END	DAYS
Fall 2021 Semester					
Establish Baseline Antenna Propertie	1	0%	10/11/21	10/17/21	7
Draft Project Summary	1	0%	10/18/21	10/22/21	5
Familizarization with Design Tool	2	0%	10/23/21	11/5/21	14
First Design	1	0%	11/1/21	11/7/21	7
First Simulation	2	0%	11/8/21	11/21/21	14
Project Proposal	1	0%	11/15/21	11/21/21	7
Second Design	0.5	0%	11/22/21	11/28/21	7
Second Simulation	1	0%	11/26/21	12/2/21	7
Create Fabrication Plan	2	0%	11/20/21	12/3/21	14
Order Parts	1	0%	11/28/21	12/4/21	7
Spring 2022 Semester					
Shipping Parts	2	0%	1/10/22	1/23/22	14
Oral Project Presentation	1	0%	1/10/22	1/16/22	7
Assemble Parts	3	0%	1/17/22	2/6/22	21
Antenna Testing 1	2	0%	2/7/22	2/20/22	14
Test Feedback	1	0%	2/21/22	2/27/22	7
Antenna Testing 2	2	0%	2/28/22	3/13/22	14
Senior Design Expo Preparation	2	0%	3/14/22	3/27/22	14
Website	1	0%	3/28/22	4/3/22	7
Expo	1	0%	4/22/22	4/28/22	7
Final Project Summary	1	0%	4/29/21	5/5/21	7



Appendix C – Project Pert Chart



Appendix D – Cost Analysis

Non-Recurring Cost		
Total Non-Recost		$ 172,984.07
Overhead %	**200%**	$ 345,968.13
Adjusted Non-Recurring		$ 152.63
Total Units Sold		3400

Recurring Costs	Year 1		Year 2		Year 3		Year 4		Year 5	
Sales Volume	500		700		1000		800		400	
Unit Price	$ 3,500.00		$ 3,500.00		$ 3,500.00		$ 3,500.00		$ 3,500.00	
Sales Revenue		$ 1,750,000.00		$ 2,450,000.00		$ 3,500,000.00		$ 2,800,000.00		$ 1,400,000.00
Non-Recurring Cost	$ 152.63	$ 76,316.50	$ 152.63	$ 106,843.10	$ 152.63	$ 152,633.00	$ 152.63	$ 122,106.40	$ 152.63	$ 61,053.20
1. Research and development										
Redesign		$ 10,000.00		$ 10,000.00		$ 10,000.00		$ 10,000.00		$ 10,000.00
Engr Change Order		$ 10,000.00		$ 10,000.00		$ 10,000.00		$ 10,000.00		$ 10,000.00
Testing	$ 800.00	$ 4,000.00	$ 800.00	$ 5,600.00	$ 800.00	$ 8,000.00	$ 800.00	$ 6,400.00	$ 800.00	$ 3,200.00
2. Production										
Aluminium	$ 99.00	$ 49,500.00	$ 99.00	$ 69,300.00	$ 99.00	$ 99,000.00	$ 99.00	$ 79,200.00	$ 99.00	$ 39,600.00
Transmission Line	$ 60.00	$ 30,000.00	$ 60.00	$ 42,000.00	$ 60.00	$ 60,000.00	$ 60.00	$ 48,000.00	$ 60.00	$ 24,000.00
Mount	$ 20.00	$ 10,000.00	$ 20.00	$ 14,000.00	$ 20.00	$ 20,000.00	$ 20.00	$ 16,000.00	$ 20.00	$ 8,000.00
DAC	$ 2.40	$ 1,200.00	$ 2.40	$ 1,680.00	$ 2.40	$ 2,400.00	$ 2.40	$ 1,920.00	$ 5.25	$ 2,100.00
ADC	$ 4.00	$ 2,000.00	$ 4.00	$ 2,800.00	$ 4.00	$ 4,000.00	$ 4.00	$ 3,200.00	$ 9.95	$ 3,980.00
Mixer	$ 10.00	$ 5,000.00	$ 10.00	$ 7,000.00	$ 10.00	$ 10,000.00	$ 10.00	$ 8,000.00	$ 20.00	$ 8,000.00
LNA	$ 7.00	$ 3,500.00	$ 7.00	$ 4,900.00	$ 7.00	$ 7,000.00	$ 7.00	$ 5,600.00	$ 10.00	$ 4,000.00
Ferrite Circulator	$ 150.00	$ 75,000.00	$ 150.00	$ 105,000.00	$ 150.00	$ 150,000.00	$ 150.00	$ 120,000.00	$ 150.00	$ 60,000.00
Assembly	$ 100.00	$ 50,000.00	$ 100.00	$ 70,000.00	$ 100.00	$ 100,000.00	$ 100.00	$ 80,000.00	$ 100.00	$ 40,000.00
3. Package										
Labor		$ 50,000.00		$ 70,000.00		$ 100,000.00		$ 80,000.00		$ 40,000.00
4. Marketing										
1 Non-Engineer		$ 50,000.00		$ 50,000.00		$ 50,000.00		$ 50,000.00		$ 50,000.00
5. Sales										
1 Non-Engineer		$ 50,000.00		$ 50,000.00		$ 50,000.00		$ 50,000.00		$ 50,000.00
6. Distribution										
1 Non-Engineer		$ 50,000.00		$ 50,000.00		$ 50,000.00		$ 50,000.00		$ 50,000.00
7. Support										
1 Non-Engineer		$ 40,000.00		$ 40,000.00		$ 40,000.00		$ 40,000.00		$ 40,000.00
Total Cost/Year		$ 566,516.50		$ 709,123.10		$ 923,033.00		$ 780,426.40		$ 503,933.20
Overhead	150%	$ 849,774.75		$ 1,063,684.65		$ 1,384,549.50		$ 1,170,639.60		$ 755,899.80
Adjusted Cost		$ 1,416,291.25		$ 1,772,807.75		$ 2,307,582.50		$ 1,951,066.00		$ 1,259,833.00
Cost/Unit		$ 2,832.58		$ 2,532.58		$ 2,307.58		$ 2,438.83		$ 3,149.58
Total Profit/Year		$ 333,708.75		$ 677,192.25		$ 1,192,417.50		$ 848,934.00		$ 140,167.00
Annual Profit/Unit		$ 667.42		$ 967.42		$ 1,192.42		$ 1,061.17		$ 350.42
Percent Annual Profit/Unit		19%		28%		34%		30%		10%
Total Profit		**$ 3,192,419.50**								
Total Profit/Unit		**$ 938.95**								
Percent Total Profit/Unit		**26.83%**								