The Design and Implementation of a FMCW Radar System

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Contents

1 Executive Summary

This technical report discusses the design, implementation, testing, and function of our FMCW radar system. The task at hand is to design a system that could accurately measure the distance between the radar system and a target ranging from 5-50 meters away. The success of the system operation is dependent on the overall weight, power consumption, and accuracy in measurement. The proposed radar system [1] at the beginning of Quarter 2 is realized in this report; we detail how the initial proposal evolved into the final product and evaluate its performance.

2 Problem Definition

2.1 Problem Scope

The accuracy of the human eye to accurately measure the distance of an object at a distance is limited to an extremely short range. In addition, our ability to give such heuristic guesses varies greatly depending on the environmental conditions such as rain, snow, or darkness. As an improvement and replacement to trained observers, a realizable system to detect objects at long distances with reasonable accuracy would enable the development of many new technologies.

2.2 Technical Review

The applications for being able to determine the accurate distance and speed of an object are many. Although the primary driving force of detection systems, such as radar, has been military in the past century, detection systems can eventually be applied to assisting the visually impaired, enabling autonomous vehicles, and assist in factory production lines among other uses. Such a system will be able to give accurate and precise information on objects that are both incredibly far away and extremely close by much faster than any human could.

Radar systems are one form of detection system that use electromagnetic waves to determine the range, position, speed, and direction of both fixed and moving objects [2]. Without it, many common applications today would not be possible. Aside from delivering speeding tickets, radar systems are essential to ensuring safe operation in applications such as air traffic control, air defense systems and missile defense systems.
Radar systems operate by generating electromagnetic waves to transmit over a distance. When the transmitted wave collides with an object, there will be a reflection that is picked up by the radar system's receiver. After some analysis is performed, it is possible to extract information about the object that was struck by the wave.

There are two classifications of solitary system radars: pulsed and continuous wave [3]. Pulsed radars are typically used in long range applications. They send out short high power, high frequency pulses from their antenna and then wait and listen for the reflection. This type of radar utilizes both the travel time delay and the frequency Doppler shift to determine the range and velocity of distant objects. Continuous wave radars, the second classification type and the one we will be using for our system, are more often used for closer ranged applications. A continuous wave system will emit a range of high frequency signals and analyze the time delay of the returning signal. Unmodulated continuous wave radars may measure velocity using the Doppler effect, but the signal must be frequency modulated in order to detect distance. The main advantage of having a continuous wave system is its signal continuity, the constant transmitting and receiving allow for a continuous stream of information about the object(s) being detected — much more useful for short to mid range detections where objects more often do not move in predictable patterns. Disadvantages compared to pulsed wave systems include more power consumption due to more up-time and greater space requirements due to having two antennas rather than one.

Radar may have been invented as early as the 19th century but much of its large advancements can be tracked to around WWII. Initially, such systems were large and cumbersome, using large parabolic dishes and reflectors and drawing huge amounts of power in order to detect smaller objects at longer distances. However, the miniaturization of many other technologies has increased the importance of a small, low power detection system. Because it is effective in many conditions and can detect most objects, radar was an obvious choice. Such systems have been and are being developed with emphases on power efficiency and lower weight and size — examples include Echodyne's recent drone radar system and can range as far back as a patented radar glasses system for the blind filed in 1968[1].

2.3 Design Requirements

Our design requirements revolve around a final competition held at the end of the quarter. Our system will be tasked with tracking a person holding a small metal reflector as they walk closer and stop at specific distances. The target will be a 0.3 x 0.3 m^2 corner reflector held about 5 feet high. Our system will be mounted on a tripod and will be provided with a single positive and negative voltage from a power supply. The maximum and minimum distances that we are measuring for are 50 meters and 5 meters.

The final rating is based upon the following equation:

$$Score = P_{dc} W \sum_{1}^{N} \left(\frac{|L_i^{`} - L_i|}{L_i} \right)$$

where P_{dc} is the total power consumption of your radar, W is the total weight of your radar, L_i‘ is the measured distance to the i_{th} target, L_i is the actual distance to the i_{th} target, and N is the total number of targets.

The following requirements are given:

- Dual sided DC power source up to 15V

[1] US3383682 A

- No batteries on the radar unit
- Energy harvesting from ambient sources is not allowed
- Any commercially available technology can be used
- Internal circuity inspection must be possible
- No external signal sources
- Radar must operate at room temperature

Therefore, our main design goals were to minimize power consumption, system weight, and maximize range. Additionally, we strove to minimize the size of our system and make it easy to operate. Our budget is limited to $300, and the output voltage swing out of the radar must be able to output to a standard laptop sound card during data processing.

3 Design Description

The main driver behind our design is the design requirement of accurately measuring the distance between our radar an object 5-50m away. The calculated maximum path loss for an object 50m away determines the minimum requirements for our transmit and receive system.

$$\text{Path Loss} = \frac{\lambda^2 \sigma}{(4\pi)^3 R^4} \approx 119 \text{ dB at 50m, 2.4GHz}$$

$$\text{Thermal Noise Floor} = \text{kTB} + \text{NF}_{R_x} = \text{-161} + 1 + \frac{6}{24} + \frac{NF_{bbamp,audio,computer}}{24} \approx \text{ -155 dB}$$

Although we have a calculated NF of 155 dB, we know that the baseband amplifier (which we cannot accurately calculate the NF of) and the audio cable will contribute largely to the NF of the overall system. Therefore, we establish a minimum signal reception goal of -90 dBm at the RX antenna. Anything lower than that we will consider noise. Due to a maximum path loss of 120 dB, we design our system to transmit 1W, or 30 dBm, and receive between -50 to -90 dBm depending on the location of the target object.

Given the weight constraints, the proposed system design is designed on PCBs and custom planar antennas will be fabricated. The custom antennas will cut down on weight and cost, but will also allow for designing a wide operating frequency range of 2.2-2.6 GHz to improve resolution.

3.1 Overview

Our system generates a 25 Hz triangle wave signal that is FM modulated to transmit a continuous RF signal spanning the frequency band 2.2 GHz to 2.6 GHz. The transmitted signal will travel radially outward from a transmit antenna, reflect off an object and return to separate receive antenna. The received signal will be amplified and down mixed to roughly 15 kHz where it will be sampled and processed for analysis. The signal processing component compares the receive signal with a simultaneous clock signal to determine the duration of travel. From the time and frequency of the signal, the distance of the object away from the system is calculated. A general diagram of the system is provided below.

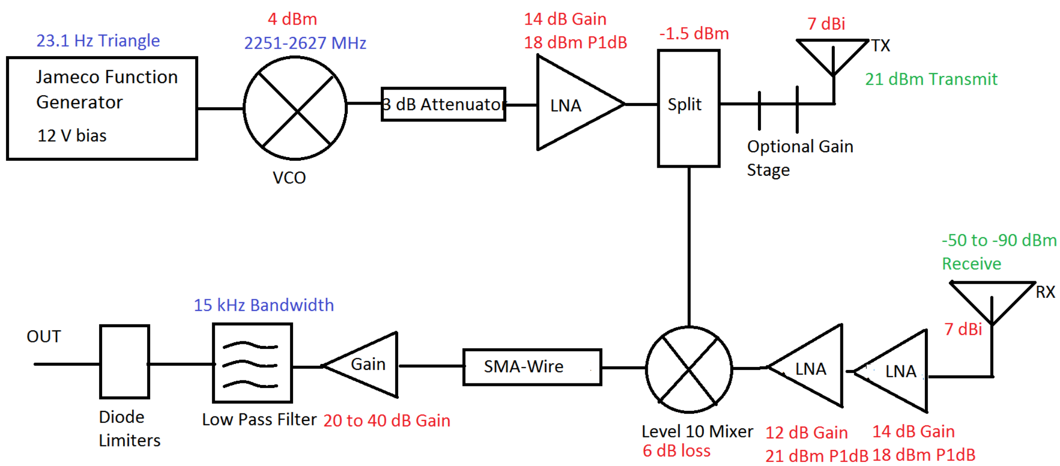

Figure 1: System Level Diagram of FMCW Radar

3.2 Design Overview

Transmit Path:
From the System Level image in Figure 1, we designed to have 6 stages in our transmit path: the generated signal from the Jameco, VCO, 3 dB attenuator, an LNA, the power splitter, and finally the transmit antenna. A description of each component used is given below.

- Jameco XR-2206: Monolithic Function Generator.
  The Jameco will be biased at ± 12V to send out a 23.1 Hz triangle wave linear sweeping 4.5-9 V into the VCO. The function generator has low distortion and excellent temperature stability.

- Crystek CVC055BE: Voltage Controlled Oscillator
  The voltage controlled oscillator is rated for 2.27 to 3.18 GHz controlled with a voltage between 1 and 20 Volts. The outputted signal power is about 4 dBm. For our project we are controlling it from 4.5to 9 Volts and getting frequency range of 2.25-2.62.

- VAT-3+: Mini-Circuits 3 dB Attenuator.
  The 50 Ohm matched attenuator is placed after the VCO to minimize any possible reflections back into the oscillator, and pushing the subsequent amplification stages into compression.

- ZX60-272LN-S+: Mini-Circuits Low Noise Amplifier.
  At our center band of 2.4 GHz, the LNA has a noise figure of 0.74, 18 dBm P_{1dB} and 14 dB gain.

- ZX10-2-42-S+: Mini-Circuits 2 way Power Splitter
  This power splitter operates at 1900 to 4200 MHz, creates an even power split and has a 50 ohm match at each port. It has a total loss of about 3 dB from each port.

Transmit Path

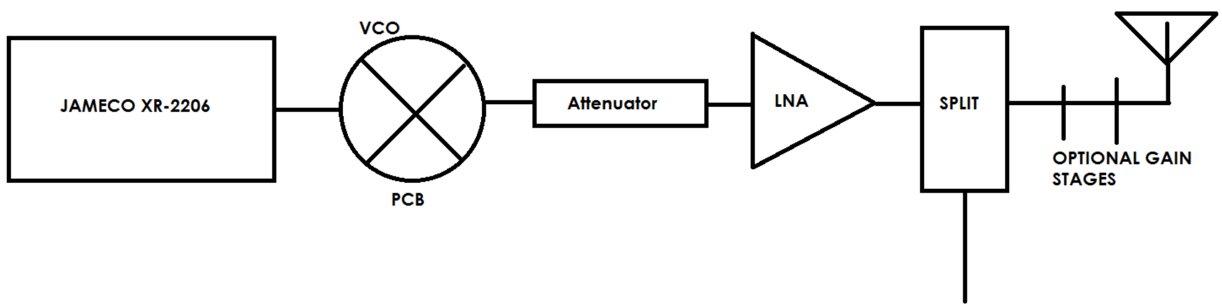

Figure 2: Transmit Path

Antenna Design:
We designed our planar vivaldi antennas using ANSYS HFSS with the a resonant frequency of 2.4 GHz, 7 dBi gain, 20% fractional bandwidth, and at least -15dB insertion loss. We decided to design our own antennas due to the strong skill set of the team, cost savings, and custom manufacturing availabilities. The final antenna design for the transmit antenna is given below.

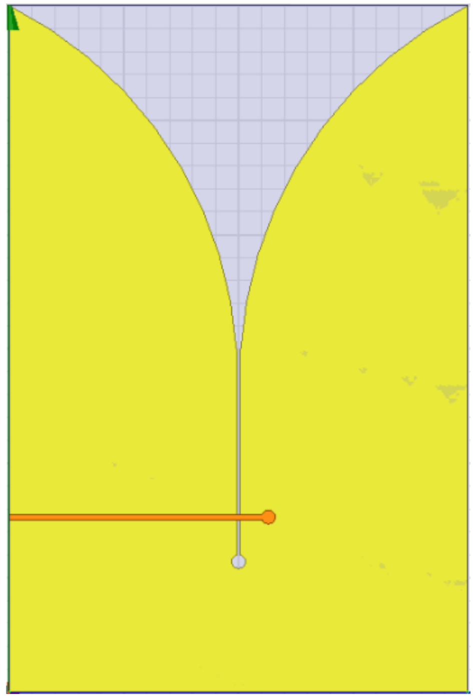

Figure 3: Vivaldi Antenna Design in HFSS

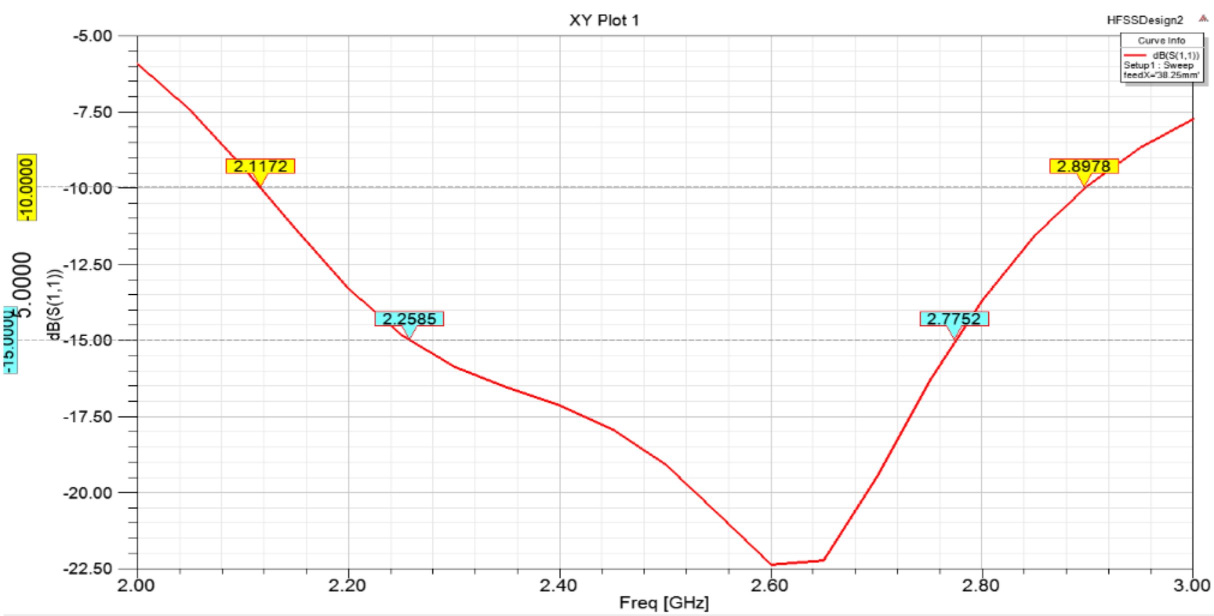

Figure 4: Vivaldi Antenna Simulated S11 in HFSS

The receive antenna will be the coffee can from Quarter 1. In testing, it was found that for longer range applications, using the coffee can for the receive antenna yields better results.

Receive Path:
From the System Level image in Figure 1, we designed to have 6 stages in our transmit path: a two-section gain stage, the mixer, a third order filter, a second two-stage gain stage, and finally a diode limiting stage to control the voltage swing. After we noticed some undesired distortion coming from our third order filter, we replaced it with a first order filter just to make sure we had a working system by competition day.

- HMC639ST89: Analog Devices Low Noise Amplifier.
  At our center band of 2.4 GHz, the LNA has a noise figure of 2.3, 21 dBm P_{1dB} and 12 dB gain.
- ZX60-272LN-S+: Mini-Circuits Low Noise Amplifier.
  At our center band of 2.4 GHz, the LNA has a noise figure of 0.74, 18 dBm P_{1dB} and 14 dB gain.
- ZX05-43MH-S+: Mini-Circuits Level 10 Mixer
  The level 10 mixer has excellent isolation and about a 6 dB conversion loss factor.
- Custom Design: SMA-to-Wire Adapter
  A SMA cable was cut open and soldered to two jumper wires for signal and ground for a custom SMA-to-Wire adapter.
- Custom Design: Quad Op Amp low pass filter and tunable gain stage.
  One set gain stage of 20 dB and another tunable gain stage of up to 20 dB. Initially, third-order filter designed for cutoff frequency of 20 kHz. Later on, first order filter with cutoff frequency of 15 kHz.
- Custom Design: Diode Limiters
  Two 0.7V forward voltage drop diodes placed in anti-parallel. Limits voltage output to a 0.7 to -0.7 volt swing to protect audio card.

Receive Path

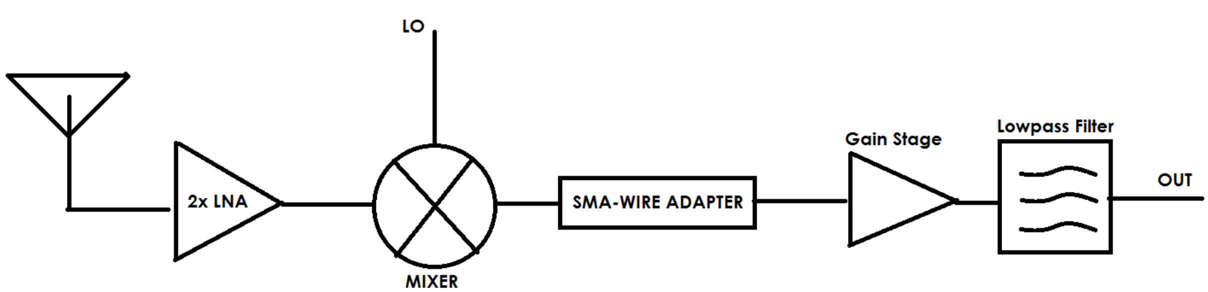

Figure 5: Receive Path

PCB Design
Our initial PCB design tried to combine all of the circuits into a single board. Ultimately,

it was too ambitious for our first design and did not include enough redundant paths and test points to isolate issues. Our second and final PCB design emphasized modularity and testability by separating each RF component into its own board and including many test points. A major secondary goal for both designs was to minimize size; to that end, our components were all packed as tightly as possible while maintaining adequate clearance and clear paths for our traces.

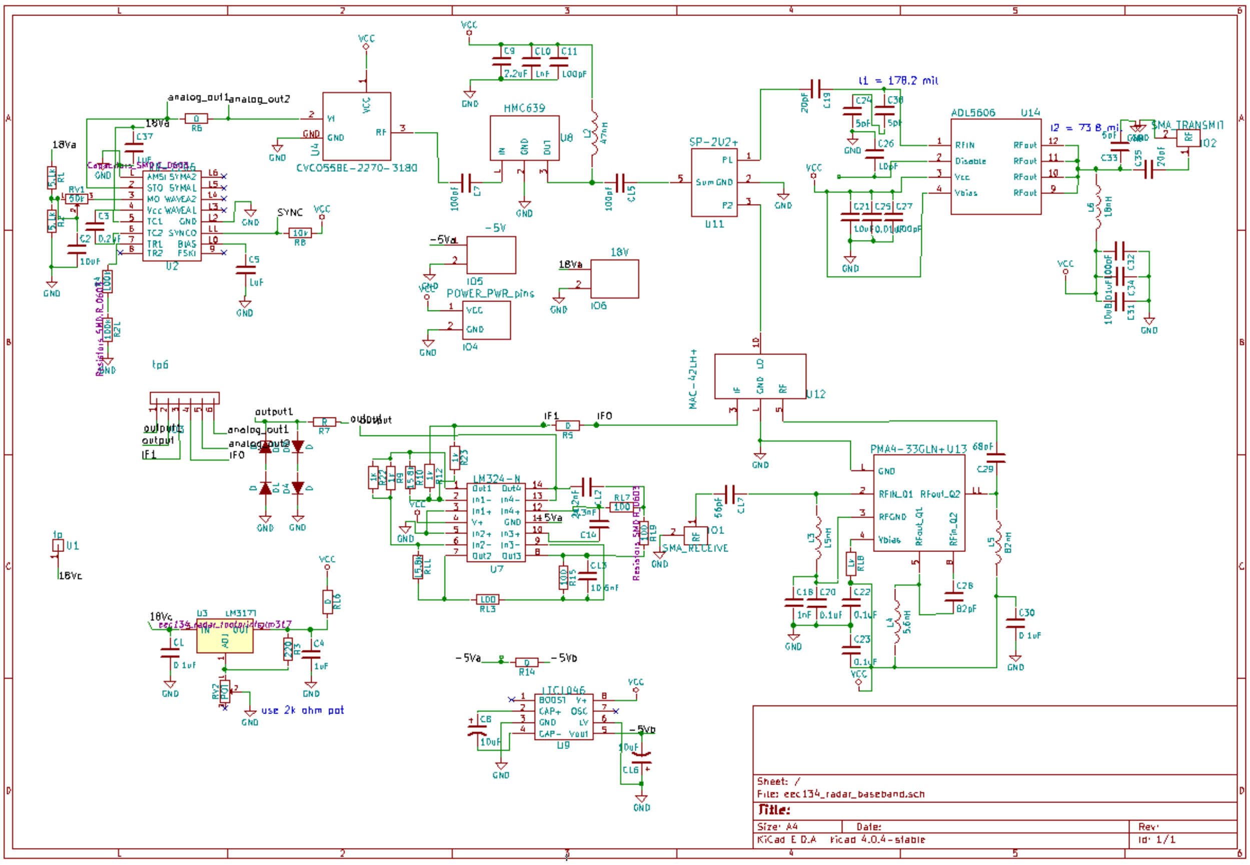

Figure 6: System circuit schematic.

The figure above shows the overall circuit schematic of our system. After designing each of our application circuits and/or matching networks for our components, we laid them all out and designed how they were to be connected. Most of the circuits were taken from the datasheets of the respective component, but the lowpass filter and power supply circuits were self designed. The figure below is the combined PCB layout for our initial run that contained the entirety of the circuit. One of the modular PCBs we designed for our second run, the VCO in this case, can be seen in the next figure after that. The PCBs for this final run were individual components and the required matching network and input/output components.

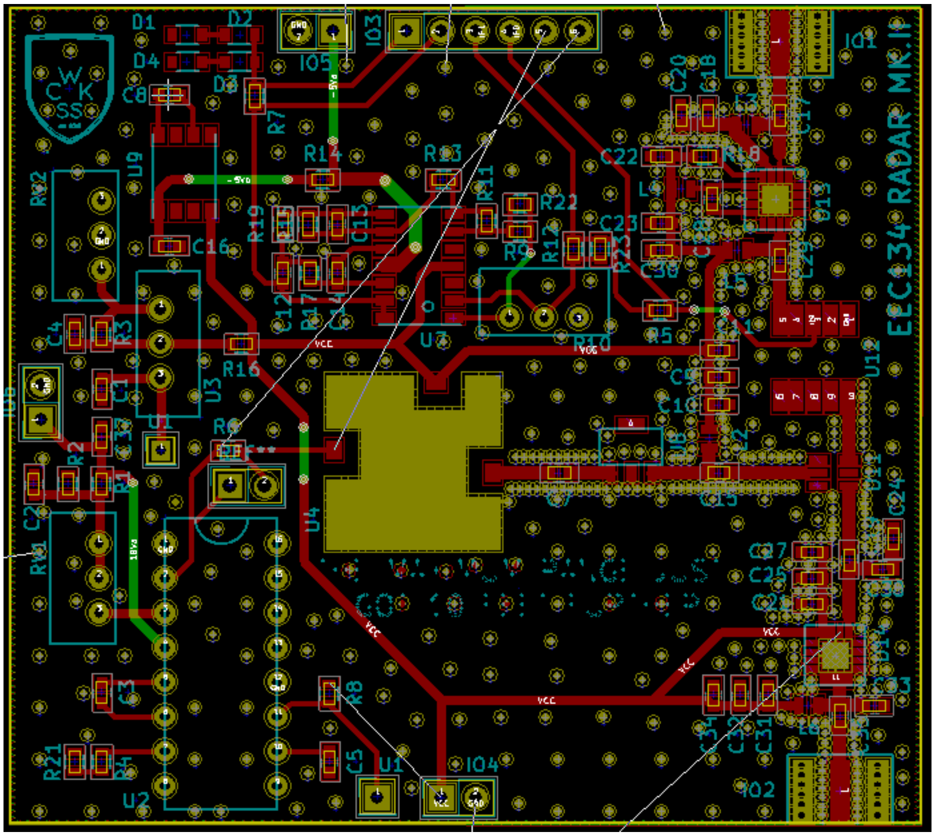

Figure 7: PCB layout for initial run.

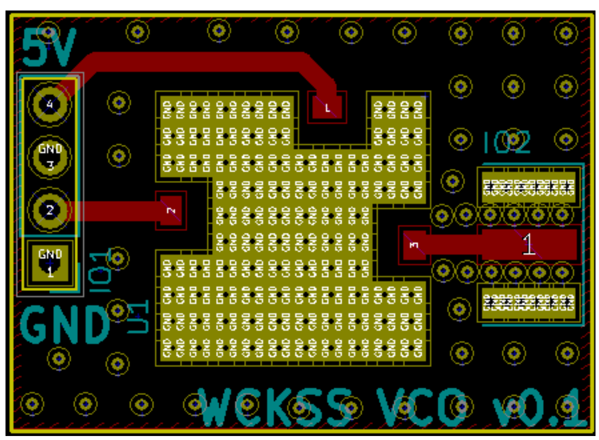

Figure 8: One of our modular PCBs for final run.

Signal Processing:
Signal processing will be executed using a laptop to read in the signal data via Audacity and using Python code to generate a visual report. A copy of this code is given in the Appendix. The code is taken straight from the class git directory and is largely unmodified — our only change being the filename, pulse duration, and start/stop frequencies. The signal we sent to the laptop is the mixed down baseband signal taken straight after the active low pass filter

and diode limiters.

4 Evaluation

4.1 Overview

Our approach in building this radar was to build separate PCBs for each RF stage in the transmit and receive paths to allow for easy testing and part swap-outs as needed. Through testing and and time-limitations, it was decided to incorporate some Quarter 1 components rather than the PCB ICs for reliability. The components outlined in the previous Design Overview section are the final components used in our radar system.

4.2 Prototype

The deviations from Quarter 1 parts are given below.
Transmit Path
On the transmit side, the final VCO IC was used.

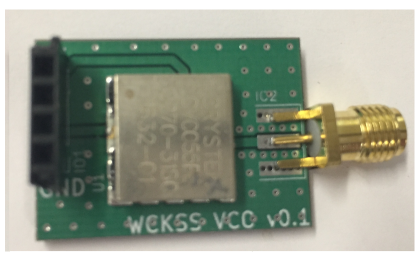

Figure 9: Designed PCB on Transmit

The transmit antenna used for our radar was the self designed vivaldi antenna. The antenna was fabricated on a Rogers dielectric 3.0 board in HFSS and fabricated in-house using a drill machine that etched away the unwanted copper cladding.

Antenna Path

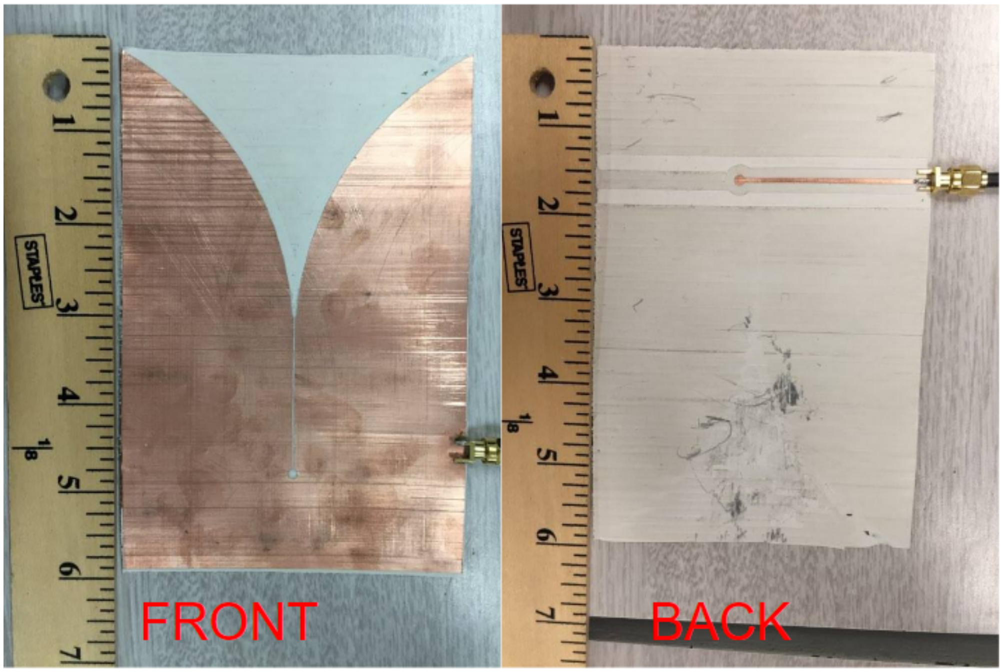

Figure 10: Vivaldi Antennas

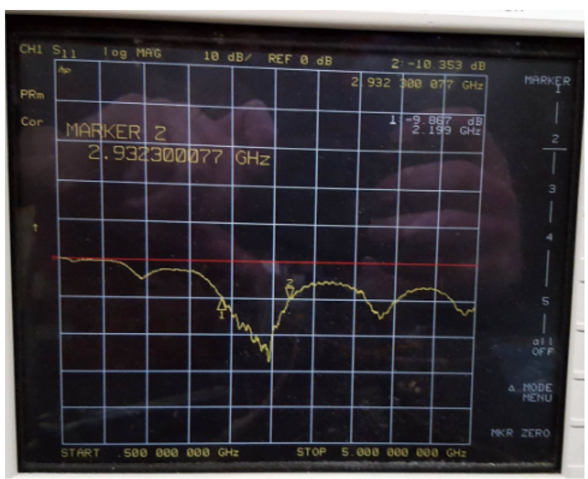

Figure 11: Vivaldi Antenna Measured S11 Response

The vivalidi antennas are usable from 2.1 to 2.9 GHz, with an optimal band of 2.2 - 2.7.

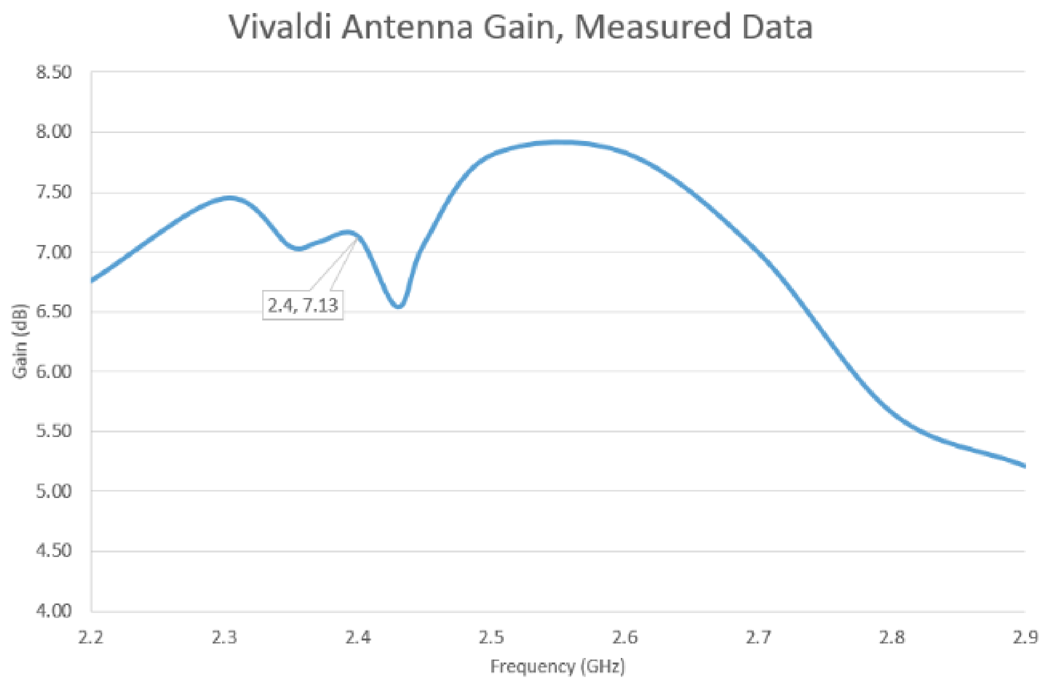

Figure 12: Vivaldi Antenna Measured S21 Response

Receive Path

The Analog Device HMC639ST89 LNA was also designed on a PCB. The Datasheet for this LNA did not provide a matching network at our design frequency, and a custom one was designed in ADS. the final PCB is given below.

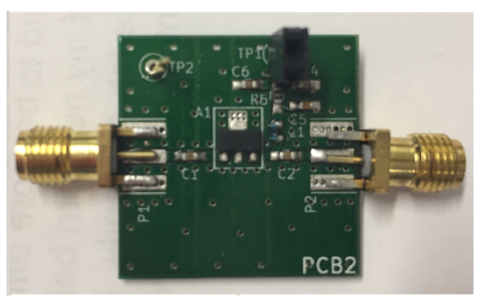

Figure 13: Designed PCB on Receive

To transition from SMA cable to wire after the mixer so we could process the baseband on a breadboard, a SMA cable was cut and soldered to a jumper wire for easy placement into our breadboard.

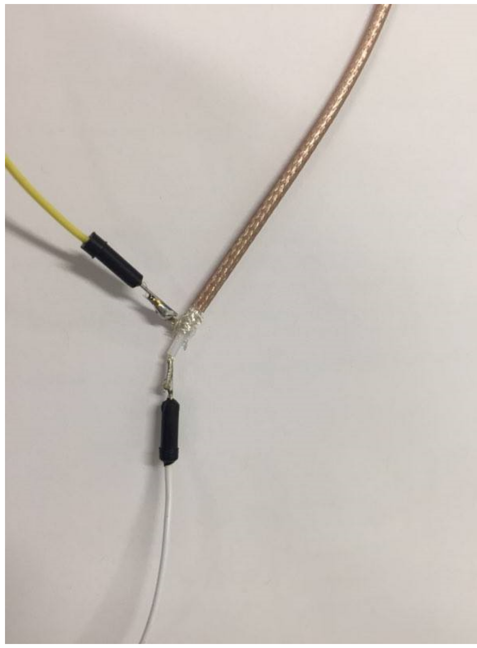

Figure 14: Custom SMA-to-Wire Adaptor

Our breadboard with the gain, filter and diode limiter stage is shown below.

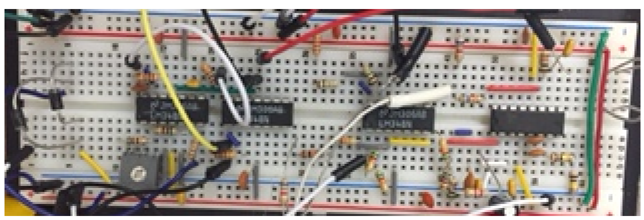

Figure 15: Designed Baseband on Receive

Final Radar Construction

The final radar system on the testing field is shown below. We used one of our Vivaldi antennas on the transmit side and one of our can antennas on the receive.

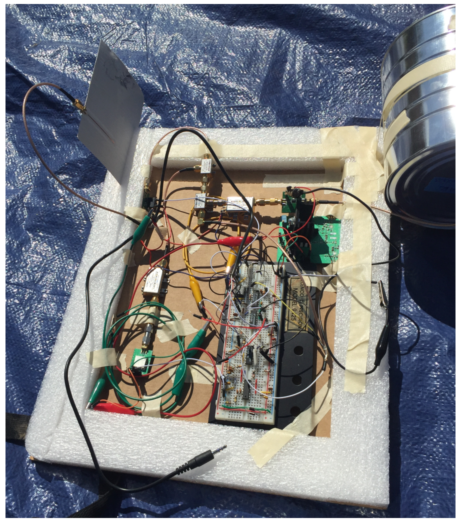

Figure 16: Prototype in Field Test

The final system was assembled using masking tape and a cardboard/foam combination that a Rogers dielectric board sample came in

4.3 Testing and Results

4.3.1 Preliminary Tests

We first tested each component individually to make sure that they each matched their expected performance. We tested components such as the Jameco function generator and the VCO by using a lab bench function generator to create an input signal and check whether the output matched the listed output on the datasheet. We tested the RF components using the synthesizer and the spectrum analyzer, sending in a signal of a certain frequency and power and checking the gain or attenuation of the outputted signal.
After we had evaluated that each component was performing as expected, we tested the performance of the entire system by emulating what would occur in the final competition. The results directly below were from one of our trials inside the Kemper 2112 laboratory: for that trial, one of our members held up a metal plate and moved back and forth in front of our system, stopping periodically and then restarting. Once we had captured the data using the same method as we would in the competition, by writing our measured signal into an audio file using Audacity and then processing it with Python, we then interpreted the results by reading the distance from the brightest spot.

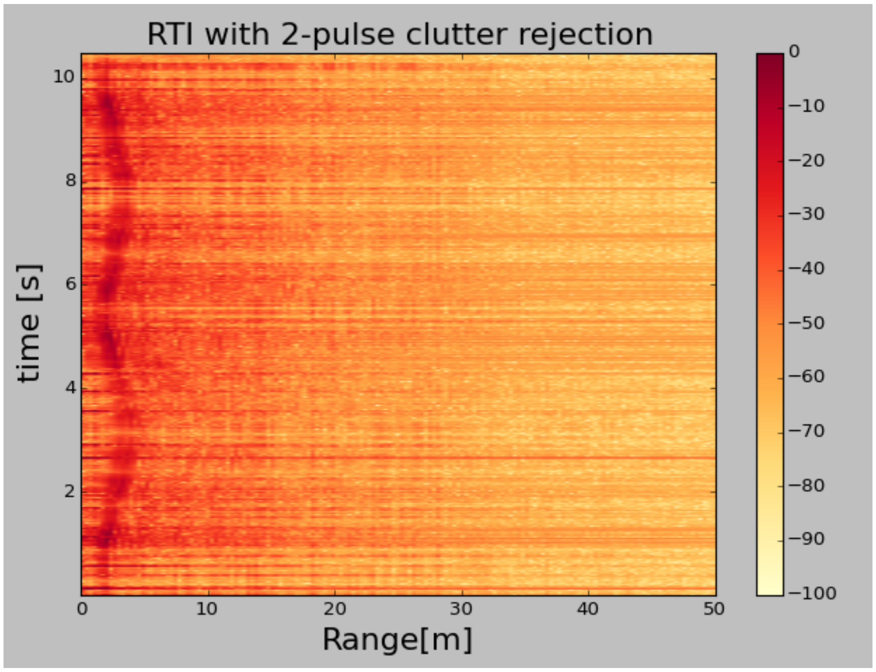

Figure 17: Test continuous motion

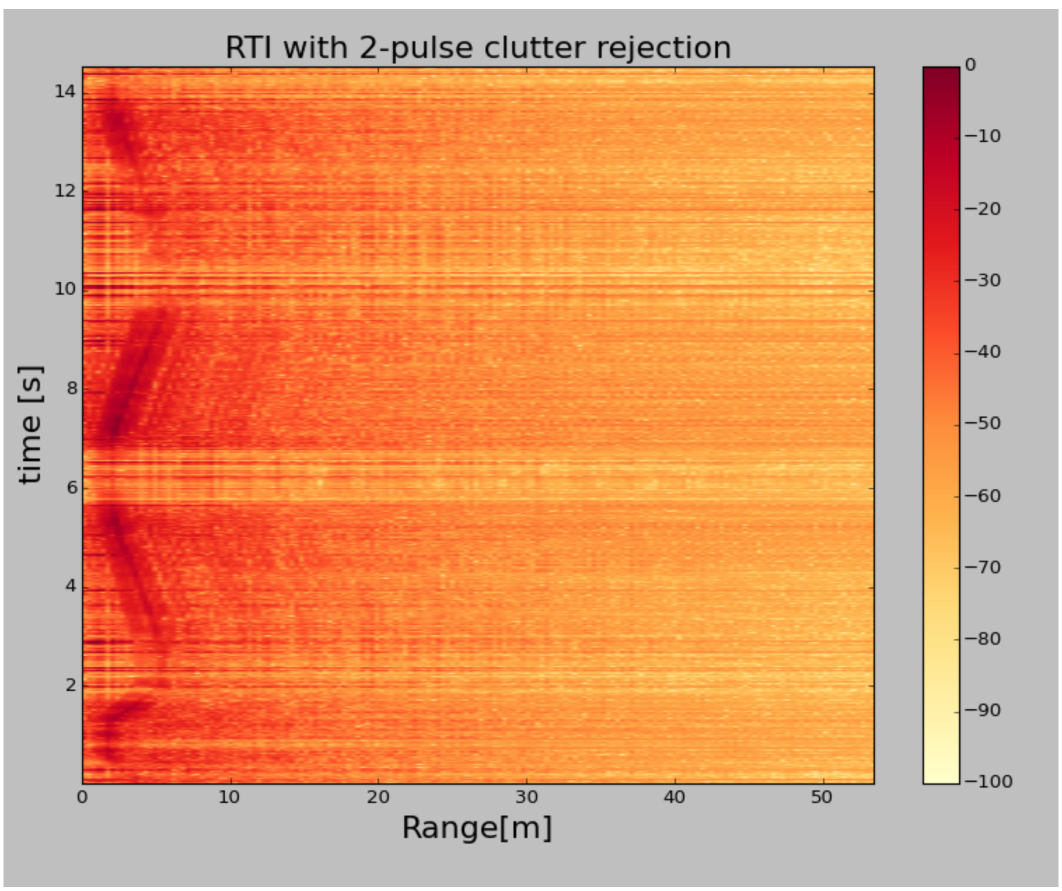

Figure 18: Test with start and stop movements

4.3.2 Radar Competition

We performed decently in the competition. Our first attempt was a failure. We had added an additional LNA and maximized the gain of our baseband active low pass filter in an attempt to increase our range. As a result, the data from our first run showed no distinguishable indications of the the reflector because we were deep into compression. When we remove the additional LNA and reset the baseband gain to our default levels, we read in some decent data.

We were fairly close on most of them, average error being around 5 meters, and our system performed about as well as we expected considering the preliminary testing. Given more time, we felt that we could have further refined the resolution of the system and found methods to deal with the many harmonics that were showing up, but as it is, we were satisfied with the results that we achieved. From the competition results, we identified that our next developments would be better gain control and signal processing.

weight: 710g
power consumption: 3W

4.4 Assessment

This section details the pitfalls of our systems:

- **Flimsy vivaldi antenna**. The antennas were designed on too small of substrate to be put in a rigorous system designed to be used outside.

- **High harmonic content**. The harmonics in our system are generated from two sources, but only one matters. First, we drive our RF amplifiers into compression. This will generate harmonics at the scale of 4 GHz and 6 GHz. These harmonics are generally harmless, and we would only worry about these if we designed for an FCC standard.
  The other source of harmonics is the diode limiters. Because use diode limiters to cap our input signal into the audio jack, our input signal is usually a square wave. The harmonic content of this square wave can be seen by Fourier decomposition and contains significant harmonics up to 9 times the frequency. These harmonic contents can be seen in our radar results.

- **Poor Construction**. The way we approached our radar - if a piece stops working, swap in another- lead to a very bulky design. This of course increased weight and the connectorized modules would increase cable loss compared to a PCB.

- **High Power Draw**. Because we designed our system around a $\pm 12V$ supply, we end up losing a lot of power regulating down to 5V for our RF components, which draw most of our power. We also lose out on space due to the power circuitry and the large heat sink we use. Looking back, there is no definite need for a 24V swing for our baseband system; with clever use of DC/DC converters we could definitely make do with a single 5V input and have a smaller, less power hungry system.

Strengths:

- **Wideband Vivaldi antennas**. Because our antennas are so wideband, we can sweep a larger frequency range compared to the other groups. This means that we could potentially have much greater depth resolution, although in practice our baseband system was not designed to accommodate that. As it is, our Vivaldi antennas are still much lighter compared to other coffee can or patch antennas, although that also leads to its flimsiness.

- **Modularity**. Besides the drawbacks of our connectorized design mentioned above, the modularity of our system also enables us to swap out parts at will. This enables us to test individual components with ease and also change our system to fit the situation.

A comparison of our expected system performance and our measured performance.

Metric	**Designed**	**Measured**
TX Output	1W (30 dBm)	21 dBm
Bandwidth	2251-2627 MHz	2251-2627 MHz
Range	250-500m	45m
Resolution	0.472m	0.472m
Weight	500g	710g
Power consumption	1.5-3W	3W

Table 1: Performance of Radar System

4.5 Next Steps

The immediate next step for our radar system would be to attempt to put everything onto a single PCB. This would greatly reduce weight and also reduce complexity, reducing the chances of some error in the field that would require readjustment. Our next version would include a major redesign to use a single 5V supply; this will significantly lower the power draw and size of our system because most of our power is lost rectifying from 12V to 5V and we have had to use a large, heavy heatsink to compensate. Additionally, we would like to include an automatic gain control circuit so we can detect distant objects with greater fidelity.

Once those immediate goals have been met, long term advancements include adding additional functionality and refining our current designs. We would like to try to design a phased patch array for the next step of our antennas. While more complex, a phased array would take up less surface area compared to the Vivaldi and also give us a smaller beamwidth. We would also like to try to achieve real time signal processing, either through an on-board microcontroller or through a smartphone app.

Our ideal end product would be a lightweight, low cost, small form factor system that could be handheld, wearable, and/or designed for the drone use market. If possible, it would either have on board processing or be configured to connect to a microcontroller. Possible applications include use as a motion, speed, or distance sensor, part of an environment awareness device for the visually impaired, or as a proximity detector for small autonomous robots.

5 Acknowledgements

Preparation and success of this project would not have been possible without assistance from many people. We particularly thank the following persons for their support and assistance during this project: Professor X. Leo Liu, Daniel Kuzmenko, Songji Bi, Hao Wang, Team Falcon 9: Marco Venegas, Alejandro Venegas, Gerardo Abrego, Jesus-Alexis Torres, Team One: Alexander Coffman, Jinhua Cao, Jo-Han Yu.

References

[1] Quarter 2 proposal report

[2] http://www.innovateus.net/science/what-are-different-uses-radar

[3] https://www.engineersgarage.com/articles/types-of-radars

6 Appendices

Design Files: Circuit Schematics, KiCAD Drawings, Antenna Schematic
Bill of Materials
Computer Code