Final Design Document

Project 02: Pringles Radar

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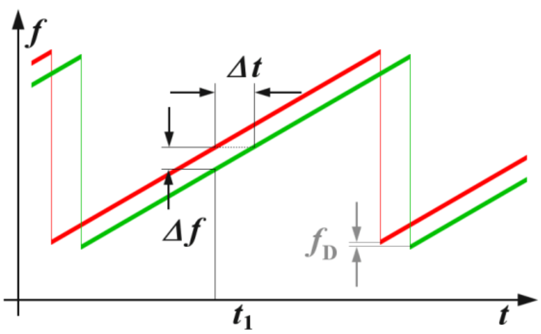
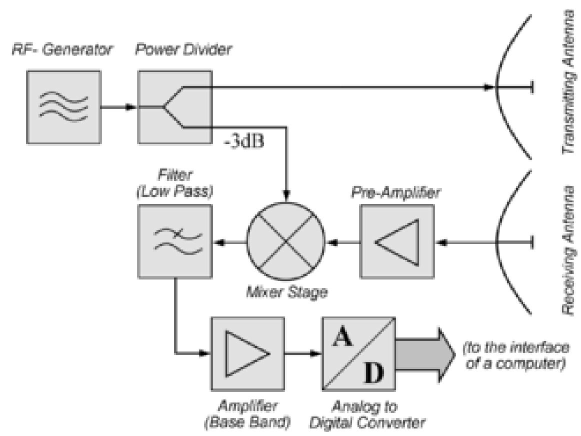
User Guide

This design document explains the electrical engineering theory, technical requirements, and test results of our ECE 485 Senior Design project: Pringles Radar. The project was adapted from a similar project undertaken by a group of MIT students. Our intention and goal was to build a radar for less than $50. It is supposed to be inexpensive so that a college student, engineering faculty professor, or RF enthusiast can easily build it in a day. An instructor could also use this project to format a class to teach radar with hands-on design and fabrication opportunities. Each RF circuit component is explained throughout the document with a discussion on its design, fabrication, and cost. A system overview and theory of operation is included to provide a starting point for those users unfamiliar with RADAR concepts.





Theory of Operation

Our RADAR system transmits a Frequency Modulated Continuous Tone (FMCW) to determine the range of objects that the signal reflects off of. The system generates a Sawtooth voltage waveform which it uses to vary the frequency output of a Voltage Controlled Oscillator (VCO) at high radio frequencies (RF), in our case 2.4GHz. An example of this signal is shown in the above figure. This RF signal is amplified by a power amplifier in boost the signal to a level that will propagate far enough to meet the system range requirements.

Once the RF signal is generated and boosted to an appropriate power level, it is split by a power coupler. This sends the majority of the power to the Transmit (TX) antenna where it propagates in the direction of the antenna radiation pattern. This is typically a narrow beam which allows the system to determine the range of objects only in the direction it is currently pointed in. The RF signal bounces off objects and returns to the receive (RX) antenna where it's power is boosted by the gain factor of the antenna in the direction that it arrived. The received signal is of very low power due to the attenuation of the channel it traveled in and needs to be amplified. The signal is amplified by a Low Noise Amplifier (LNA) which provides high levels of gain without adding noise. This is important because due to Frii's equation, the first gain stage needs to have the lowest noise figure in order to preserve signal quality, or Signal to Noise Ratio (SNR).

The amplified RX signal is delayed in time due to the finite speed of light. The delay is proportional to twice the distance of the object that reflected it since it had to travel out and back. This signal is then mixed with the other portion of the original RF signal, now called the Local Oscillator (LO), that was coupled at a low power. This mixing produces two signals, one at the sum of the two signals and one at the difference. The sum is filtered out and the difference is amplified by a low frequency Video Amplifier (VA). This amplifier boosts the signal to a level that can be sampled by an Analog to Digital Converter (ADC). The difference signal contains a frequency product that is proportional to the time the RX was in flight. Since it is delayed proportional to this distance, the LO frequency is now higher than the received RF frequency. This difference signal that is amplified and digitized is what is used to determine the distance of reflecting objects in the RADAR's field of view.

A Discrete Fourier Transform (DFT) is taken of this digitized signal. The 'peaks' in frequency in the DFT output represent the reflecting objects. Since further away objects produce a greater time delay, the mixer outputs a higher frequency for far away objects. This relationship between distance and frequency is used to scale the axes of the DFT output and produce a plot of object distances.

System Requirements

Requirements Achieved and Requirements Not Achieved

<u>Achieved</u>

I. **Fabrication Cost**
   A. The system shall cost no more than $50.
   B. The system cost shall not include consumable board fabrication costs.
   C. Users of the system will be assumed to have a laptop equipped with audio jack.

II. **Educational Appeal**
   A. The system shall be buildable by a senior in college.
   B. The system shall be buildable by a graduate student.
   C. The system shall be buildable by a practicing RF engineer.
   D. The system shall have proper documentation about the design process and design schematics.
   E. The system shall have a simple demo for the user.

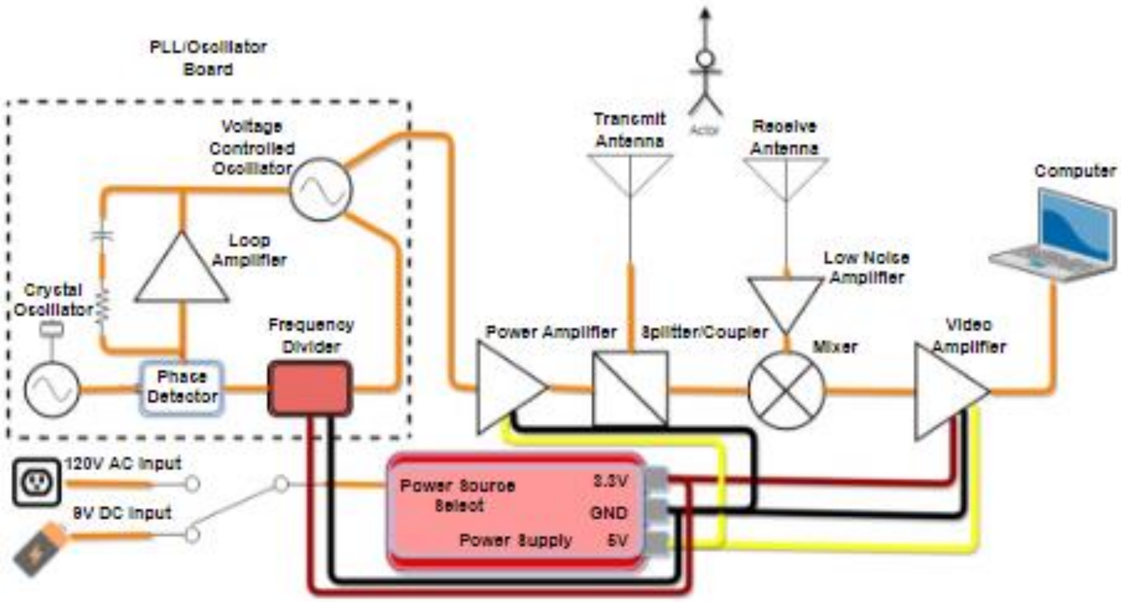
III. **Design Challenges**
   A. The system shall not utilize pre-built circuits.
      1. Integrated circuits (IC's) will not be considered "pre-built."
   B. The system shall operate in an ISM band.
   C. The system shall follow all ISM band regulations.
   D. The system shall be able to measure distance of moving objects.

IV. **Range of Operation**
   A. The system shall operate between 2.3 - 2.5 GHz.
   B. The system shall detect non-stationary objects up to 100 feet away.

<u>Not Achieved</u>

I. **Design Challenges**
   A. The system shall rotate 360 degrees.
   B. The system shall be water resistant and be operable in rain.

Detailed System Block Diagram



Detailed system block diagram - final design

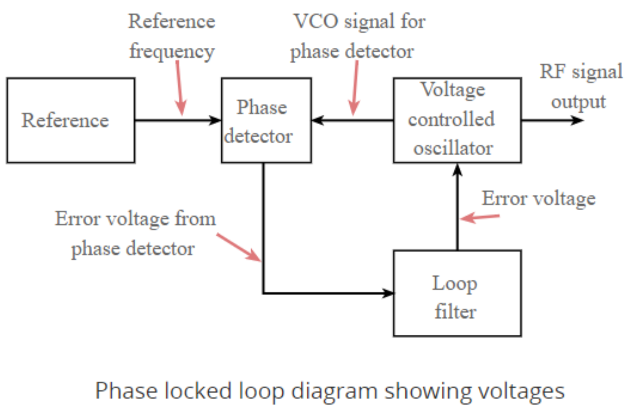
The signal chain through our radar is as follows: power is supplied to the voltage controlled oscillator (VCO) from the voltage regulator (fed by either 9 V battery or a wall plug). The VCO generates the signal from the crystal oscillator in the phase locked loop (PLL). The signal is amplified when it moves from the PLL to the power amplifier (PA). A rat-race coupler splits the signal into a local oscillating (LO) signal and the transmitted (Tx) RF signal. The LO signal is sent to the mixer while the Tx RF signal hits a distant object and returns to the receive (Rx) antenna. The received RF signal is then amplified by a low noise amplifier (LNA). The LO and input (Rx) RF signals both enter the mixer and combine them into an intermediate frequency (IF) output signal. Lastly, the IF is fed through the video amplifier (VA) so it can be processed on the computer.

In summary,
VCO → PA → Coupler → Antennas → LNA → Mixer → VA → Computer Display

Circuit Design

Phase Locked Loop and Voltage Controlled Oscillator

A phase locked loop can control the local VCO with high accuracy given a reference oscillator. Phase locked loops compare the phase of the signal output by the VCO it is connected to with the phase of a lower frequency reference oscillator. The VCO signal is frequency divided down so that it can be compared to a lower frequency reference oscillator. This is useful because a VCO has a nonlinear and imprecise tuning curve. While ideally a linear voltage sweep would linearly sweep the VCO output frequency, variations in the design mean this is not the case in practice. This is important because a nonlinear sweep in an FMCW radar causes the results to be “smeared” over multiple frequency bins. To fix this a PLL can be used.



Phase locked loop block diagram https://www.electronics-notes.com/articles/radio/pll-phase-locked-loop/tutorial-primer-basics.php

We chose to use the ADF4158 for our PLL. It operates over a range of 0.5-6.1GHz, has on board FMCW ramp generation built in, and can be run off of 3.3v and an external oscillator. It is programed over a standard 3-wire interface suitable for low cost uController (Arduio, MSP430) software bit-banging. The programming logic and configuration are included in the code repository. The PLL circuit uses a 26MHz reference oscillator which was selected for its simplicity, frequency stability of 10ppm, and ability to run off of 3.3v. It is included on the PLL board and outputs directly into the ADF4158. The PLL requires an external VCO and loop filter. The MAX2750 was selected as a VCO due to its wide tuning range of 2.25GHz-2.65GHz at 3.3v and its relatively high output power of -6dBm. This power output is helpful because our power amplifier won’t need to provide as much gain.

The loop filter is essential to the operation of the PLL. It smooths out the control voltage going to the VCO tuning pin and its frequency response characteristics determine how quickly and accurately the PLL ‘locks’ to the correct frequency. The resistor and capacitor values for the loop filter are included in the schematic. They were calculated using the Analog Devices PLL sim tool. Our design files for that software are included. The loop filter was designed with a quick reset time and close tracking in mind. A screen capture of the loop response is below. It shows a quick reset to tracking after the sawtooth resets with only mild overshoot. The top trace is high when the PLL is locked and low when it is unlocked.

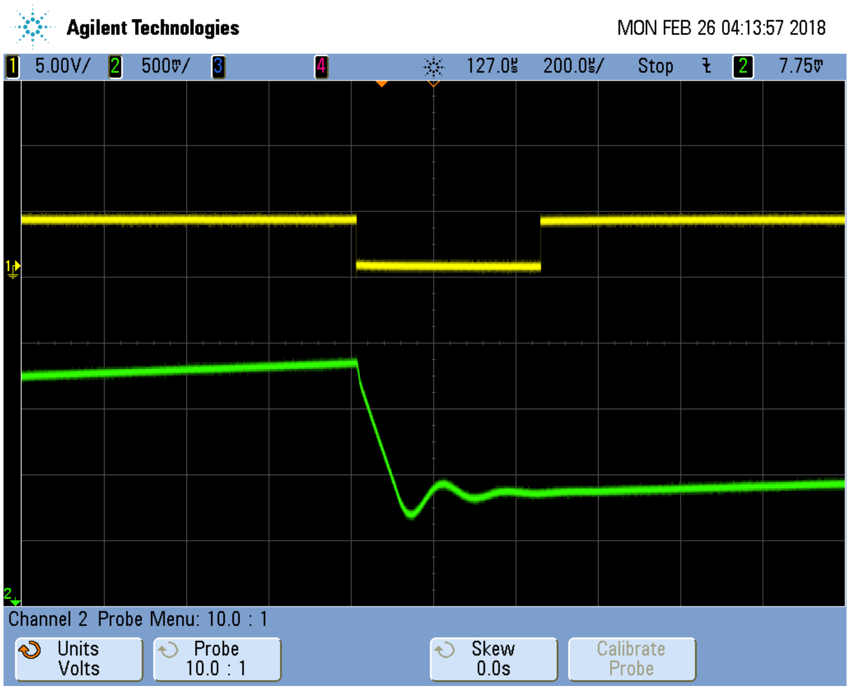


Figure 1. PLL loop filter response

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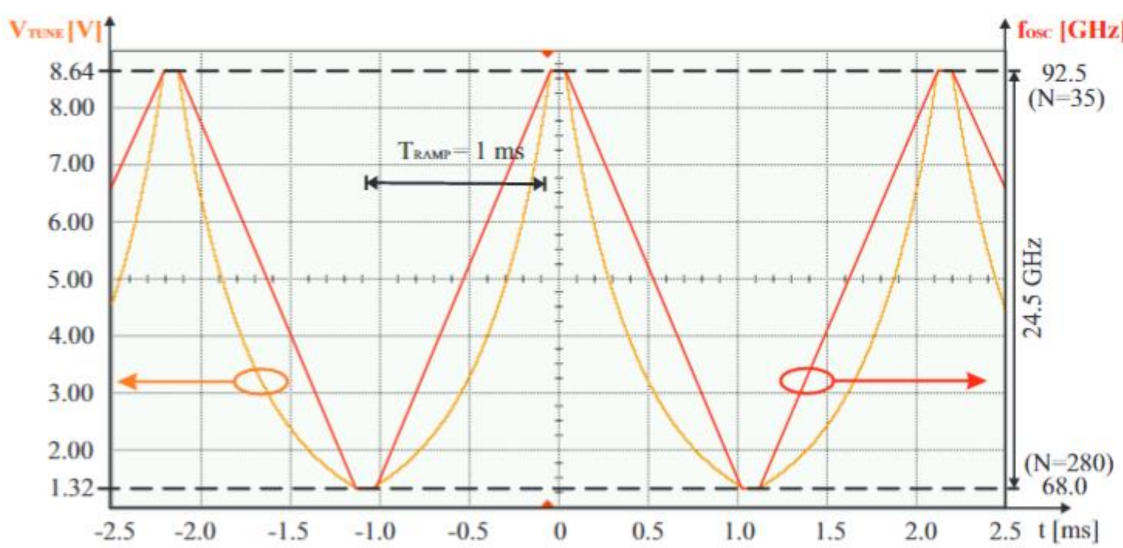


Illustration of how a PLL can generate a nonlinear tuning voltage sweep to compensate for a non-linear VCO tuning curve. "Fractional-N PLL based FMCW sweep generator for an 80 GHz radar system with 24.5 GHz bandwidth T. Jaeschke , C. Bredendiek, M. Vogt, and N. Pohl (2012)"

Pros/Cons: (Phase Locked Loop)

Pros:

- Extremely accurate output frequency ramp
- Can use a cheaper VCO
- No need for ramp generator circuit
- Greatly increase RADAR resolution and accuracy
- Easily changeable modulation schemes
    - Ramp is only one type of FMCW signal, many others out there

Cons:

- IExtra part so increased cost
- Loop filter design is critical to performance
- Increased board layout complexity
- Requires digital programming

PA and LNA

The power amplifier and low noise amplifier were designed to be low cost and buildable on a basic PCB. The amplifiers need to operate at 2.4GHz which means special considerations needed to be taken to match the inputs and outputs to 50 ohms, the transistors had to have a transition frequency (point of no gain) well above our operating frequency, and the matching network had to be buildable with realistic parts.

Typically, a power amplifier is designed to operate with good efficiency and a high total power output. Low noise amplifiers are designed to provide gain while having the lowest possible noise figure. These requirements are at odds with each other. It was determined that for simplicity, the LNA and PA would use the same circuit. This circuit was designed as a tradeoff between a low noise figure and high overall power gain. This was done because our PA didn’t need to operate near the 1dB compression point (where the maximum power output is) nor did it need to have the lowest possible noise figure since at our ranges, the signal was found to be strong enough already. These trade-offs allow system builders to reduce the overall complexity and BOM size.

The amplifier was designed in AWR using the BFU660F. This transistor has a transition frequency of 40GHz and is low cost and widely available. The AWR simulations were done by matching the input and output to 50 ohms artificially and finding the bias point (collector current) which provided good gain with an acceptable noise figure. We do not have the equipment to measure amplifier noise figures but the simulated value was 1.6dB which is acceptable for our purposes. The matching networks were then designed as transmission lines using techniques demonstrated by Dr. Ricketts. The amplifier stability was initially a concern but Dr. Ricketts told us that our results were acceptable.

Figure 1. shows the AWR layout of the circuit which was transferred to a KiCad schematic using a Python script I have included in the files. This takes an AWR .gerber file and turns it into a .kicad_mod file. Run “python3 gerb2kicad.py --help” for usage instructions.

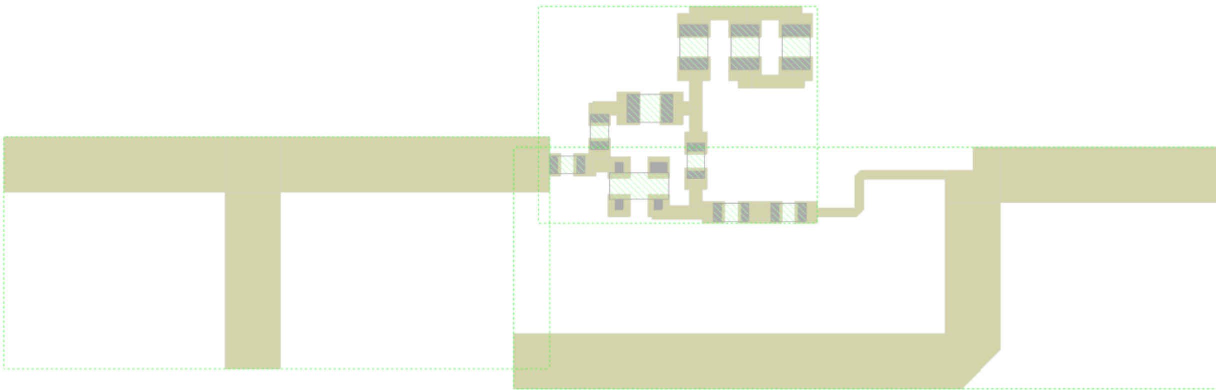


Figure 1. AWR layout

Figure 3. shows the measured gain (S21) results. The simulation matches the real-world results although there is slightly less overall gain in the real world. The simulation predicted a gain of 18 dB so 15dB is reasonable. This is likely due to losses in the PCB, losses in the wires, and a poor Vector Network Analyzer calibration.

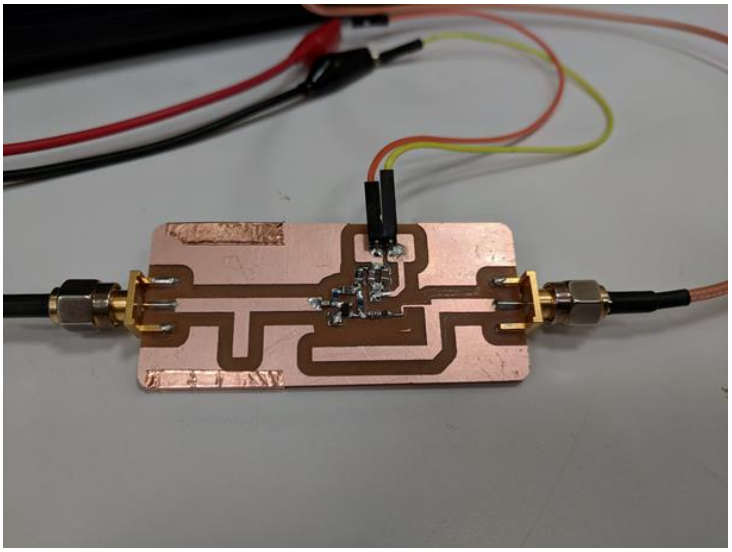


Figure 2. Fabricated and assembled PA

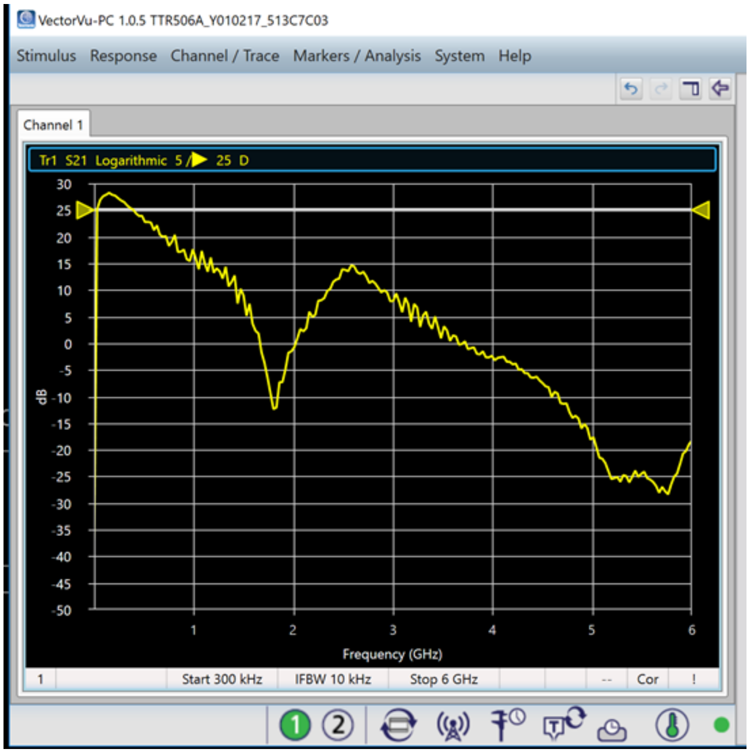


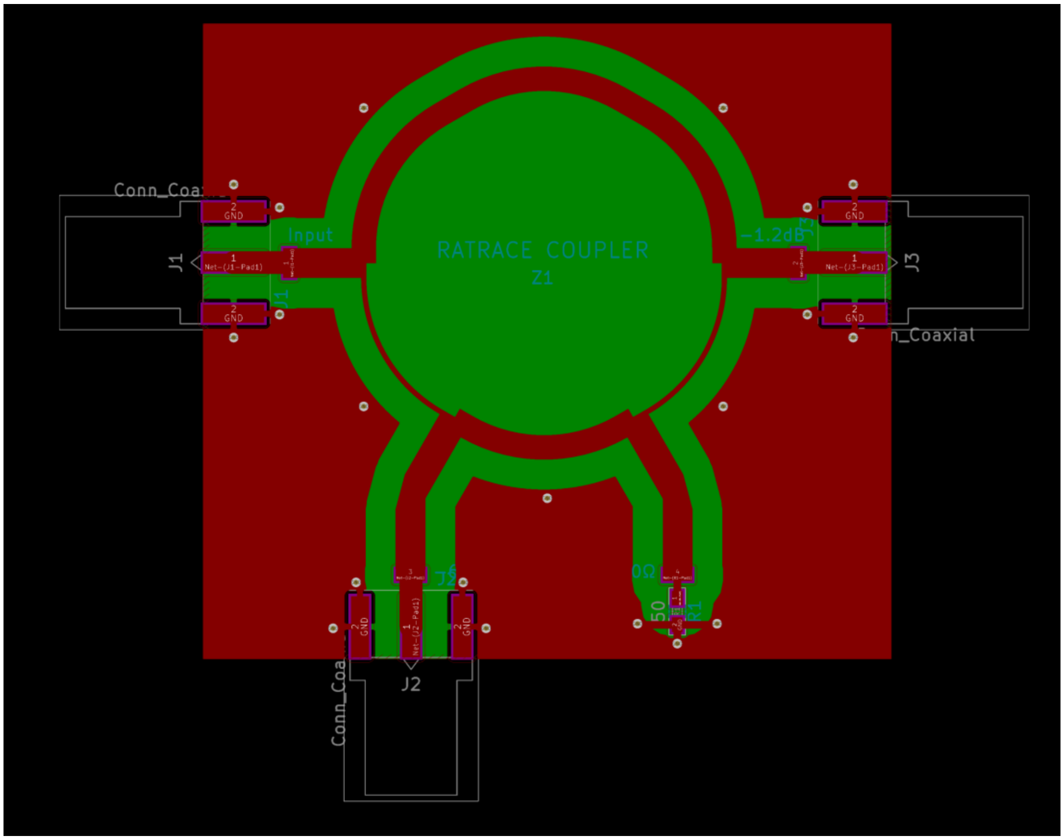
Figure 3. Assembled amplifier gain measurement

Coupler

The power coupler needs to split the power between the transmit antenna and the mixer. The mixer does not require as much power as we want the transmit antenna to have to there needs to be an unequal power split. A simple resistive splitter would work and is what we used for the alpha but it throws away half (3dB) of the power as heat. This reduces our range unnecessarily.

A rat-race coupler was chosen as it provides unequal power splitting without losing power to heat. This was designed in AWR and was based on paper found in the NC State library. The AWR layout was transferred to KiCad and SMA connectors were attached along with the single required 50 ohm resistor.

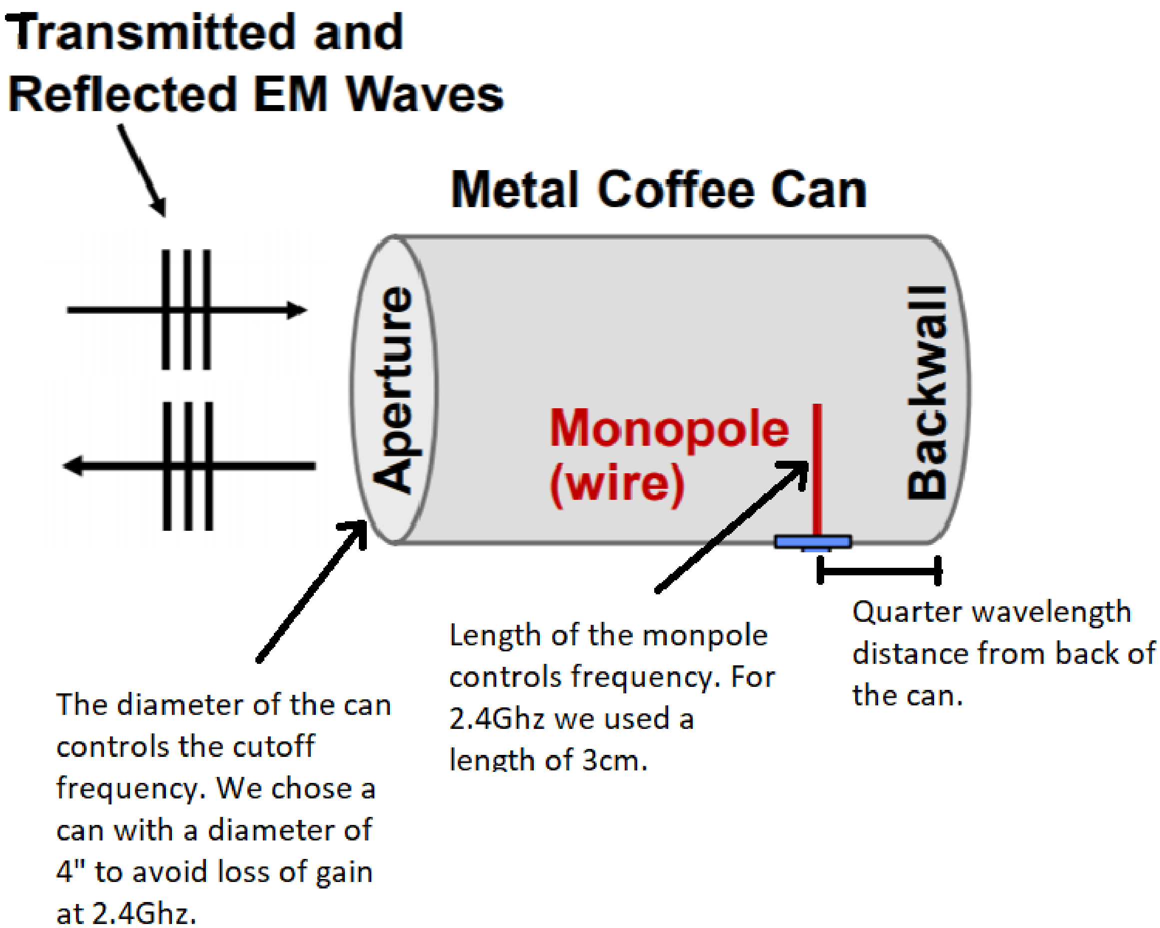
The simulated results predicted a -2.5dB gain on the main output to the transmit antenna and a -8.5dB gain to the mixer. The measured results on the Vector Network Analyzer were -2.6dB and -8.2dB respectively which matches the simulation exceptionally well. There is an extra 1.5dB of loss present due to the low quality of the PCB material used. Professionally made boards would have less losses and is an option for future users.



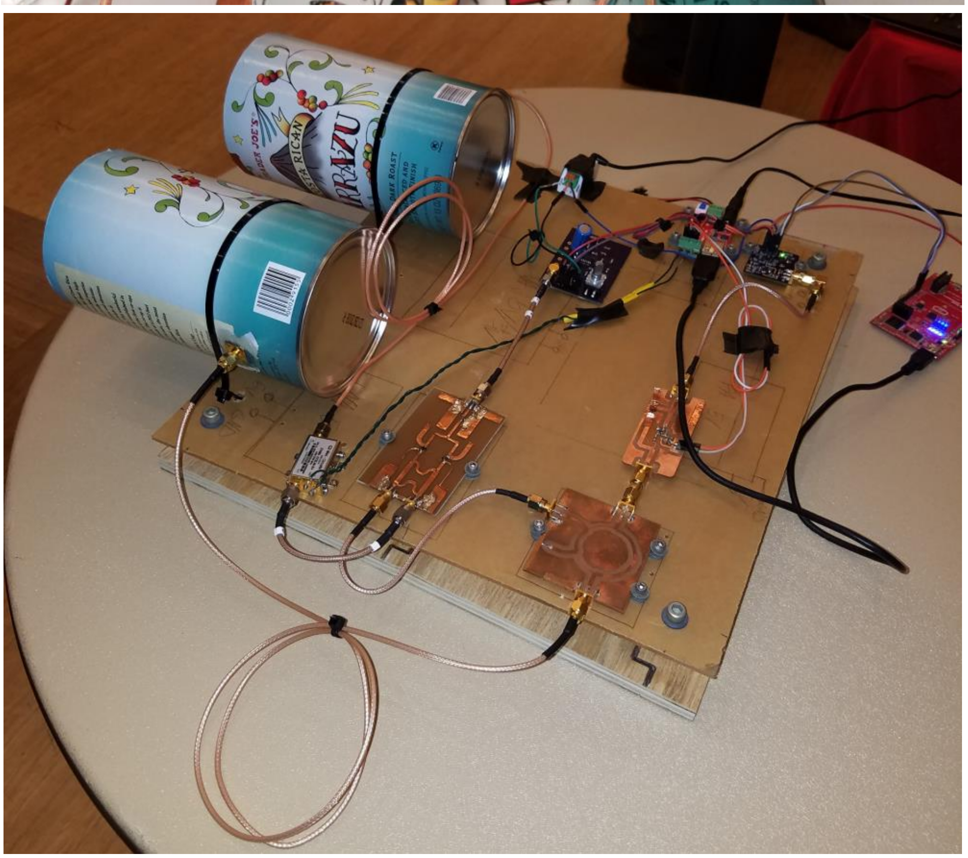
Coupler layout in KiCad

Antennas

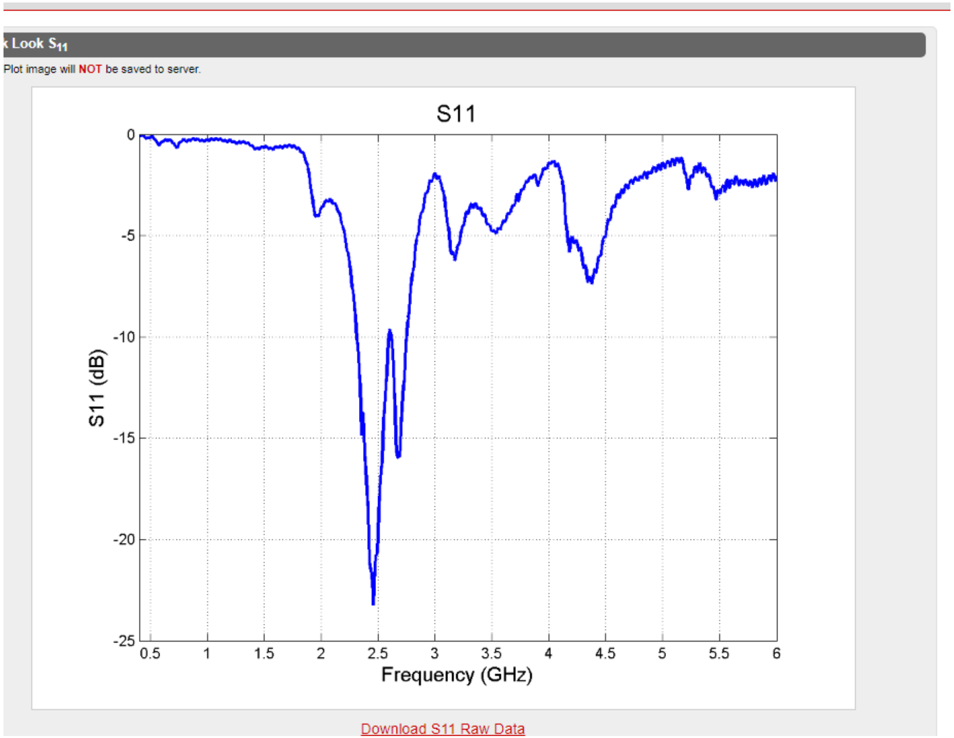
The design our team chose to stay with were metallic coffee cans from the grocery store. We found that this was the most cost-effective way to build the antennas without sacrificing performance of the transmit and receive signals. The design for the cans are shown below:



The image below is our final antenna design we chose. The test parameters are shown along with this.



The following images below show the test results for the chosen cantenna design:

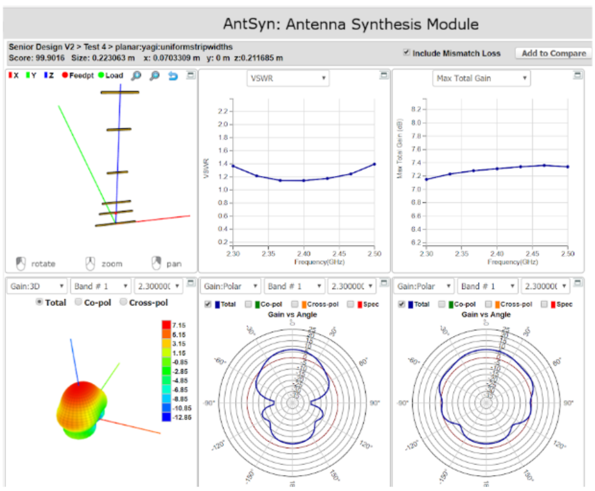


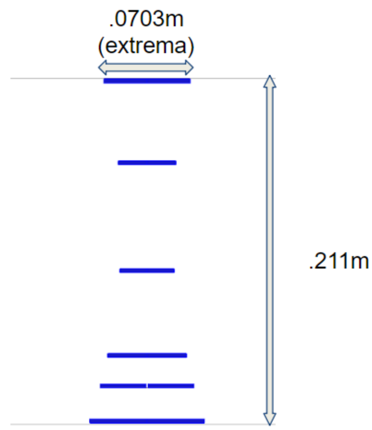
As you can see, the antenna has a gain of about 7dB at 2.4 GHz from the bottom graph. The “cantenna” also produces an S11 of about -20dB at 2.4 GHz which tells us that we are not losing a significant amount of power while transmitting.

2.4 GHz Antenna Design Options

There are many ways to design a 2.4 GHz antenna. One of the programs we used to design the antennas is called AWR AntSyn, which will design an antenna based on a list of parameters the user inputs. From this software we manufactured an array of antennas that could be used for our project. The following antennas below were all produced and tested for use on our design.

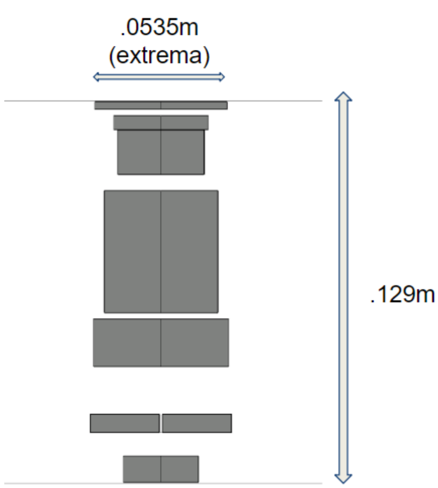
VAGI VARIABLE STRIP WIDTHS

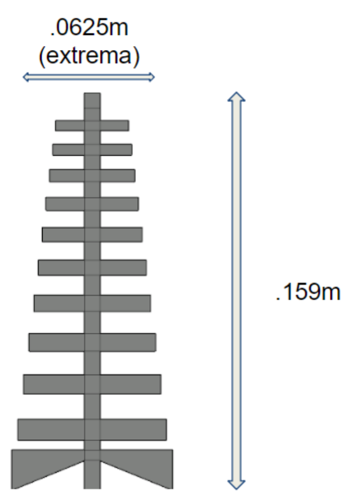




Material: Conductive Copper tape applied to a piece of foam board

The following were not chosen due to low gain at 2.4 GHz after being built:





Material: Conductive copper tape applied to foam board.
Results: 2dB at 2.4Ghz

Material: Conductive copper tape applied to foam board.
Results: -15dB at 2.4Ghz

Mixer

A mixer is built to produce a signal at the difference frequency (or IF) with the same modulation (hence, information) as the original RF signal. This figure helps visualize that.

$$f_{\mathrm{IF}} = |f_{\mathrm{RF}} - f_{\mathrm{LO}}|$$

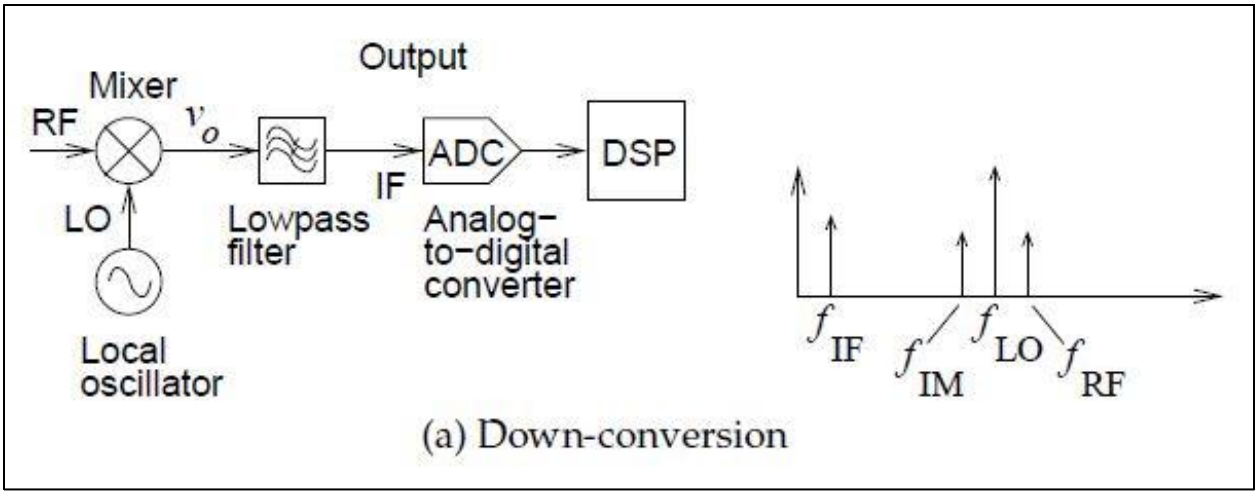


Figure 4: Down-conversion in an RF mixer

The way the mixer in our system works is it receives the LO and Rx RF as input signals. The LO is set at 2.4 GHz and the RF signal is swept from 2.3 - 2.5 GHz. The output IF is the magnitude of the difference of the two input signals so the IF is produced close to 0 Hz (DC). This is done because of our frequency modulated carrier wave (FMCW) calculations, explained earlier.

Design

The design process of this mixer was inspired by the work of Dr. Kikkert at James Cook University in Queensland, Australia. In his book, “RF Electronics: Design and Simulation,” Dr. Kikkert discusses how to implement a microstrip, high frequency mixer using a branchline coupler. I adapted his design of a 1.7 GHz mixer to meet our 2.4 GHz system requirement. The design was implemented using AWR simulation software. The design file can be found with our final designs package on our team website but the figures below show the circuit schematic and PCB layout.

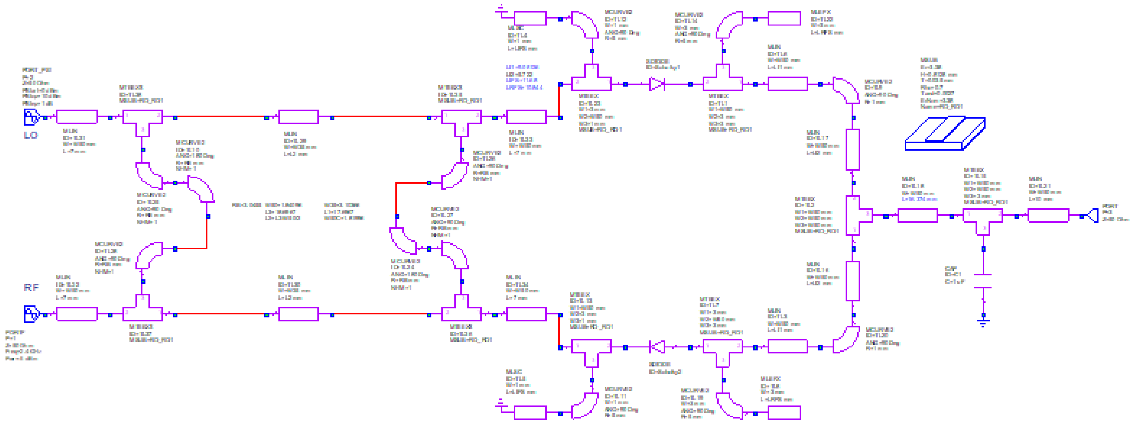


Figure 5: Microstrip schematic of 2.4 GHz mixer from AWR

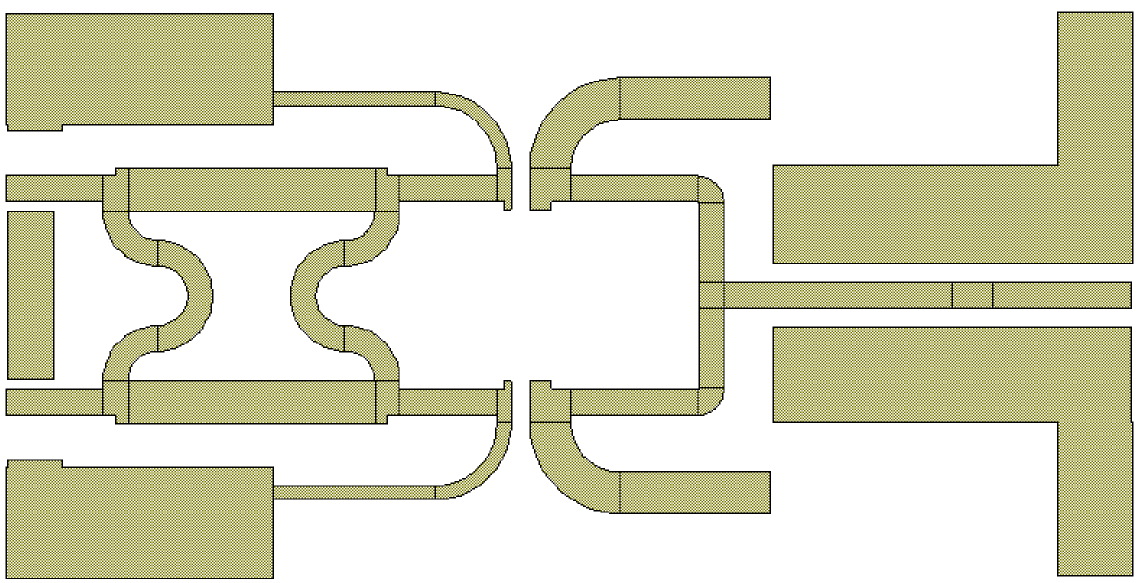


Figure 6. PCB layout of 2.4 GHz mixer from AWR

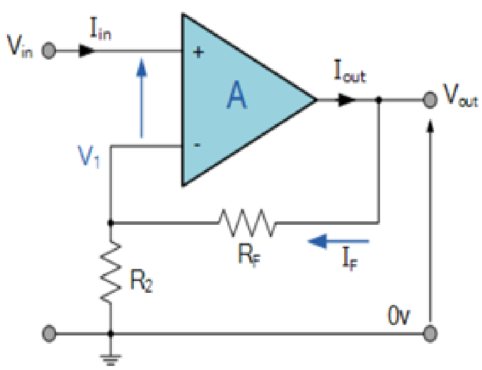
Video Amplifier

The Video Amplifier is a key component in our design as it allows us to send a down converted signal from the mixer to the computer to be processed in Matlab. The amplifier itself consists of a non-inverting amplifier that feeds into two active low pass filters and one high pass prior to being sent to a computer through the sound port to be processed by the audio card. Due to constraints with the sampling rate of the soundcard, we would only be able to process RADAR signals that have been down converted to frequencies that are less than 22 KHz. With that said, this makes the maximum range of our RADAR equal to 800m in a noiseless environment.

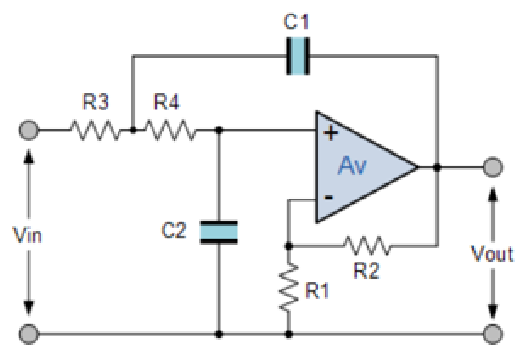
Design

The amplifier had two discrete designs that worked as intended. In the first design, three separate OP amp circuits were used, a non-inverting amplifier, and two low pass filters to remove any high frequency signals. Even though this worked for our first iteration, we simply had too much gain resulting in clipping of our signal and a much lower range. We also had other noisy elements at low frequencies that interfered with our system. To compensate for this, we modified our design to include a high pass filter and we lowered the gain on other filters within the system. In the end, we had an amplifier that had the same setup as below. Fc represents the frequency cutoff, where the signal strength is ½ of its max.

High Gain Amplifier

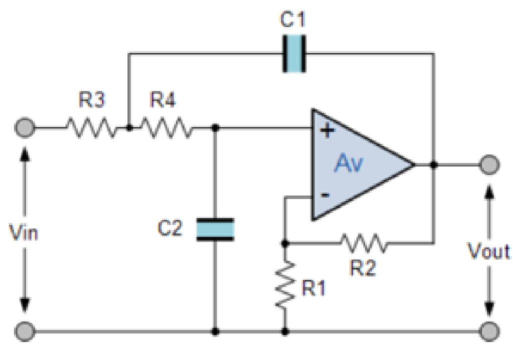


Low Pass Filter

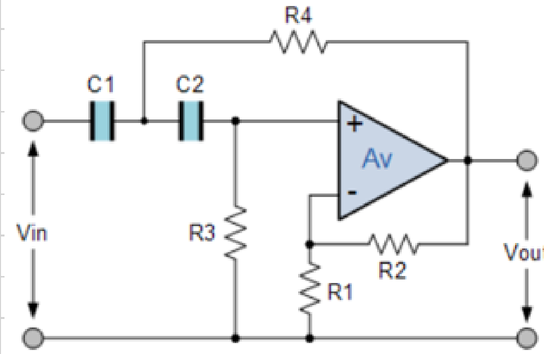


R2	220	R1	10000
RF(Changes)	1-101k	R2	1000
RF(Min)	1000	R3	10000
Gain	5.545454545	R4	10000
RF(Max)	101000	C1	0.000000001
Gain	460.0909091	C2	0.000000001
		fc (Ideal)	15000
		fc (calculated)	15915.49431
		Gain	1.1

Low Pass Filter



High Pass Filter



R1	10000	R1	10000
R2	1000	R2	1000
R3	10000	R3	200000
R4	10000	R4	200000
C1	0.000000001	C1	0.000000001
C2	0.000000001	C2	0.000000001
fc (Ideal)	15000	fc (Ideal)	800
fc (calculated)	15915.49431	fc (Calculated)	795.7747155
Gain	1.1	Gain	1.1

The Video Amplifier for our design is needed in order to convert the received signal from the radar into an audio signal that can processed through a traditional computer’s audio port. Thus, specific filters using everyday components need to be inserted in series to allow for a signal that encompasses only lower frequency signals.

Final Bill of Materials (BOM)

Voltage Regulator

- LM YN DC-DC LDO Multiple Output Power Supply Module Buck Regulator Input 9V / 12V / 24V (7-28V) Output 3.3V / 5V = $9.80

PLL & Reference Crystal

- MAX2750 2.4GHz VCO = $6.06
- ADF4158 PLL = $5.68
- DSC1001DL5-026.0000 crystal oscillator = $2.08
- 3x 18 ohm resistors = $0.09
- 2x 220pF ceramic capacitors = $0.10
- 2x 10pF ceramic capacitors = $0.10
- 4x 100pF ceramic capacitors = $0.20
- 1x Green LED = $0.17
- 2x 0.1uF capacitor = $0.10
- 1x 10uF ceramic capacitor = $0.20
- 1x 5.1kohm resistor = $0.05
- 1x 2x4 2.54mm header = $0.15
- 1x SMA connectors = $0.30
- 4x assorted SMD resistors / capacitors for tuning = $0.20
    - See PLL section for loop filter calculation
- OSHPark PCB Fabrication = $5.0
- Total = $21.48

Power Amplifier

- BFU660F = $0.46
- 1x 0.1uF capacitor = $0.05
- 3x 100pF ceramic capacitors $0.10
- 2x 100nH inductors = $0.14
- 1x 3.3kohm resistor = $0.02
- Total = $0.77

Antennas

- Coffee cans = $2.50
- Copper wire = $0.15
- Stub SMA connector = $0.50

Low Noise Amplifier

- BFU660F = $0.46
- 1x 0.1uF capacitor = $0.05
- 3x 100pF ceramic capacitors $0.10
- 2x 100nH inductors = $0.14
- 1x 22kohm resistor = $0.02
- Total = $0.77

Mixer

- 2 diodes (@ ~$0.25 each) = $0.50
- 1 ceramic, surface mount 1uF capacitor = $0.10
- Not taking into account cost of copper foil or substrate
- Total = $0.60

Video Amplifier

- 4x .22uF Capacitor (Ceramic) = $0.40
- 6x 1nF Capacitor (Ceramic) = $0.60
- 1x 22uF Capacitor (Tantalum) = $0.37
- 7x 10k Resistor = $0.84
- 2x 330 Resistor = $0.24
- 1x 100k Resistor = $0.12
- 1x 470k Resistor = $0.12
- 3x 1k Resistor = $0.36
- 1x 47k Resistor = $0.12
- 1x OPA1679IDR Audio Amplifier = $1.20
- PRSS11S-N20F Bourns potentiometer = $3.65
- Total = $8.02

Other Materials

- Copper Foil Tape (1 inch x 12 yards) = $9.99
    - Only ~¼ was used so that fraction is represented in the total system cost
- 5x Male to Male SMA Connectors = $5
    - Ordered in bulk, these can be found for much cheaper
- Total = $7.50

Materials not included in product price requirement

There are not included in the price as they were deemed consumables that electronics hobbyists, professors, and students would have access to for little marginal cost. The original product requirements have always stated that these were not to be included in total system cost.

- Insulated hook-up wire = $6
    - A basic electronics work supply, a full roll was not used
- PCB blanks, 20 can be had for $5 shipped on eBay, Alibaba etc.
- PCB fabrication equipment or chemical consumables
    - We used the Bantam OtherMill Pro which may not be available for all users
    - Cupric Chloride and Ferric Chloride etching are common hobbyist fabrication methods with miniscule marginal costs
- Arduino or other common uController board for PLL programming
    - Not needed for system function, 1-off programmer

Total System Cost

$50.70 which includes lab supplies such as hook-up wire

Program User Interface

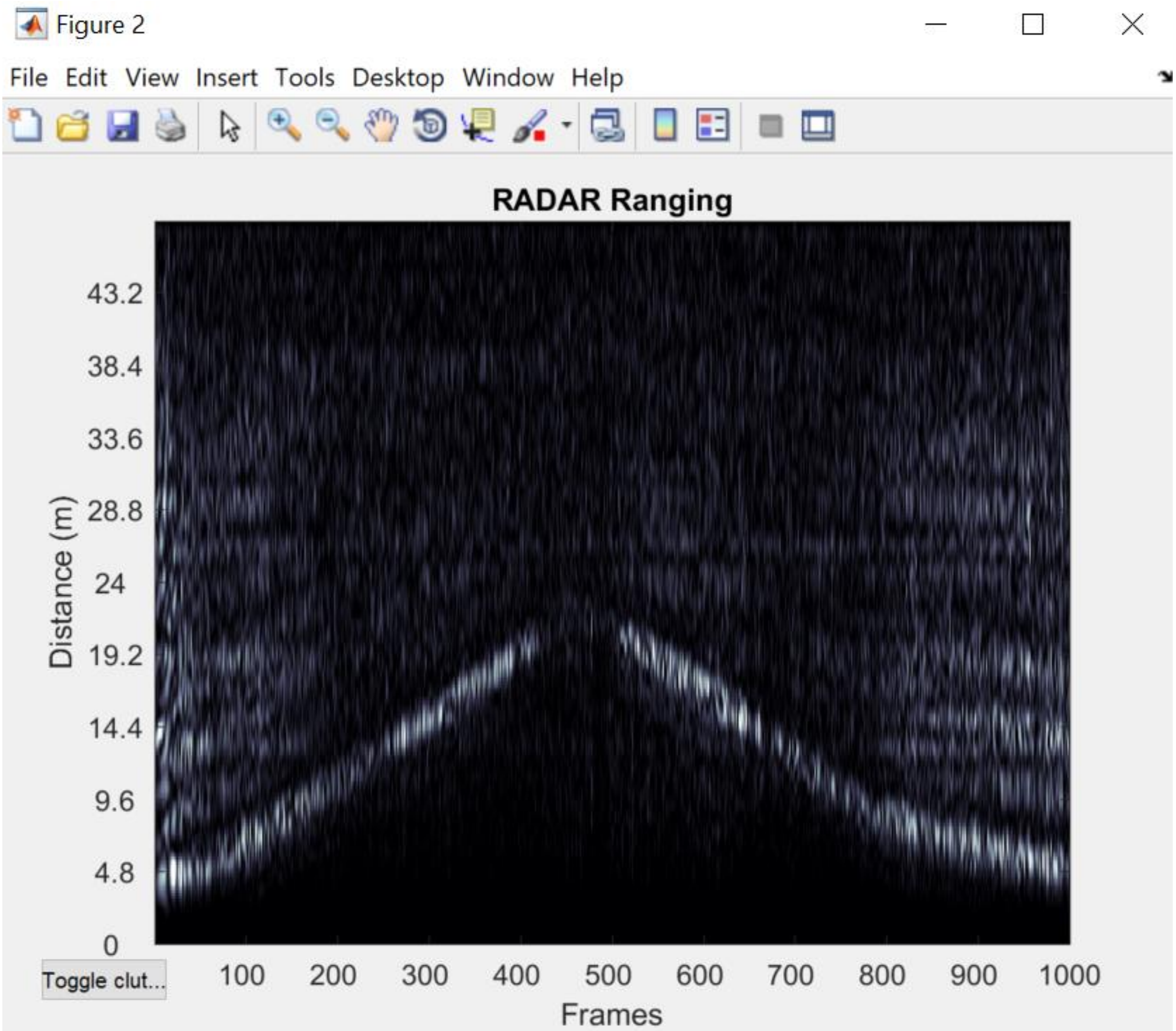


Figure 7. User Interface displaying a person walking towards and away from the RADAR over time

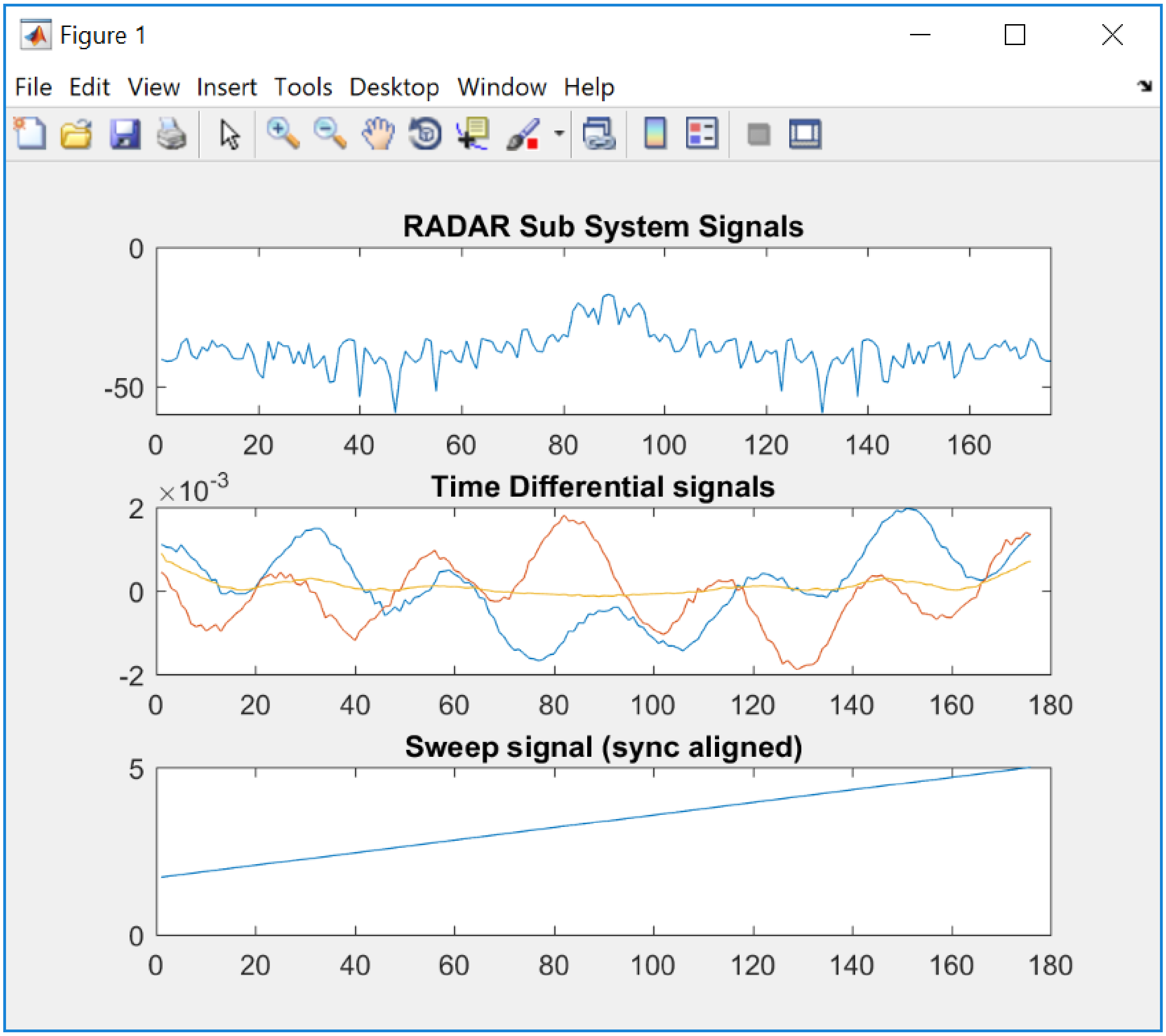
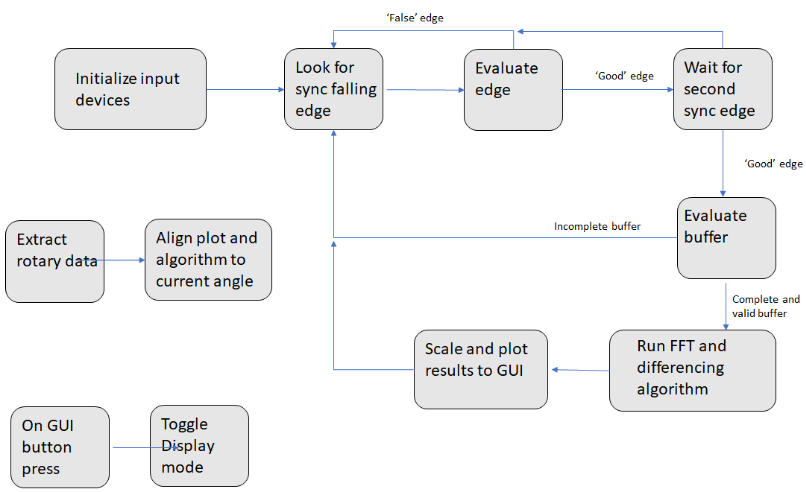


Figure 8. User Interface displaying the various raw signals prior to digital signal processing

The user interface shows a range vs time plot and the input signals pre-processing. It has a button to turn on and off clutter removal.

Software Design Documentation

Program flow overview



Program Description

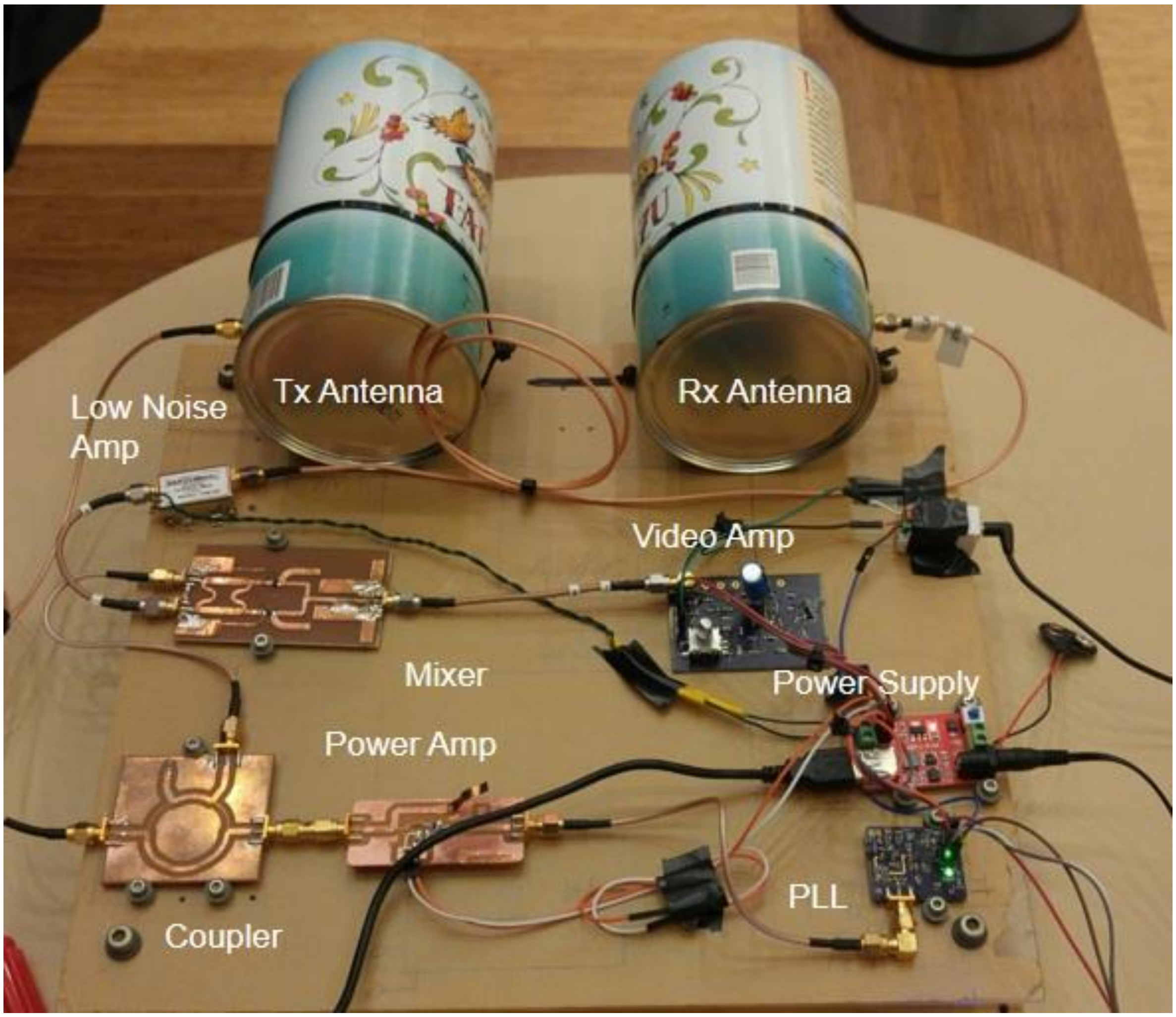
The software program flow is straightforward. The program initializes itself on startup by opening the audio input device, setting up buffers, and calculating range and frequency constants for later use. It reads in data from the audio jack inside of an always running loop. The audio signal is read in and then iterated over. The program looks for the sync pulse falling edge to figure out what section of data to use. This is needed because processing data offset from the sweep causes massive aliasing which vastly reduces performance. The falling edge is then evaluated to test if it is the result of noise or if it is valid. If it is valid the program continues, if not, it goes back to looking for a falling edge.

Once the valid edge is found the program looks for another valid edge. When one is found, the data input buffer is tested to ensure a full sweep has been found. This is needed because the audio device can become overloaded and drop samples. Dropped samples cause aliasing. If a valid buffer is found, the program runs the FFT algorithm, on the data. This processed data is then fed to a differencing algorithm and lines up the previous sweep to figure out what has changed. This reduces static clutter that otherwise would obscure targets. Clutter like walls would cause a very strong signal to be shown that might swamp out the target. From here, the data is scaled based on the specified parameters set up at initialization. The results are output to the GUI.

A GUI button controls the drawing mode for the range vs time plot. When pressed, it toggles on and off the clutter removal. This is useful for demonstration purposes and for calibrating the system against a known distance like from the receiver to a wall.

Happening separately, the input data stream is run through Finite Impulse Response (FIR) filter to adjust the gain on the signal over frequency. This is done to prevent the powerful low frequency signals from nearby reflecting objects from overpowering the lower power further away signals. This FIR filter is designed with a very gradual high pass cutoff frequency with a stopband slope of -20dB / decade. This aims to match the squared term in the free-space path-loss equation. The exact cutoff frequency is left as a tunable parameter for the user based on their observed environment.

Full Build



The picture above displays our full build for the end phase of the project. Our implementation uses the design process explained earlier.

Build Instructions

After the completion and assembly of all the subsystem components, the full system needs to be assembled. We used a plexiglass board as our backplane. The components were laid out such that they could be connected with either short coaxial cables or male-to-male SMA connectors. This ensured a neat and tidy design which helps with portability. The long coaxial cables were used to connect the coupler to the TX antenna and the RX antenna to the LNA. Zip ties were used to secure the excess lengths of wire in place.

The components were secured to the board by marking the outlines of the components are drilling holes for non-conductive mounting terminals to be attached. Be sure not to use conductive terminals as we did and this killed on of our boards.

The secured components are then connected to the power supply using hook up wire. We recommend using tape or zip ties to keep these wires tidy to prevent them from getting snagged and coming loose.

The antennas were mounted to drill holes using zip ties. The video amplifier output was connected to the audio cable through an adapter which was secured using tape. This solution was temporary but hot glue, zip ties, or Velcro also works.

Startup sequence

Power the subsystems on by connecting power to the power supply and pressing the button. A red LED should turn on. Now connect the uController to the PLL board. Run the programming script (should run at power up) an ensure the green LED on the PLL board turns on. This indicates the PLL has a lock. Now connected the audio cord to the laptop and select ‘line in’. Run the MATLAB script and look for results. If nothing is plotted, swap the 1 and 2 in the script for the audio reading. This changes the Left + Right channels which may be swapped on your setup.

Conclusion

The biggest change we made from the first phase of our project to the final phase was use different antennas. Originally, we used Pringles cans as our antennas but their operating frequency was too high for our needs. We switched to coffee “cantennas” that operated very nicely at our desired 2.4 GHz. The final phase of our project involved each teammate replacing a Mini-Circuits RF block with our designed and fabricated circuits. We used AWR to simulate output behavior in each of our components and implemented a variety of fabrication methods. We ordered some designs from OshPark and used ECE department Makerspace fabrication equipment for others. After each component was manufactured, we verified testing results using appropriate vector network analyzers (VNAs). We verified the range of our radar through incremental tests inside and outside. We were able to view distance of moving objects through a Matlab plot. We verified upper limit in our range detection (about 150 feet) by testing in the full length of an academic building hallway and outside in a field.

Works Cited

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