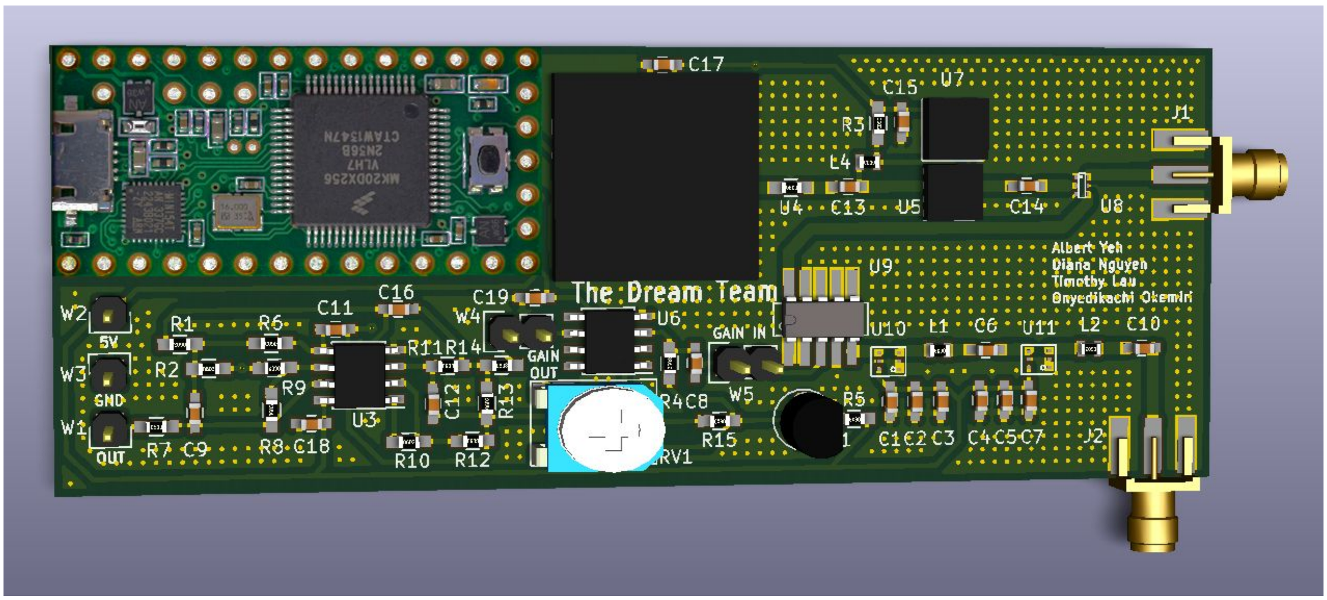
THE DREAM TEAM

Frequency Modulated Continuous Wave Radar



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Course: EEC 134 RF Systems Design

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Abstract:

The goal of this project was to design a frequency modulated continuous wave (FMCW) radar system. This FMCW radar system should be capable of determining the distance or range of an object. In order to determine the distance of an object, we examined the differences in frequency between the transmitting and receiving signals; this can be found by running MATLAB and Audacity. When designing the FMCW radar system, we had to take in consideration in making the system as light as possible, maintaining a $300 budget, and getting the radar hit the target as accurate as possible.

Recap and Plan for Improvement:

Power Consumption: 1.05 Watts
Weight: 550 Grams
Accurate Detection/Range: 90 meters

Some plans to improve the system include changing the RF blocks to pcb components to save both weight and power, as well as streamline the entire radar system. Getting rid of weight from the added sma cables and connectors would greatly minimize the overall footprint of the radar.

Block Diagram/ADISimRF:

To begin our FMCW radar design, we started off making a block diagram layout of what the components should be on both the transmitting and receiving side. The block diagram layout is shown on Figure 1 below. Once we have created a scratch design, we would implement the design using ADISimRF. We've researched the components we plan to use for our radar design and adjusted ADISimRF according to the component. If there was a red box shown on ADISimRF, we would have to find a difference component that fit outs specifications. Also, this component must be within our budget.

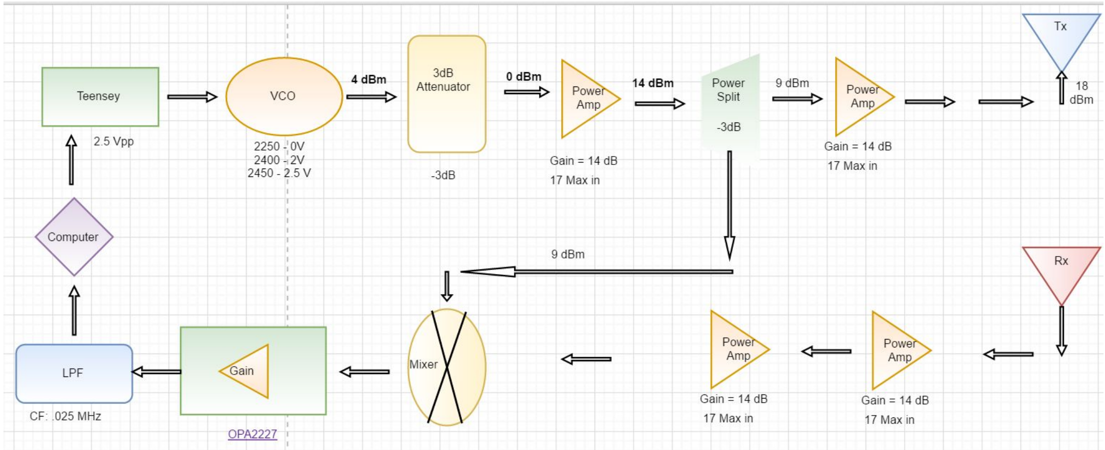


Figure 1: Block Diagram

Parts:

Component	Vendor	Model #	Price
VCO	Mini Circuits	ROS-2536C-119+	$19.95
Low Noise, Monolithic Amplifier	Mini Circuits	PMA-5455+	$1.49
Attenuator	Digi-key	AT0603T03ECATD	$6.91
Low Noise Amplifier	Digi-key	HMC667LP2	$11.22 (x2)
Mixer	Mini-Circuits	MCA1-42LH+	$7.95
Power Splitter	Digi-key	PD2328J5050S2HF	$0.74
Gain Stage	Texas Instruments	OPA2227/OPA227	$3.25
Lowpass Filter	Mouser	MAX291	$6.66
RF Choke	Mini Circuits	TCCH-80+	$3.45

Table 1: Parts List

Table 1 is the listed parts we have purchased to help put together our radar system. We purchased double of each component, just in case one of the components end up being burnt out. The parts list does not include the purchased resistors, capacitors, or inductors. Everything listed are purchased as SMD components that will be soldered onto the combined RF and baseband PCB. What would be later explained is that the rest of the spare components will be soldered on our second PCB that is only consists the baseband.

We wanted to reduce as much weight as we can, so majority of our components are SMD. Refer to the Appendix section to view the datasheets of each component.

Friis Transmission Equation:

The Friis Transmission equation is used to calculate the power received from one antenna, when transmitted from another antenna separated by a distance R. The Friis Transmission Equation operates at a frequency *f* or wavelength lambda. The equation is shown in Figure 2.

$$\frac{P_r}{P_t} = G_t G_r \left(\frac{\lambda}{4\pi R}\right)^2$$

Figure 2: Friis Transmission Equation

Referring to Figure 1,

Pt = power (dBm)

Gt = Gr = gain of transmitting and receiving antenna

λ = wavelength of system, using c = λf, when c = speed of light and f = operating frequency

σ = cross section of target, in our case it was 0.09m2.

R = range of target

Pr = received power (dBm)

We used the Friis Transmission equation to help us calculate for our power received to figure out how much amplification the signal would need on the receiver end. The goal in our design using the equation was to detect a minimum distance of 5 meters and to a maximum distance of 50 meters. In order to reach our goal, we would need to increase the amplification of our signal. In order to do this, we would need to find amplifiers that fit our specifications and budget. When running the simulations on ADISimRF, we tried to find the proper components that could help us hit up to 50 meters.

Transmitter:

We first started off with designing the transmitter side of our radar using ADISimRF.

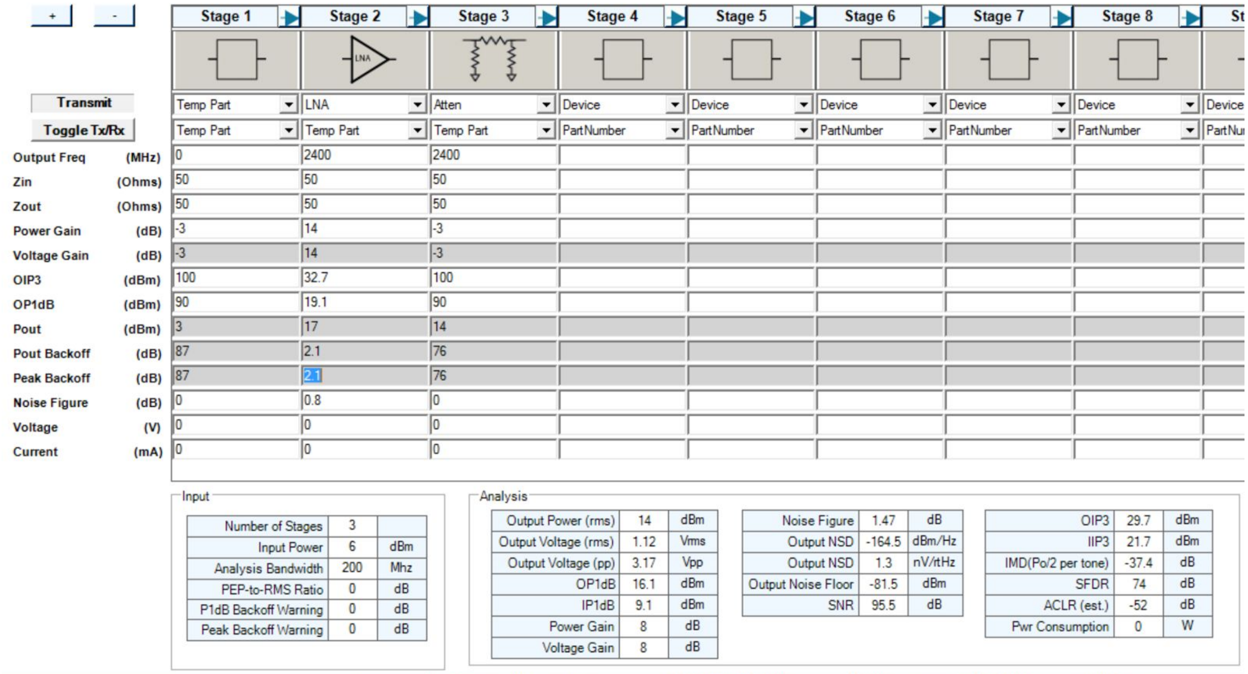


Figure 3: Transmitter Simulation using ADISimRF

As you can see in Figure 2, we have an attenuator, an LNA, and splitter. The attenuator and splitter gives a -3 dB power gain. The power amplifier we have chosen was PMA-5455+ that gave a gain of 14 dB. Our entire transmitting side consists of a VCO, attenuator, power amplifier, and a power splitter. The VCO provided an output power of +6 dBm. The VCO is inputted as the input power of +6 dBM in ADISimRF. ADISimRF assumes that our output power for our transmitter side would give out an output power of 14 dBm with an analysis bandwidth of 200 MHz, noise figure of 1.47 dB, and power consumption of close to 0 W. As you can see, there are no “red boxes” highlighted anywhere in ADISimRF. It was kind of difficult to find a power amplifier an affordable power amplifier operating at the appropriate frequency.

Receiver:

We designed the receiving side of the radar using ADISimRF.

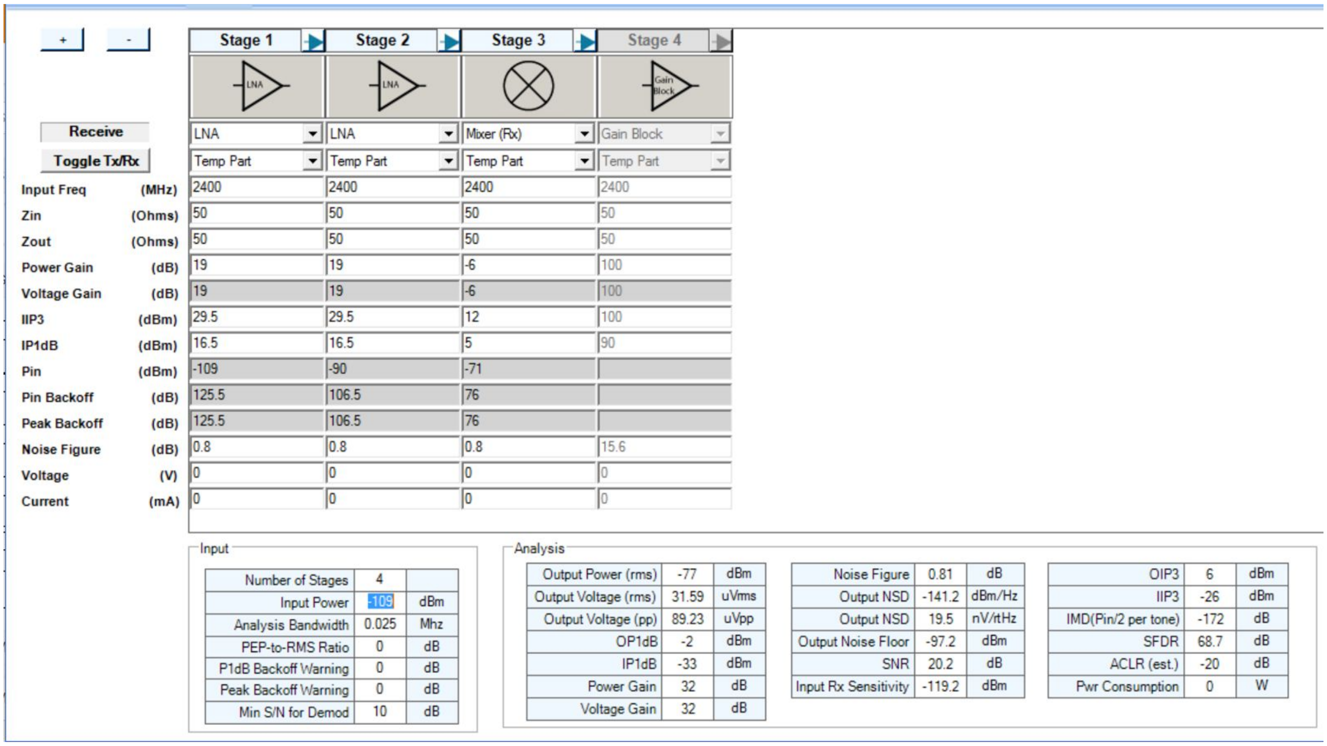


Figure 4: Receiver simulation using ADISimRF

From Figure 4, the receiving side of the radar consists of two LNAs, a mixer, and a gain stage. For now, the gain stage is omitted in the simulation. Having two power amplifiers seemed just enough for our system to save on power consumption. The more amplifiers, the greater the power consumption. The purpose of having the gain stage was to amplify the rest of our system. The two power amplifiers both have a power gain of 19 dB. The input power highlighted in Figure 4 is the calculated power received to reach 50 meters. The signal would then get amplified to -77 dBm after the mixer.

Details of the components used can both be found under the Appendix and Datasheet section.

Radar Design:

Circuit Schematic:

With simulation complete, we next moved onto the actual circuit design. On the transmitting side, the radar system schematic consisted of the Teensy 3.2 Microcontroller, Voltage Controlled Oscillator, 3dB attenuator, Power Amplifier, Mixer, and Power Splitter. The receiving side contains 2 Low Noise Amplifiers, Gain Stage, and Low Pass Filter. Along with the transmit and receive circuit are a 2.5V reference voltage and testpoints to power, ground, and output of the circuit.

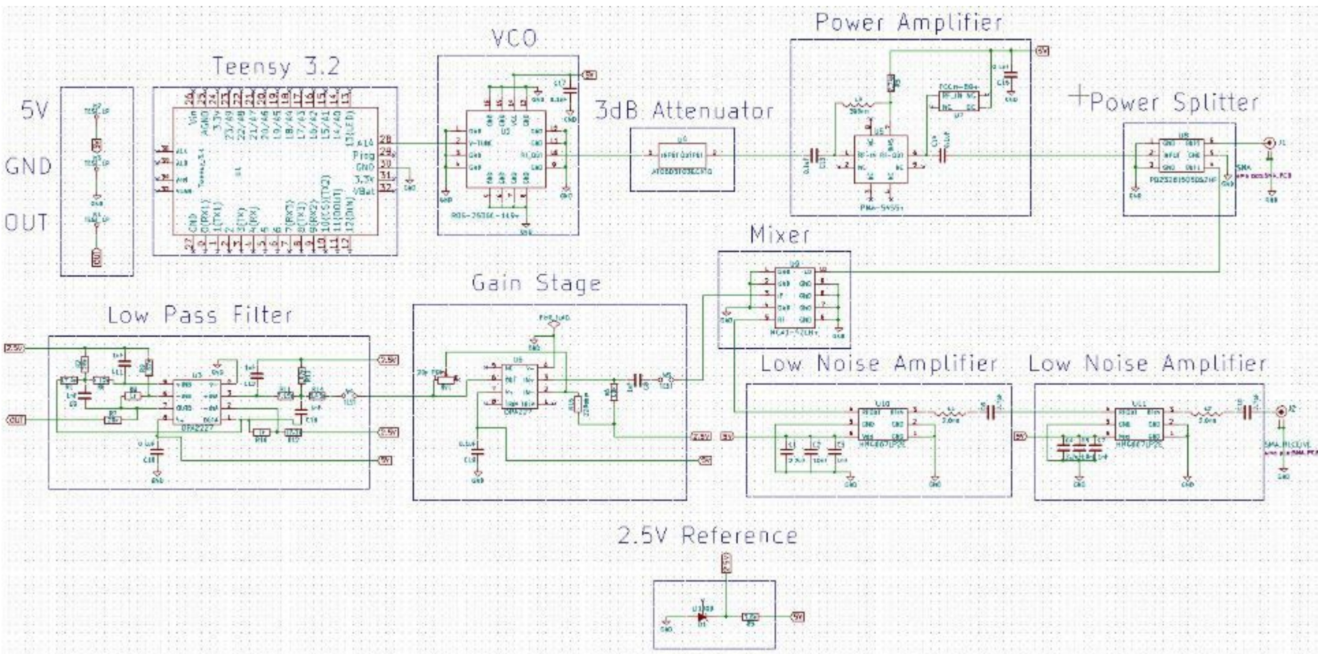


Figure 5: Radar System Schematic

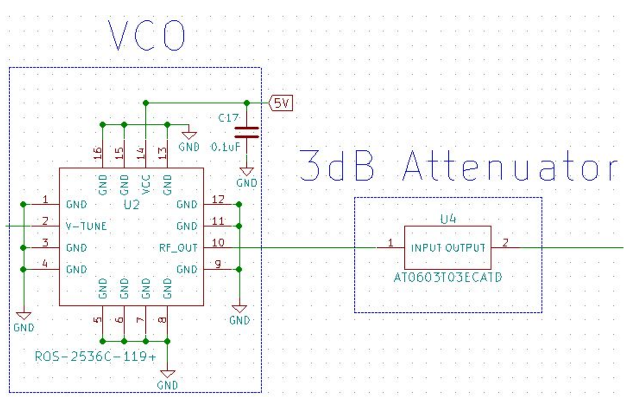


Figure 6: Voltage Controlled Oscillator and 3dB Attenuator Module

The Voltage Controlled Oscillator Module takes in input from the Teensy 3.2 into the V-Tune pin and from the 5V power rail which goes through a 0.1uF bypass capacitor. The output of the oscillator is out of the RF_Out pin and goes into a 3dB attenuator to prevent any reflections from damaging the VCO.

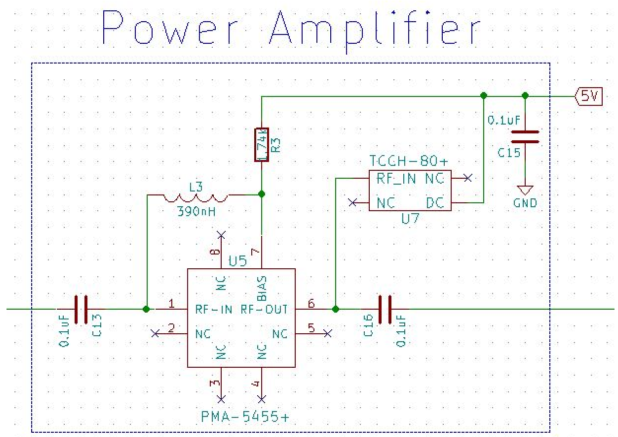
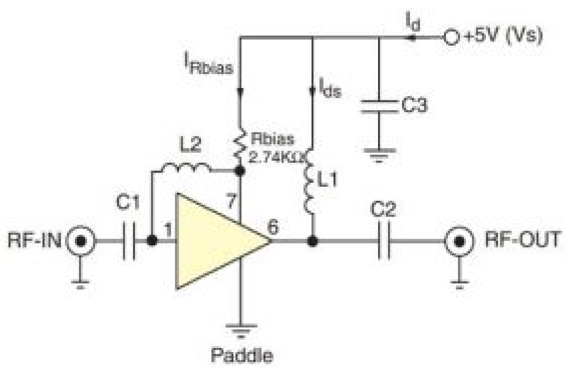


Figure 7: Power Amplifier Module



COMPONENT	VALUE/PART NUMBER
DUT	Mini-Circuits PMA-5455+
C1, C2, C3	0.1 uF
L1	Mini-Circuits TCCH-80+
L2	390 nH
R1	2.74k Ohm

Figure 8: Power Amplifier Biasing Circuit

In the Power Amplifier Module, we implemented the recommended biasing circuit found on the PMA-5455+ datasheet.

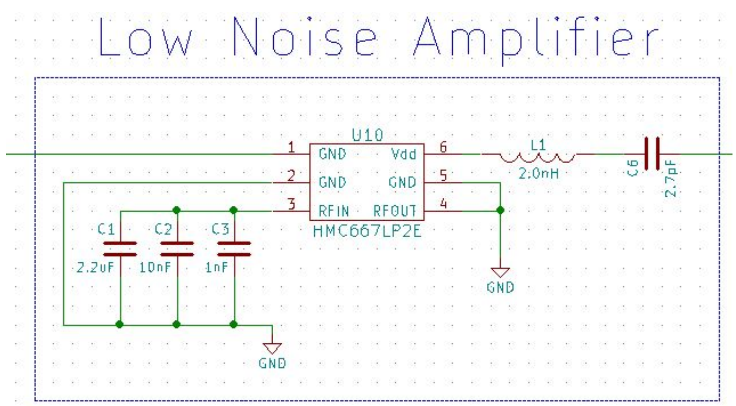
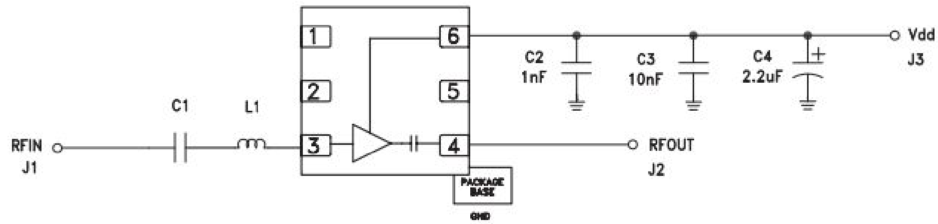


Figure 9: Low Noise Amplifier Module



Components	C1	L1	Evaluation PCB Number
Broadband	2.7 pF	2.0 nH	121891

Figure 10: Low Noise Amplifier Biasing Circuit

For the Low Noise Amplifier Module, we instantiated two of these modules and implemented the recommended biasing circuit found on the HMC667LP2E datasheet.

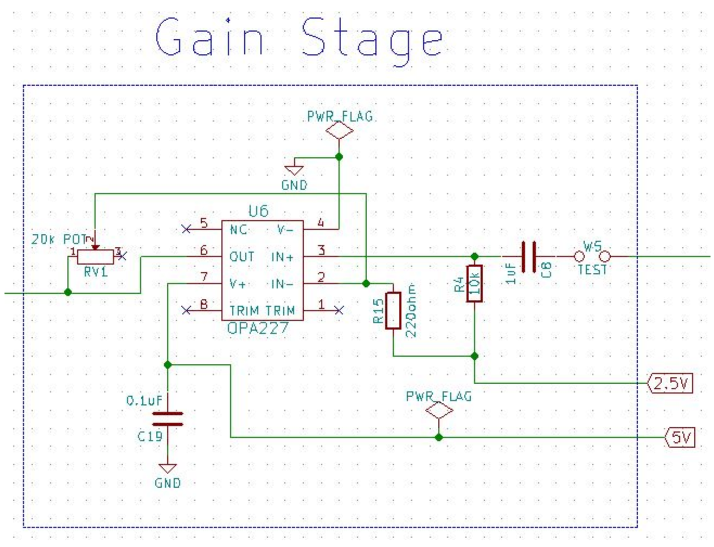


Figure 11: Gain Stage Module

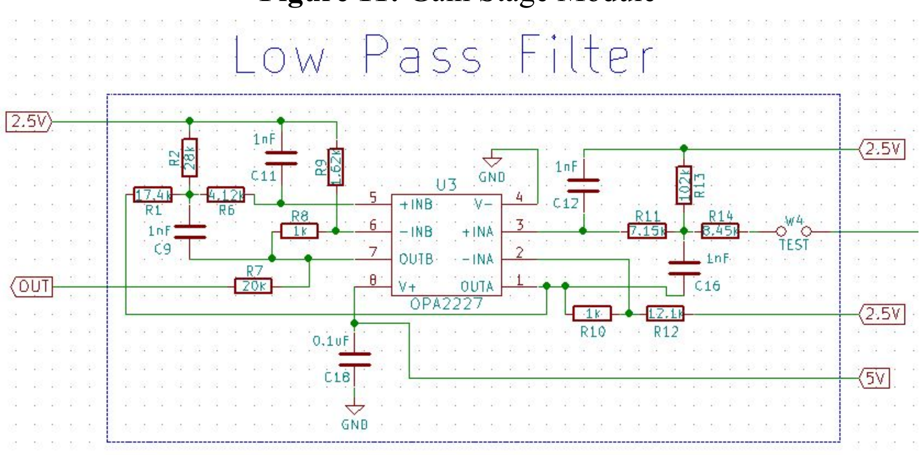


Figure 12: Low Pass Filter Module

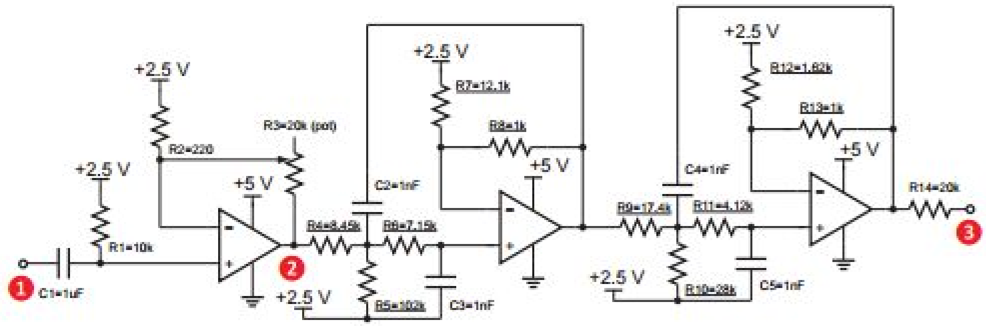


Figure 13: Gain Stage and Low Pass Filter

Moving onto the Gain Stage and Low Noise Amplifier Modules, we created the two modules and implemented the recommended circuit schematic from the Texas Instruments WEBENCH Filter Designer. Between points 1 and 2 on Figure 13 is the Gain Stage and between points 2 and 3 consists of the Low Pass Filter.

PCB Layout:

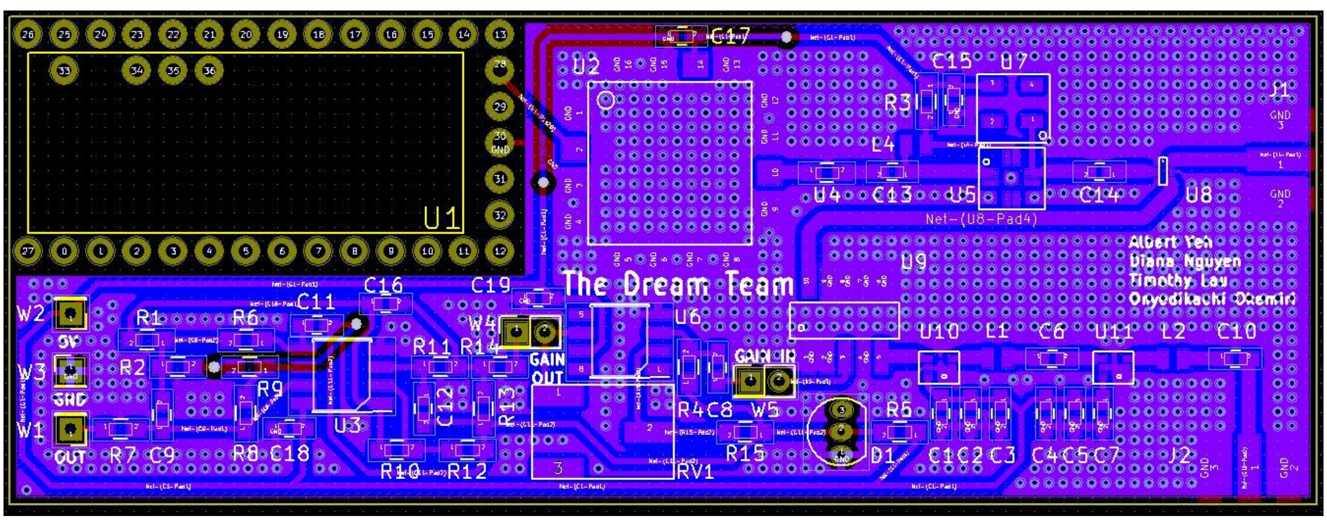


Figure 14: Radar PCB Layout

With the circuit schematic complete, we then moved onto the PCB layout. Generally, every component placed on the PCB matches the location of where they are on the radar system schematic. The RF traces are 37 mils wide for 50 ohm terminations while the baseband traces are 15 mils wide. Also, the Teensy 3.2 Microcontroller is not included in the ground plane because the digital circuits are rather noise and this may distort our signals.

3D Model:

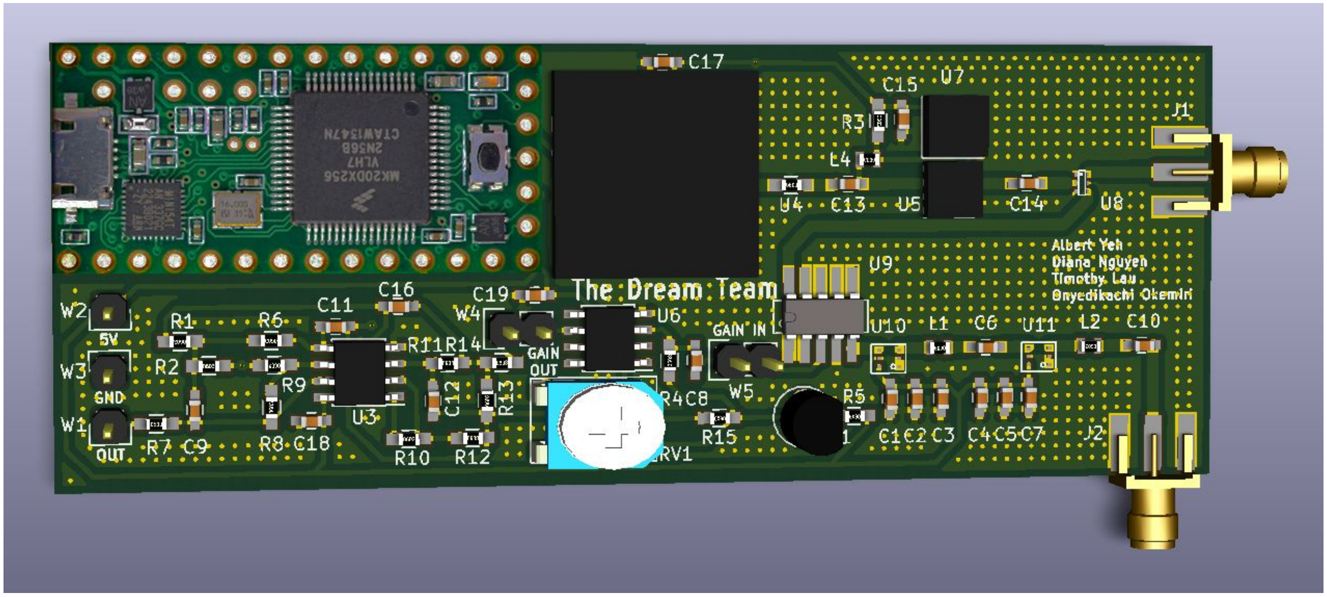


Figure 15: Radar System 3D Model

After we laid out our components on the PCB, we used Kicad to generate a 3D view of our board along with the circuit components soldered on. To make our model look more realistic, we also used Photoshop for touch ups.

Assembly:

Quarter 1:

The assembly of our quarter one system followed the lab manual closely. The general diagram of the system is shown below. The ADC is replaced by the computer's sound card and an audio cable. The modulator was replaced by the Teensy and the MCP circuit. Our antennas were two safeway coffee cans. The low pass filter and the baseband amplifier were built on a breadboard based on the circuit shown in Lab Manual 1. The circuit is also shown below. The rest of the components consisted of Mini-Circuits block components. We built the modulator circuit which consisted of a regulator circuit using an LM317, a voltage reference circuit using an LT1009, and a function generator using the Teensy 3.1 and an MCP4921.

We fed the function generator signal into the VCO block component. Then by using male to male SMA connectors we connected each block component. After the VCO we connected a power splitter. After the power splitter we connected a power amplifier and then an SMA cable to a coffee can antenna. To the second output of the splitter we connected the LO port of the mixer. Then the RF input side of the mixer, we connected another power amplifier with the receiving coffee can antenna. The IF output of the mixer is fed into our baseband circuit which consists of the gain stage and the low pass filter. The baseband circuit was made using the TL974. An audio cable is then attached to the output of the baseband circuit. One channel is the output of this circuit while the other channel is the sync of the Teensy.

We screwed all these components onto a wooden board for stability and mobility. The cans were also screwed on using L-brackets.

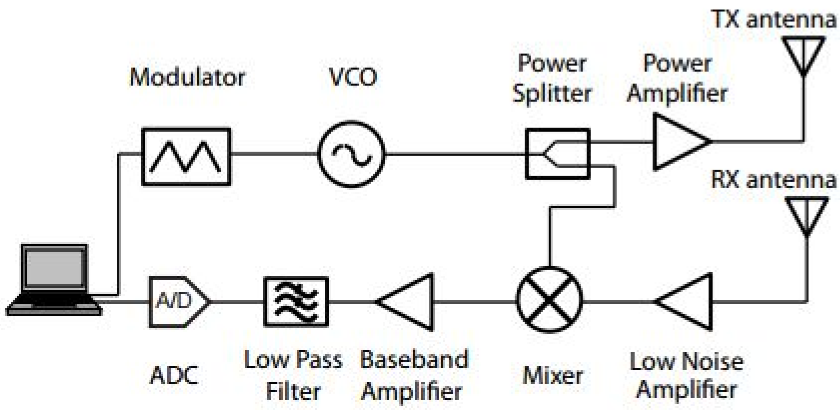


Figure 16: Radar System Diagram

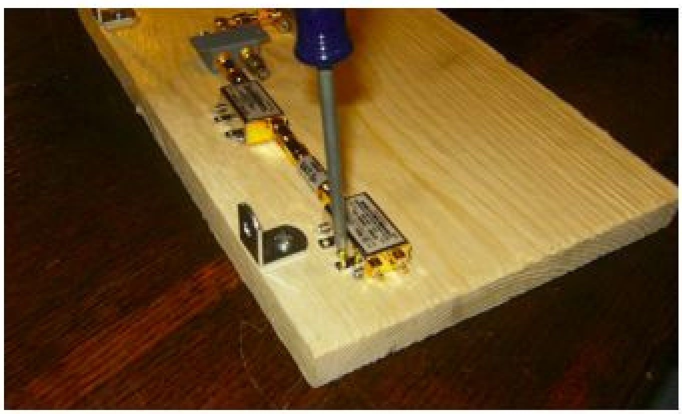


Figure 17: Quarter 1 Block Layout

Quarter 2:

The assembly for quarter 2 was a little more difficult. We had to solder on SMD components which was difficult when it came to the active components. The amplifiers, mixer, and VCO were some the harder components to solder. The pin outs on the these components were so small it was very easy to short them. The VCO footprint that we created for the first PCB run was a little too large. We had some difficulty soldering this in place. We needed to use extra solder paste to reach the pins but luckily a majority of the pins were grounded. The only way to tell if the amplifiers were soldered on right was to check the current draw after each component was soldered in place. This made sure that each amplifier was drawing the correct amount of current. Even after making sure each component was working correctly it was difficult to understand why the PCB was not performing correctly. We tried using an SMA cable connected to the spectrum analyzer to see if amplifiers were amplifying signals and if the VCO was outputting a range of frequencies. This was still a difficult process because it was inaccurate as the SMA acting as an antenna could receive multiple signals and noise. It seemed that the amplifiers were not amplifying the signal even though they were drawing current. We tried soldering the entire PCB two times, once using solder paste and a hot plate and another time using solder paste and an oven. It was much easier to use the oven because we didn't need as much solder paste and with small pins this was helpful. We could not see a signal out of the IF output of the mixer and we were not able to find a solution. Eventually we moved back to our quarter one system.

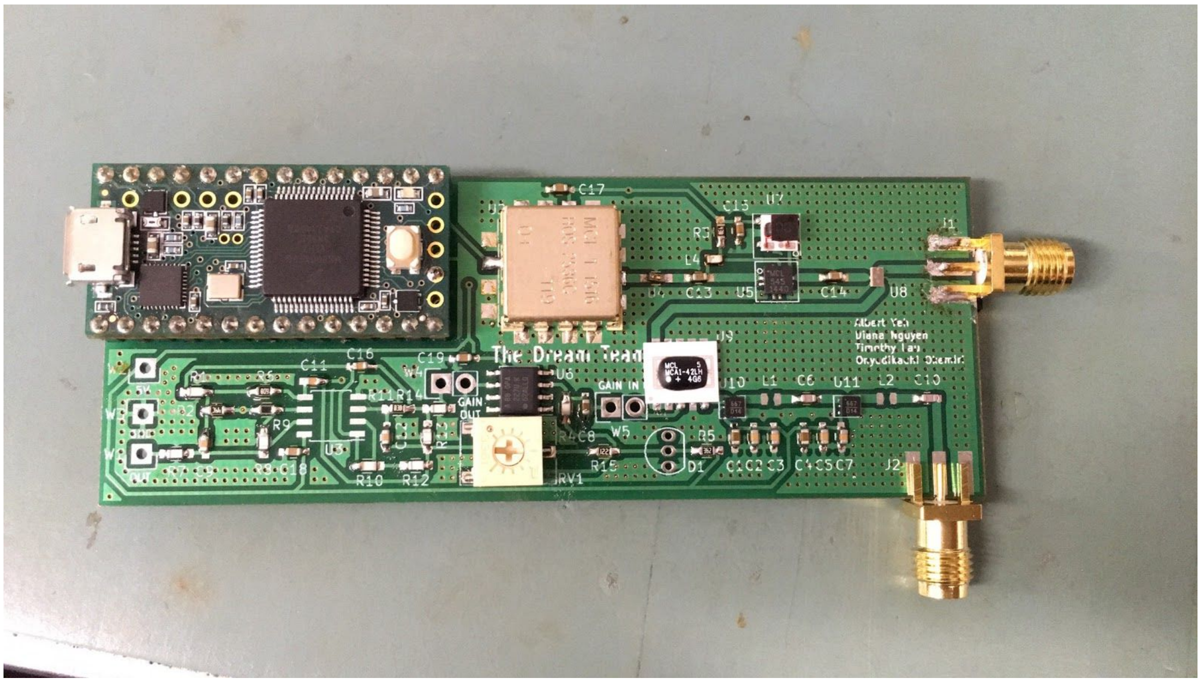


Figure 18: Quarter 2 PCB

Final Assembly:

Our final system consisted of a hybrid. We used SMD PCB components for the baseband and SMA Blocks for the RF side. In doing so we, had to sacrifice on the weight of our overall systems since the RF blocks are much larger and heavier than their pcb counterparts. Since the competition was only going to be measured up to 50 meters, we tried to minimize the number of RF amplifiers we used to reduce both weight and power consumption. Any extra performance would not be worth the increased power and weight. We connected the RF components with sma cables and connectors. The Transmit side was connected via SMA connector, while the IF signal was connected via an SMA to Alligator Clip Connector we had purchased originally for probing RF traces.

Testing/Results:

Phase 1 - Quarter 1:

We had to move back to using our quarter 1 system, because our PCB from quarter two was not giving the correct signals. We decided that it would be a lot easier to troubleshoot and test the quarter system to get a working project. After the first quarter we were only able to get the system to recognize a change in movement, but this analysis was not accurate in reference to the plot. If we started close with a metallic object and moved away and then came close again, the plot would display two pulses which represented when the object was close. This was very confusing and we found that there could be multiple problems. There was a coupling issue within our audio cable because we saw the sync signal mixed into the IF and baseband audio file. We decided to use the Analog Discovery which got rid of the Stereo Input and the audio coupling. Then we tested each of our components to make sure that they were working. We found that we could tell if an amplifier wason by looking at the current draw from the power supply. The connecting pins for the amplifiers were bad on some so it was it was difficult to connect correctly to them. We then came to our real problem. We tested the mixer using two TPI synthesizers. We saw that our mixer that we were using had an IF output with a 100 mV output sine wave. The signal was very fuzzy and not strong. We found that a brand new mixer gave us a 1.5 V sine wave output and it was a very clean signal. After replacing the bad mixer we found that the our system began to work. Our signal would change in frequency depending on the distance of the metal object reflecting the radar transmission. The plots below show tests that were done within the Kemper lab room so there is some noise that is reflected. We see plots with horizontal lines representing a stationary object and then also plots with triangular and wavy lines which represent the object moving at a distance from the radar. We were able to hit 50 meters using this quarter one system when we tested out at hutchinson field. This gave us a much cleaner signal.

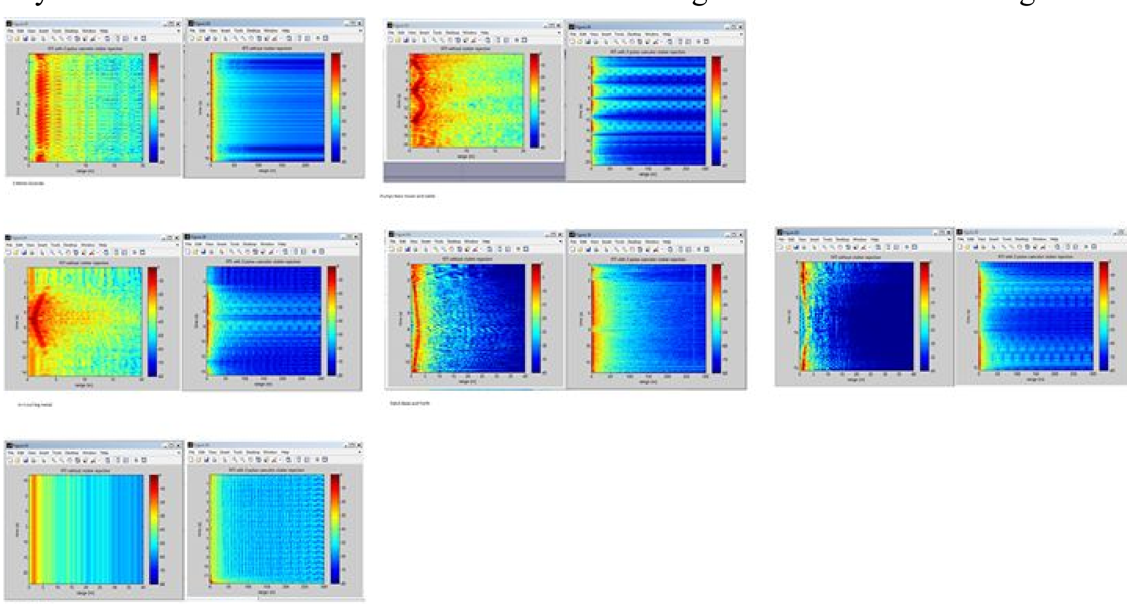


Figure 19: Quarter 1 Testing

Phase 2 - Quarter 2 PCB:

Our quarter two system did not work. We tried testing individual RF components but this was very difficult as explained in the assembly section. We were able to get the transmitter side working but the output power was very low. The VCO was outputting a span of frequencies so we know that the VCO was working. But our output power was around 0 dBm when it should have been around 14 dBm meaning that the amplifier was not amplifying the signal. This was confusing because the amplifier was also drawing current. We could not figure out if the receiver side was working because we could not see a signal out of the mixer. We had tested our baseband circuit on the PCB with a function generator input and it worked fine. We were never able to get the RF receiver side working so we moved on to the quarter one system.

Phase 3 - PCB + SMA:

We found that our pcb had some of the components soldered on backwards, namely the amplifiers. This caused extreme attenuation on our recieve side making our baseband circuits completely unusable. We switched to a hybrid of pcb and sma components to salvage any working systems we had. We had to sacrifice weight and power consumption for a working system.

Phase 4 - Adding Amplifiers:

Now that we are using the sma components we were now able to add amplification as necessary. Towards the beginning of our outdoor testing we were under the impression that our final score for the competition was going to be based on final distance, so we added 3 14dBm amplifiers to the transmit side since that's all we could actually benefit from due to compression. There were also 2 amplifiers on the receive side to ensure we could reach the furthest distance. However this was at the cost of power consumption with our total draw nearing 3 Watts.

Final Results (Furthest Distance):

After learning max distance was no longer a factor we decided to remove amplifiers for the actual competition. We were able to significantly reduce power consumption and weight for our final measurements and we easily measured objects at 50 meters. We did not test the max distance of the final configuration, but with all of the amplifiers attached we reached roughly 140 meters.

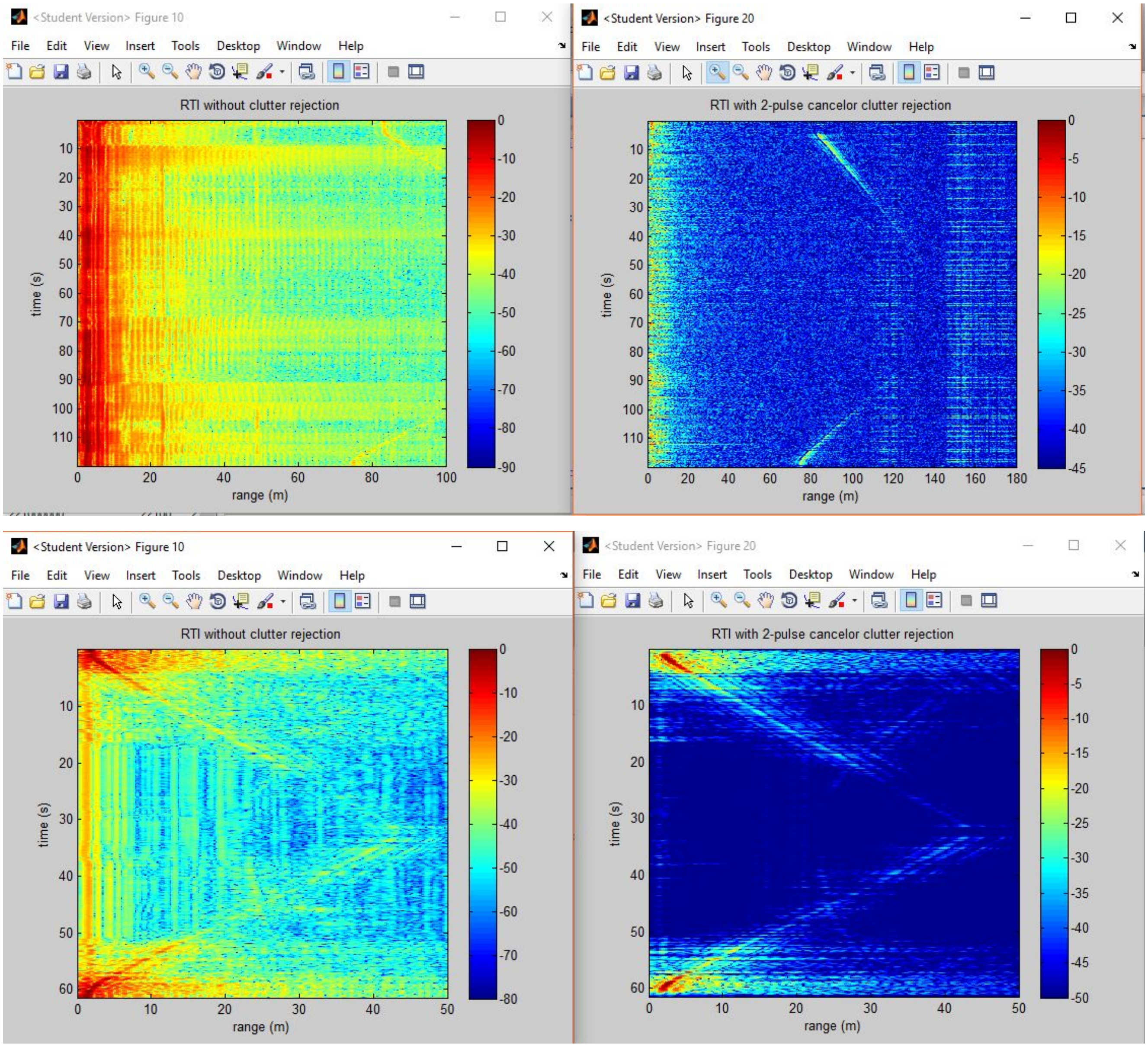


Figure 20: Test Results

Conclusion/ Final Remarks:

For Quarter 1, we followed the given instructions from the lab manual. This lab manual can be found in the Appendix. For Quarter 2, we had to implement our own design and attempt to make it better. Our original goal was to design our PCB using Allegro but instead we ended up using KiCad. This was due to time and inconvenience of not having Allegro installed on a personal computer. Another original goal of ours was to combine both the RF and baseband together on PCB. Unfortunately, our LNA components were burnt out and this was due to soldering on the wrong orientation and powering the LNA. Our final design resulted to only having the baseband PCB board connected with SMD components. Our final design was a success. We were able to detect objects that surpassed a distance past 50 meters. Originally we thought the maximum distance would be considered as a factor in the competition and we attempted to add more amplifiers to make this happen. The competition focused on how accurate our radar work between the distances of 5 meters to 50 meters as well as power consumption and weight. We enjoyed doing the competition as we have all worked hard on trying to make the radar work.

Appendix:

Datasheets:

VCO (ROS-2536C-119+):

https://www.minicircuits.com/pdfs/ROS-2536C-119+.pdf

Low Noise, Monolithic Amplifier (PMA-5455+):

https://www.minicircuits.com/pdfs/PMA-5455+.pdf

Attenuator (AT0603T03ECATD)

https://atceramics.com/UserFiles/AT_attenuator.pdf

Low Noise Amplifier (HMC667LP2E)

http://www.analog.com/media/en/technical-documentation/data-sheets/hmc667.pdf

Mixer(MCA1-42LH+)

https://www.minicircuits.com/pdfs/MCA1-42LH+.pdf

Power Splitter(PD2328J5050S2HF)

https://www.anaren.com/sites/default/files/PD2328J5050S2HF_DataSheet_RevA.pdf

Gain Stage (OPA2227/OPA227)

http://www.ti.com/lit/ds/symlink/opa2227.pdf

Lowpass Filter (MAX291CSA)

http://datasheets.maximintegrated.com/en/ds/MAX291-MAX296.pdf

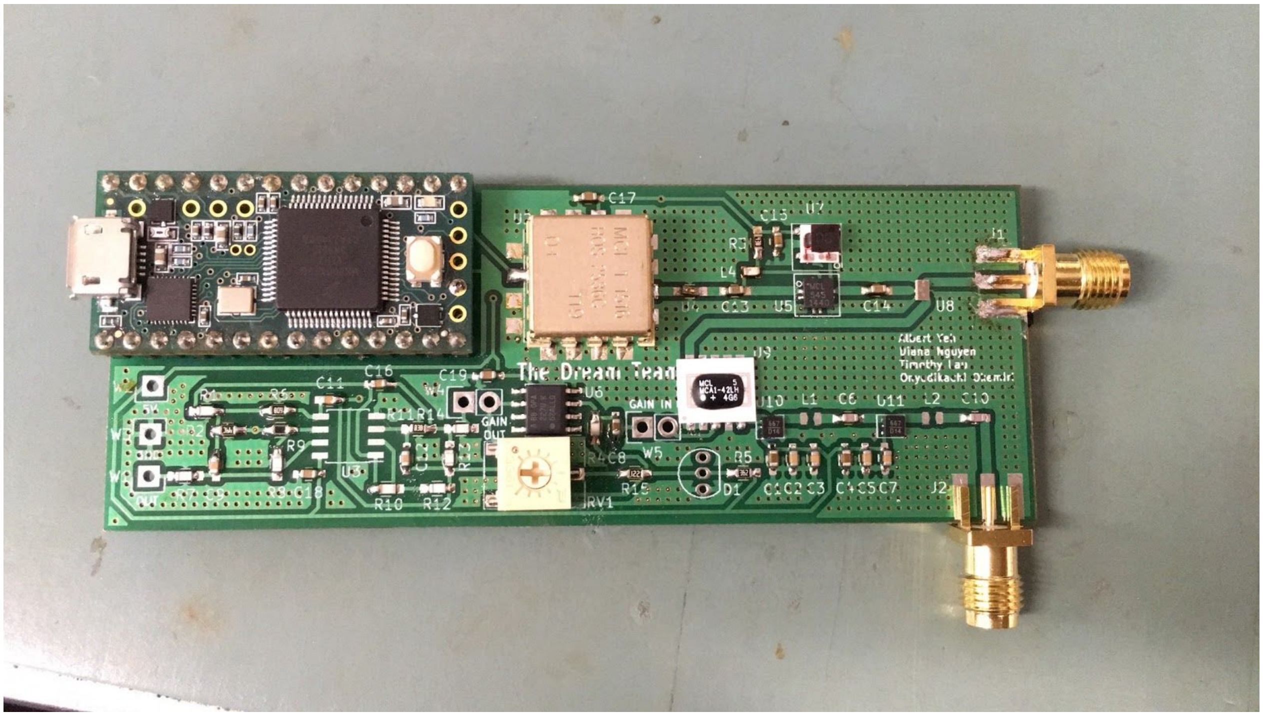
RF Choke(TCCH-80+)

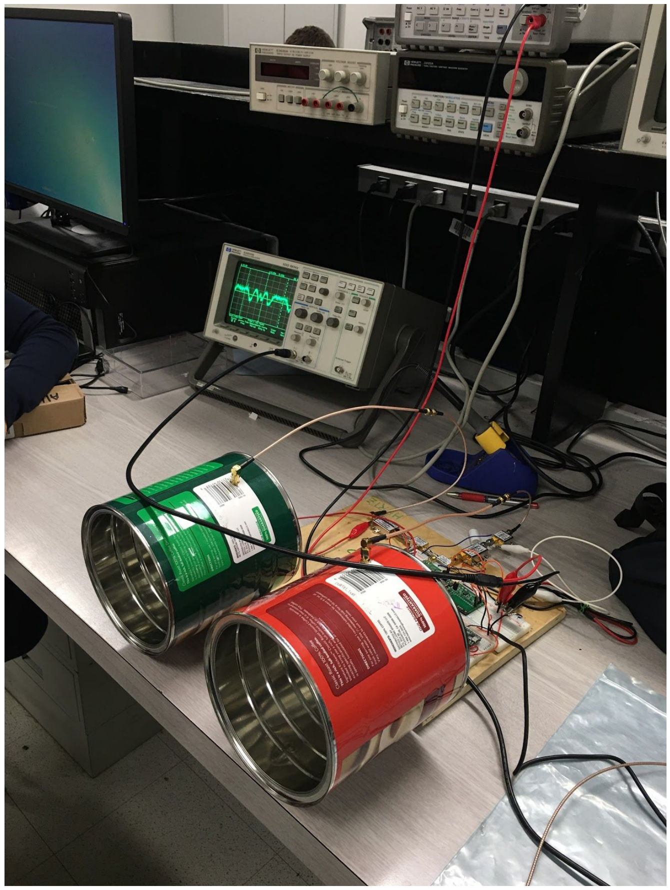
https://www.minicircuits.com/pdfs/TCCH-80+.pdf

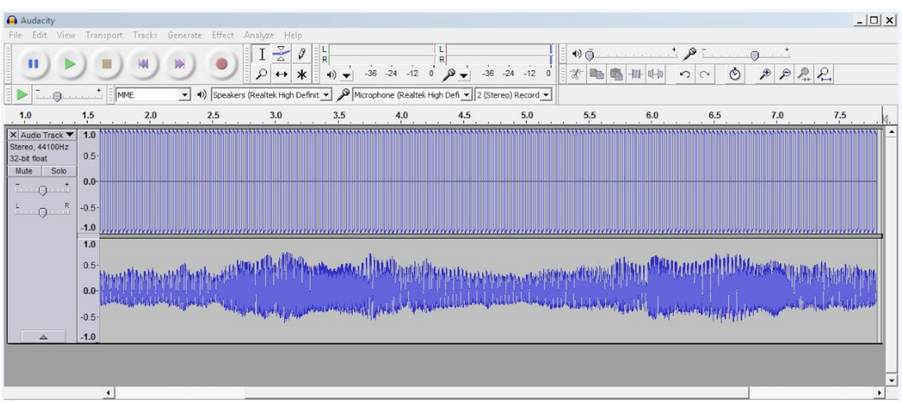
Patch Antenna

https://www.amazon.com/Alfa-APA-M25-directional-connector-WL-ANT-157/dp/B00R1PA9EO/ref=sr_1_2?ie=UTF8&qid=1486200020&sr=8-2&keywords=patch%20antenna%202.4%20ghz

Photo Gallery:



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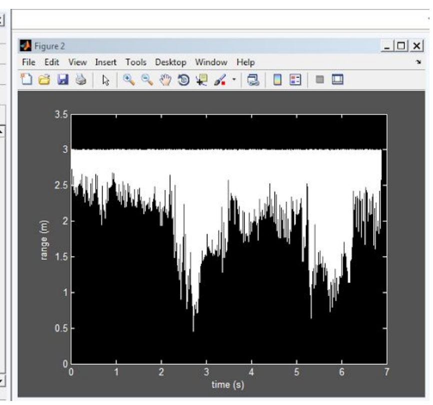
Figure 2
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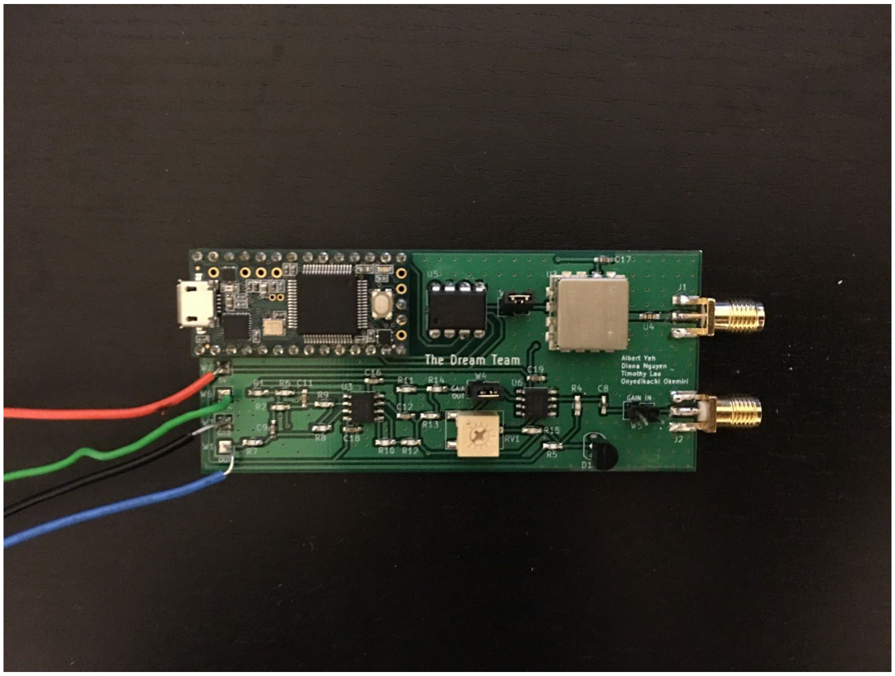
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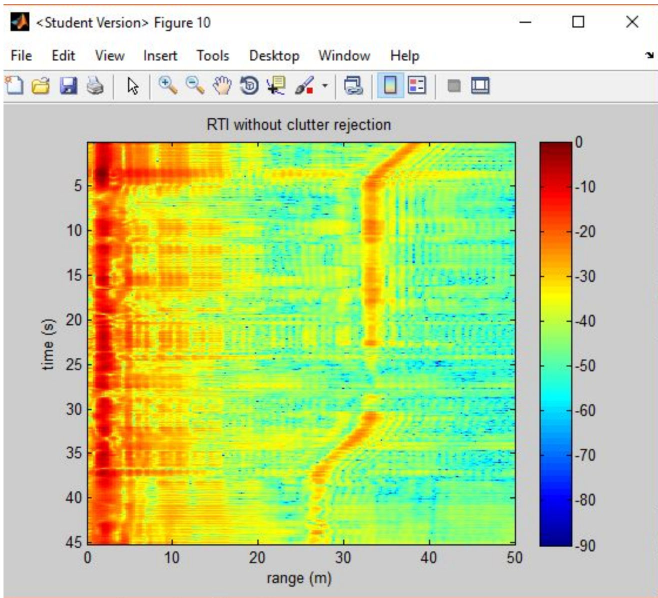
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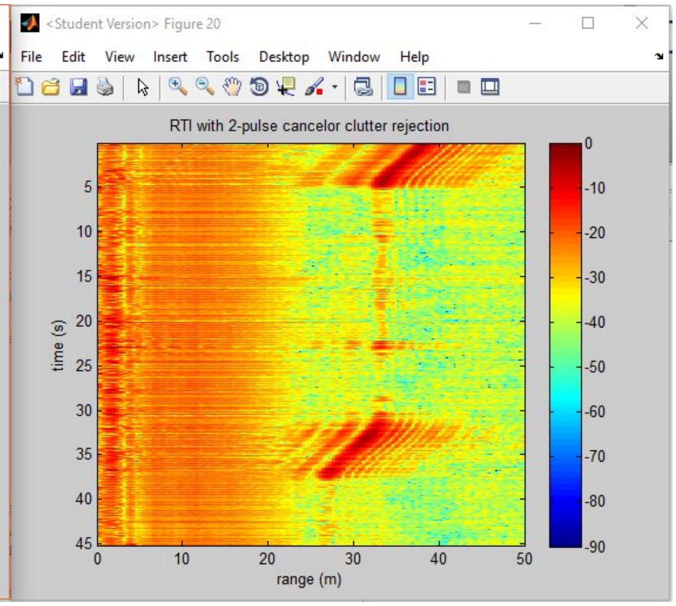
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