

# Final Group Report

**Team RadioFreqs**

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## Table of Contents

|                              |       |
|------------------------------|-------|
| Abstract .....               | 1     |
| Design Rules .....           | 1     |
| Overall Design Details.....  | 1-3   |
| PCB Design.....              | 4-5   |
| Antenna Choice.....          | 6     |
| Final Design Testing.....    | 6-7   |
| Complete System Results..... | 7-11  |
| Competition Day .....        | 11-13 |
| Conclusion.....              | 13    |
| Acknowledgements.....        | 15    |
| Appendix                     |       |
| A. Python Code.....          | 16-17 |
| B. MatLab Code.....          | 17-18 |

### Abstract

During fall quarter, we built a 2.4GHz frequency modulated continuous wave (FMCW) radar system which can perform range and doppler using cantennas. During winter quarter, we built our own 2.4GHz radar system within a competitive atmosphere where every team tries to minimize power consumption, minimize overall weight, and maximize accuracy.

### Design Rules/Scoring:

- Total budget of \$300
- Be able to detect  $0.3 \times 0.3 \text{ m}^2$  metal plate targets ranging from 5 meters to 50 meters
- The radar may use any commercially available technology
- Score is determined by total power consumption, total weight, and accuracy of measured distance

### Overall Design Details

Basing our quarter one system, we designed our quarter two system to be better with the emphasis on simplicity and accuracy. We chose simplicity as our top priority to optimize our chances of getting the system to work. We then chose accuracy for our next priority since the score effect of power consumption and total weight is roughly negligible compared to how much the accuracy score can affect the final scoring. For our contingency plan, we kept our quarter one system intact and also attempted to improve on it. Keeping these things in mind, we looked online at various parts with their specifications and came up with the block diagram shown below.

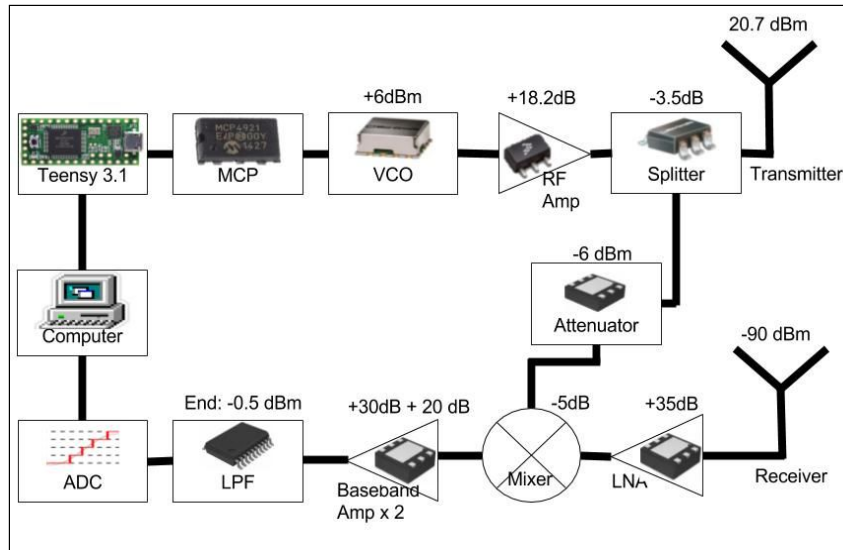


Fig 1. Block Diagram

In order to calculate the gain of the transmitting and receiving power, we used ADIsim to simulate the theoretical values. We obtained a theoretical transmitting power of 20.7 dBm and a theoretical receiving power of -90 dBm. The simulations for the transmitter and receiver are shown below.

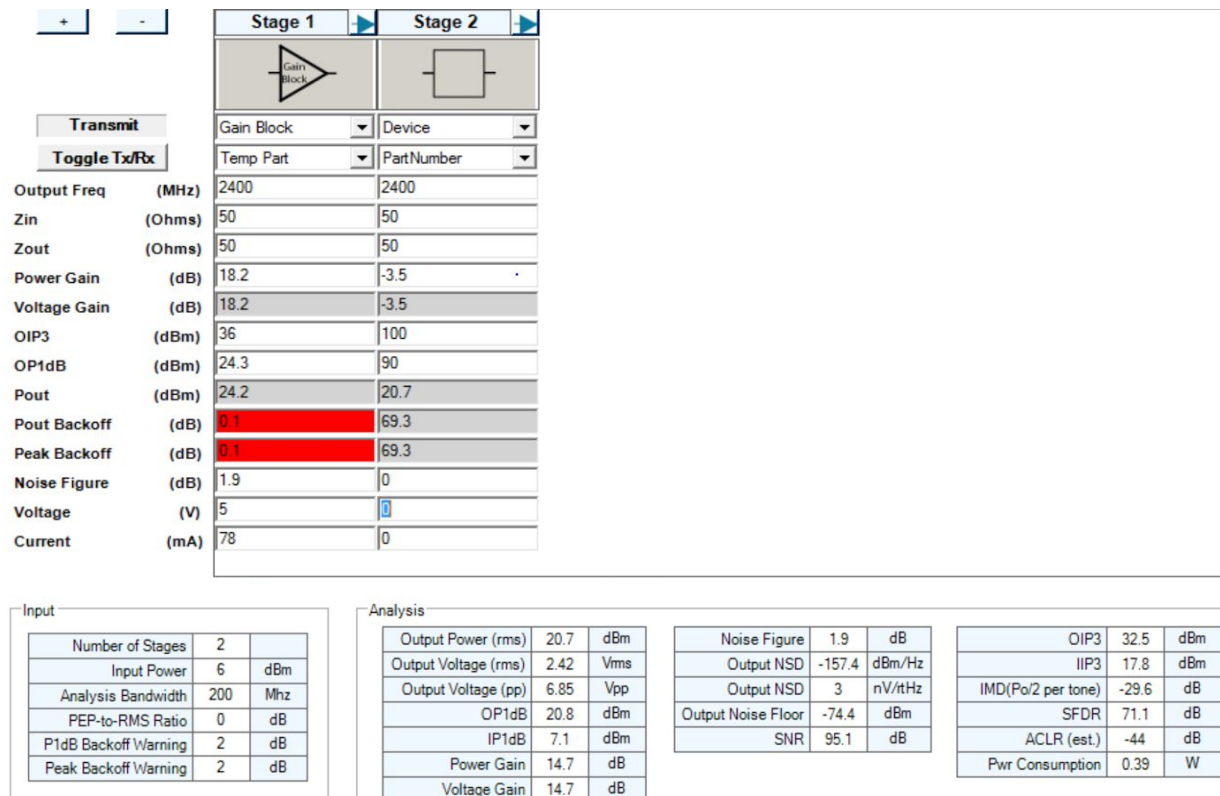


Fig 2. Transmitter Simulation

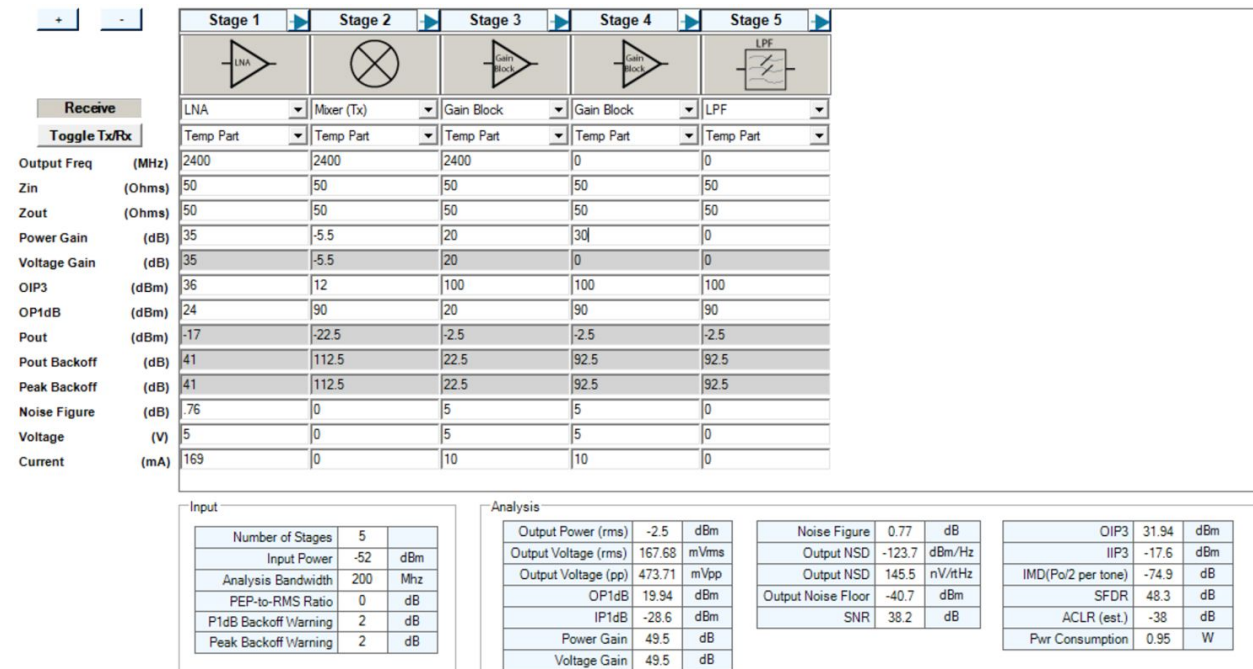


Fig 3. Receiver Simulation

The table below shows the components and its model number that we selected for the final design.

Table 1. Component List

| Component                  | Model #        |
|----------------------------|----------------|
| VCO                        | ROS-2536C-119+ |
| Splitter                   | Mini SP-2U1+   |
| Amplifier for Transmitting | MMG20241H      |
| Amplifier for Receiving    | MGA-13316      |
| Mixer                      | SIM-63LH+      |
| Low Pass Filter            | LTC1563        |
| Attenuator                 | HMC655LP2E     |

## PCB Design

The circuit diagram illustrates a multi-stage audio amplifier system. It begins with an input signal \$V\_{in}\$ connected through a resistor network (\$R\_1\$, \$R\_2\$) and capacitors (\$C\_1\$, \$C\_2\$) to the non-inverting input of an LTC1563 op-amp. The op-amp's output, labeled \$V\_{out}\$, is coupled via a capacitor (\$C\_3\$) to the base of a BJT stage. This BJT stage uses a voltage divider (\$R\_3\$, \$R\_4\$) for biasing and has its emitter bypassed by a capacitor (\$C\_4\$). Its collector is connected to the base of another BJT stage, which also features a voltage divider (\$R\_5\$, \$R\_6\$) and an emitter bypass capacitor (\$C\_5\$). The final BJT stage drives the primary of a transformer (D1), which is part of a push-pull output stage. The secondary of the transformer is connected to a full-bridge rectifier (MCP492) and a filter capacitor (\$C\_6\$). A feedback path from the output is taken before the transformer and fed back to the op-amp's inverting input. Various other components like resistors (\$R\_7\$, \$R\_8\$, \$R\_9\$, \$R\_{10}\$), capacitors (\$C\_7\$, \$C\_8\$, \$C\_9\$, \$C\_{10}\$), and diodes are used throughout the circuit for timing, filtering, and protection.

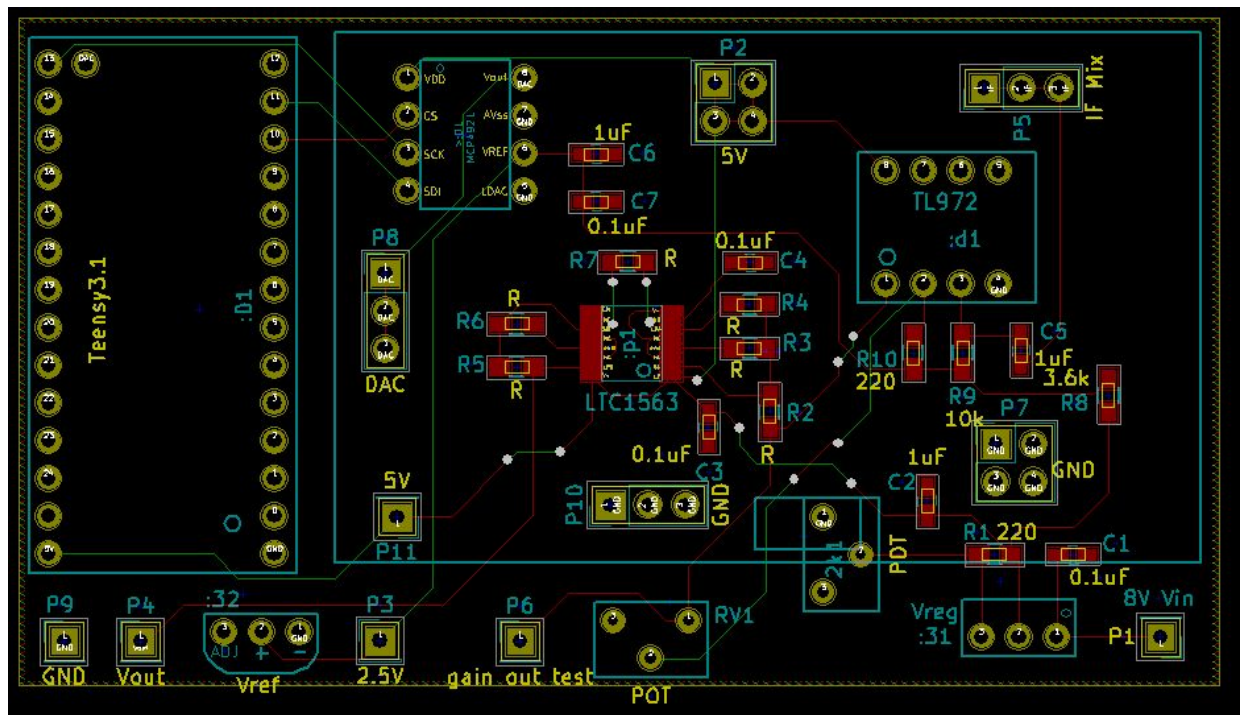


Fig 6. Baseband Layout

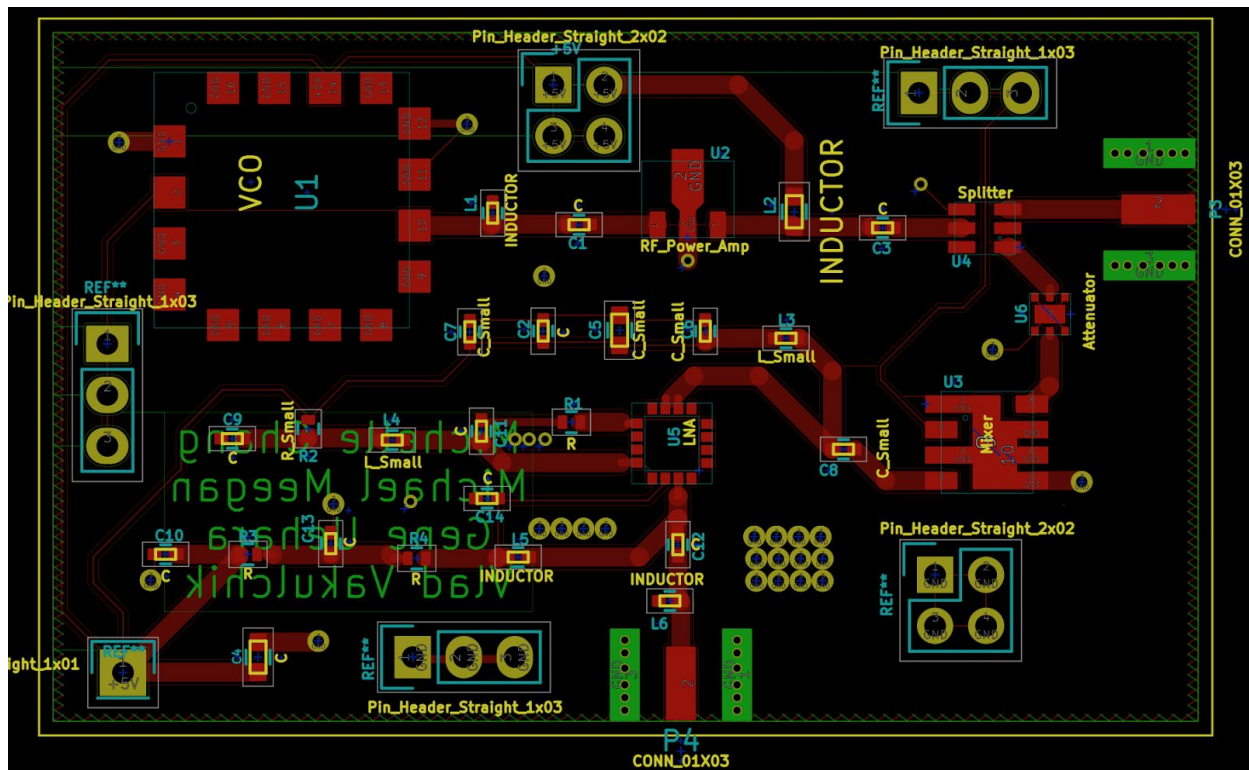


Fig 7. RF Layout





Figure 8. Assembled PCBs

### Antenna Choice

When selecting the antenna, we made sure to obtain one with high gain in order to maximize the received signal. Because of this, we decided to pick an antenna with high directivity as we know that our targets are not dispersed and we care more for gain to allow for far distance measuring. This led us to purchase a Yagi antenna from Kent Electronics at [wa5vjb.com](http://wa5vjb.com) as it provided a max signal of 10-11dBi at 2.4 to 2.45GHz. Below shows the antenna specification sheet which is accessible on Kent Electronic's website at <http://www.wa5vjb.com/pcb-pdfs/Yagi2400.pdf>

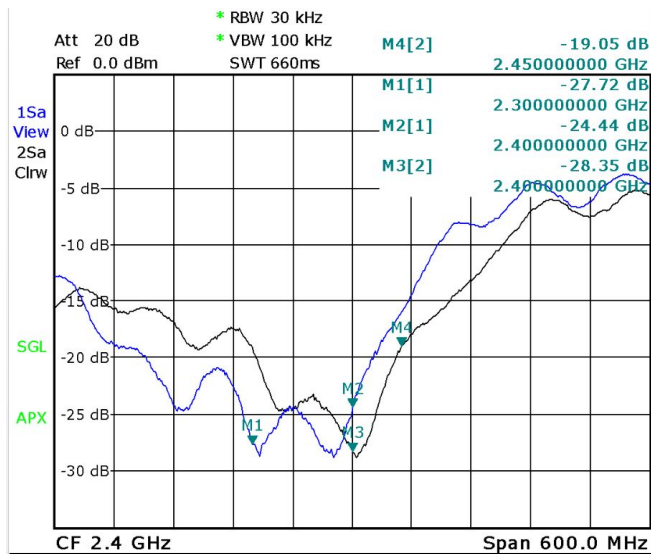


Fig 9. Antenna Specification Sheet

### Final Design Testing

Shown below are the individual testing of the components.  
LPF

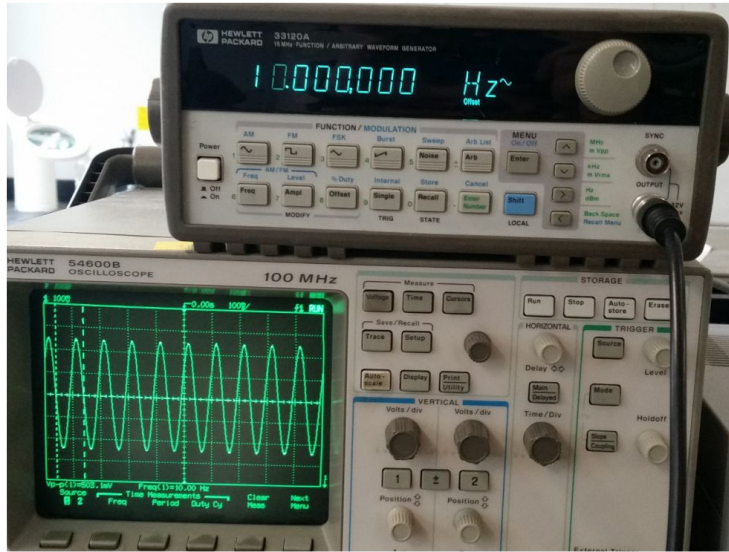


Fig 10. LPF Demonstration

LPF 3dB

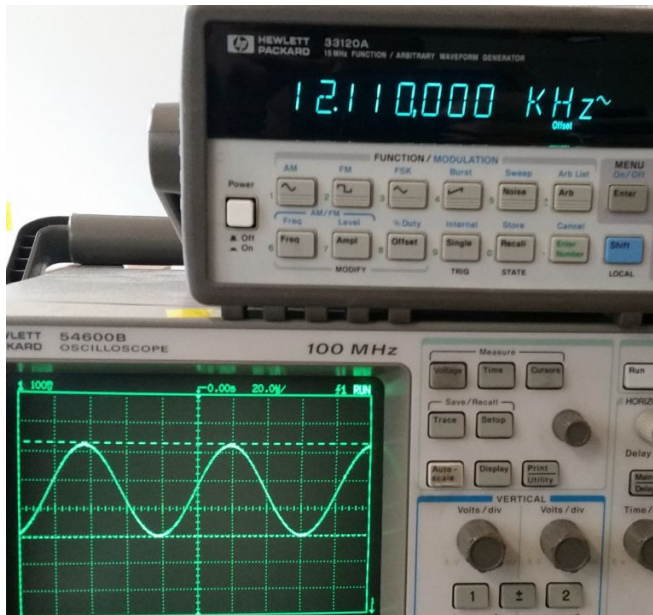


Fig 11. LPF Cutoff

## Complete System Results

We began by testing inside the lab room and also in the Kemper hallway. We found that we were getting results with a maximum distance reading of roughly 12 meters in the hallway but we noticed a good amount of noise was prevalent in our results which led us to test outside. Figure 12 shows the noisy hallway results which is most likely due to reflection.



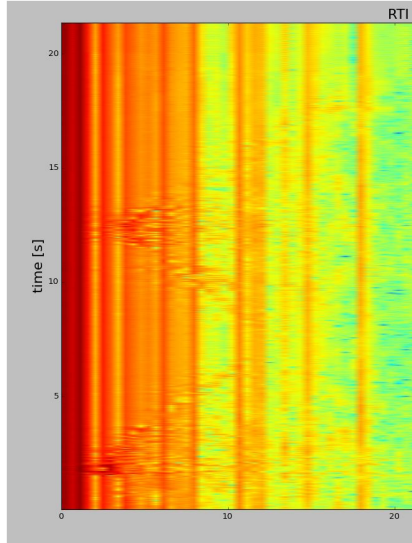


Fig 12. First Test Results

We expected better results even when testing in the hallway and this led us to notice that the low noise amplifier was not working properly on our PCB. We found the problem was caused by two unconnected nodes and so as a quick fix, we directly attached two LNAs which were used in quarter one at our receiving side. We then tested our system outside using a power supply giving 8 volts. The only purpose of the 8V supply was to provide a regulated 5V input to the rest of the system, however we decided that the battery pack was stable enough to power everything, so we choose to bypass the voltage regulator and directly power our system using the provided battery pack. Using the battery pack provided mobility and greater simplicity to the system. We then made the rookie mistake of having our system on the ground when testing which led to little to no results. The reflection off the concrete and grass when the radar was placed on the ground over powered any signal we wanted to read. After making the realization that the system needed to be elevated, we measured a maximum distance of 35 meters. Figure 13 shows the results we obtained in the field. The range in this plot is not calibrated correctly as the 0 meter position should be placed at where the yellow lines end which is at around 15 meters on this plot. This test also only utilized the cantennas as the Yagi antennas were not working properly at the time of the test.

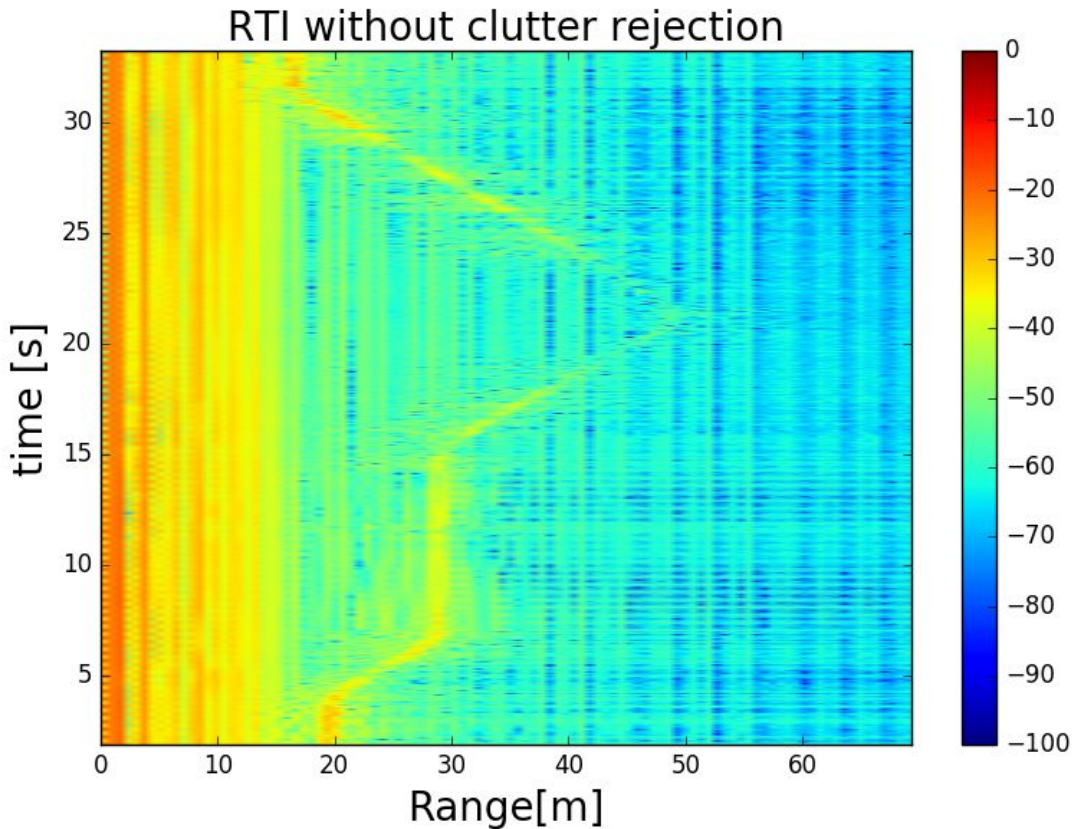


Figure 13. Outside Field Test

In an attempt to fix the unwanted yellow lines, we managed to find the MATLAB code which does the exact same processing as the Python code. We noticed that when the MATLAB code ran, the results were much more visible and provided no unwanted yellow lines. The only downside to this method was the processing time was much longer but we decided to utilize the MATLAB code from that point on as the better visibility of our radar results outweighed the con of having to wait an extra minute. After multiple tests, we finally arrived to the conclusion that the best configuration for our system was to use the cantenna as the transmitting antenna and use the Yagi antenna as the receiving antenna. After even more tests and calibrations, we also figured out that one extra LNA being attached to our receiving side provided us with the most optimal results. Shown below are results from our testing.

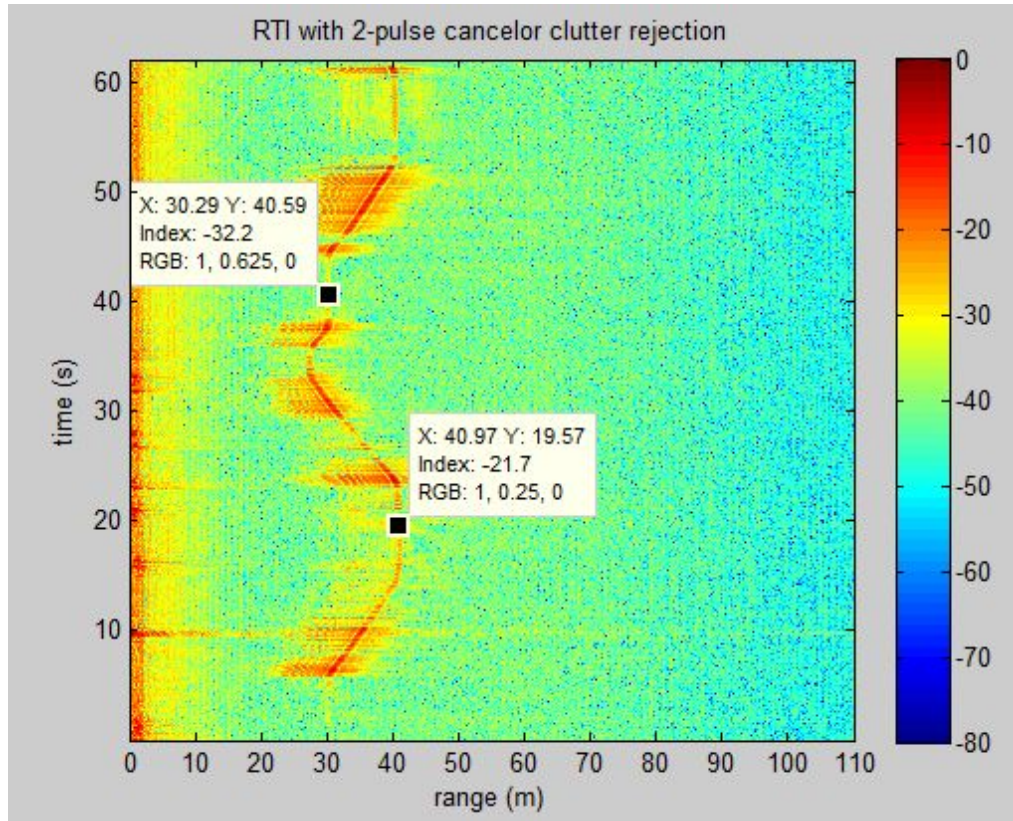


Figure 14. Matlab Code Test Run at 30 - 40 Meters

This test shows the measurement of someone walking back and forth between the 30 meter and 40 meter mark. After calibration, we were able to get accurate measurements with an error of about one meter.

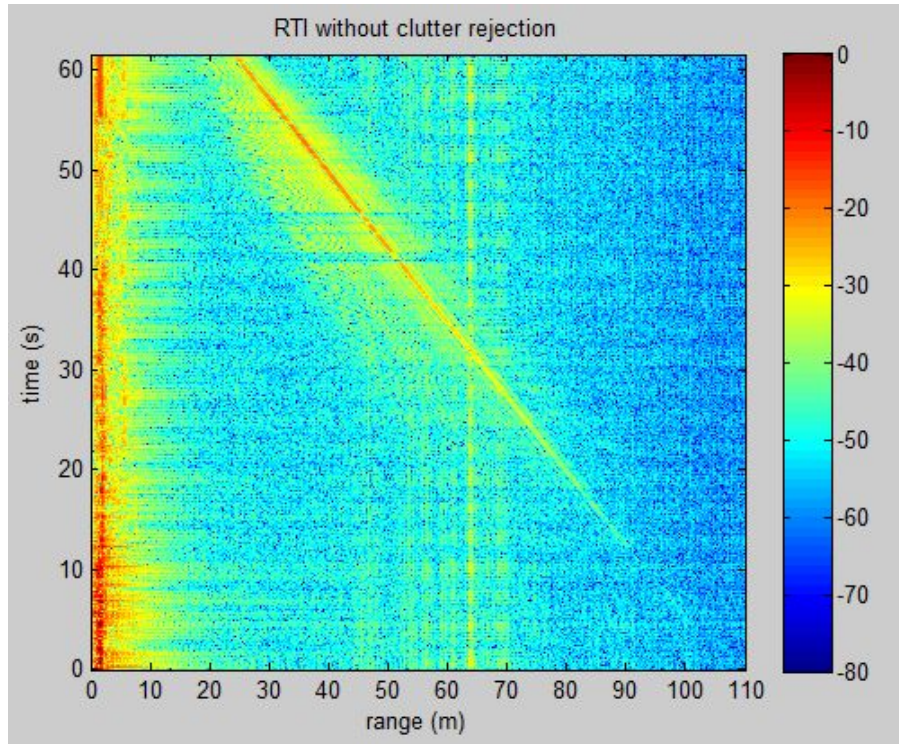


Figure 15. Measurement Showing Max Range of Near 100 Meters

This is our maximum range test and we were able to measure roughly 90 meters before the signal strength was too weak for us to make out any readings.

### Competition Day

During the day of the competition we were able to get readings for all the targets. The final weight of the system was 390 grams with a 1.2 W power consumption. The readings are weaker than we had hoped, however, we were still able to discern the signal from the background. Maximum range was removed from the competition. We took separate measurements for each target for a total of 5 measurements. We then processed the audio files with MatLab and compared the RTI without clutter rejection and RTI with 2-pulse canceler clutter rejection plots to find the distance of the target.

It had rained the day earlier so the water on the grass may have affected the clarity of the desired signal. Maximum range, however, was removed from the competition, so the drop in performance ultimately did not matter. Figure # shows the final configuration of the system with the housing.



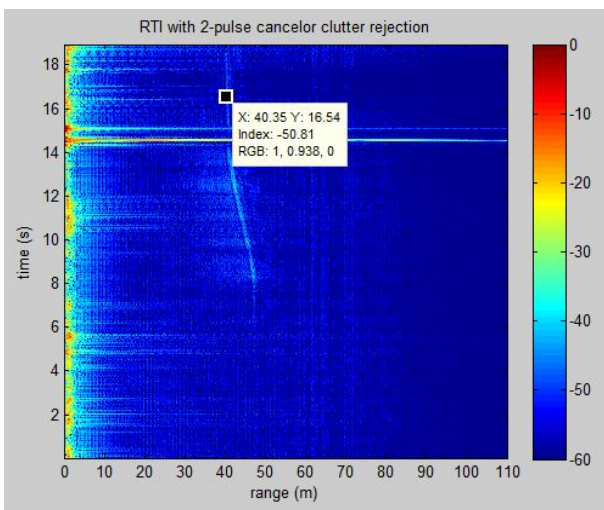


(a)

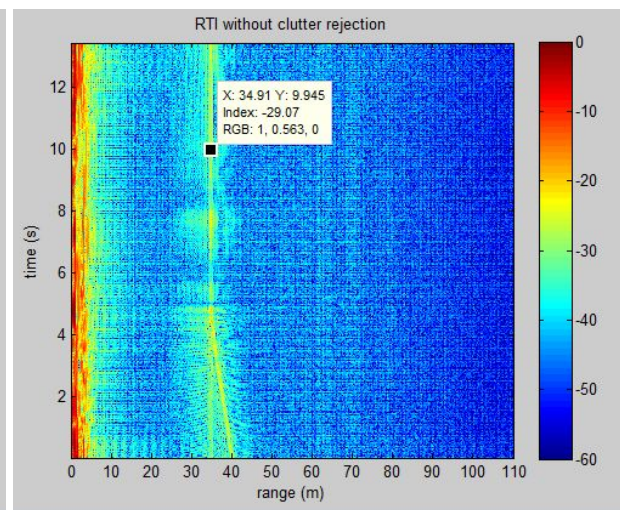


(b)

Figure 16. Final Testing Configuration

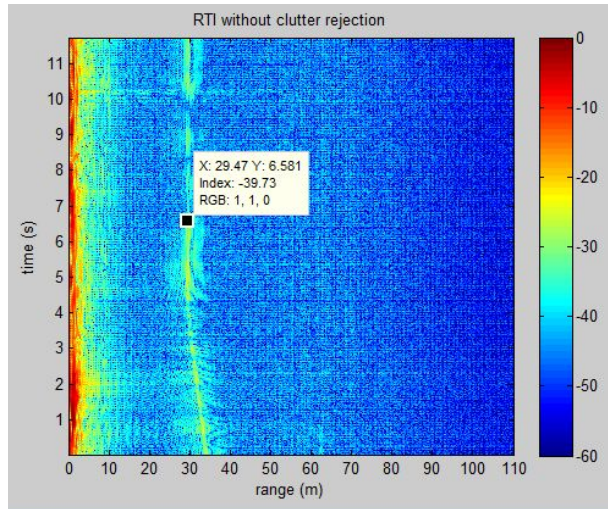


(a)

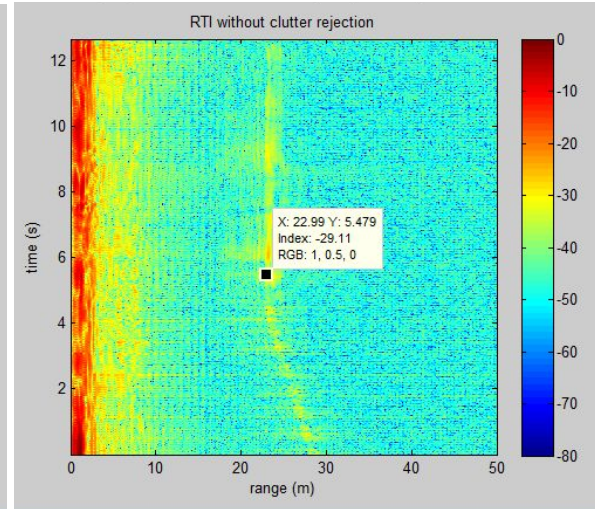


(b)

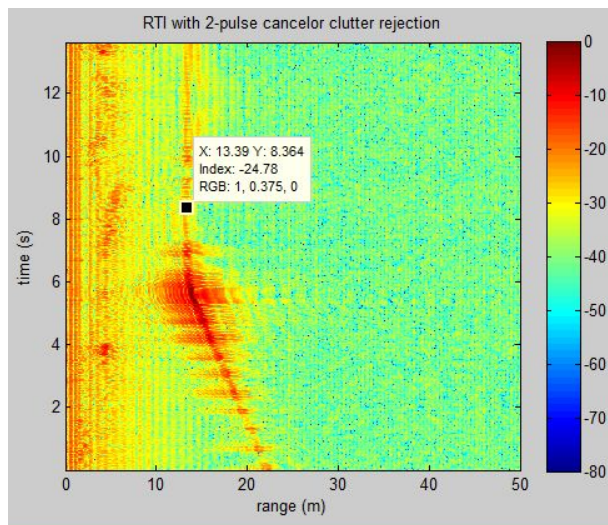




(c)



(d)



(e) Figure 17. Competition Day Results

## Conclusion

Overall, we learned that constructing a fully working radar system involves meticulous attention to detail and a good amount of luck. From purchasing enough components to connecting every node during PCB layout to debugging the complete system, we all agreed that the project, without a doubt, was an immense learning experience as problems we could have never predicted came up during the process. Minimal fixes such as testing the complete system outside instead of inside proved to greatly improve the measurements.

The real life application of this radar is limited as we did not process the data in real time. We could further improve the usability of the radar if we had on-board processing and a display to see the measurements as they occur.

## Course Suggestions

- Reference exemplified final reports during quarter one labs in order to mitigate problems that can arise in quarter two and get students more familiar with the entire system. Although we knew about the reports, we did not refer to them until quarter two. One possibility is to provide final report URLs in quarter one prelabs for students to view.
- Give the recommendation of purchasing at least three times the amount of components since each team will usually receive three PCBs and all PCBs may need to be soldered. It is usually cheaper to buy in bulk so there is not too big of a downside to doing this.

### **Bill of Materials**

| Quantity | Unit               | Item/Catalog No.     | Description                      | Unit Cost | Price |
|----------|--------------------|----------------------|----------------------------------|-----------|-------|
| 2        | MMG20241HT1        | MMG20241HT1CT        | IC DRIVER AMP 1/4W SOT89         | 3.59      | 7.18  |
| 2        | LTC1563            | LTC1563-2CGN#PBF-ND  | IC FILTER LP RC 4TH ORDER 16SSOP | 4.15      | 8.3   |
| 2        | HMC655LP2E         | 1127-3008-ND         | IC ATTENUATOR PASSIVE 6-DFN      | 6.64      | 13.28 |
| 10       | GRM1555C1H2R0BA01D | 490-6226-1-ND        | CAP CER 2PF 50V NP0 0402         | 0.027     | 0.27  |
| 10       | GRM1555C1H1R3BA01D | 490-8190-1-ND        | CAP CER 1.3PF 50V NP0 0402       | 0.044     | 0.44  |
| 10       | GRM1555C1H560JA01D | 490-1288-1-ND        | CAP CER 56PF 50V NP0 0402        | 0.012     | 0.12  |
| 10       | GRM188R71H104KA93D | 490-1519-1-ND        | CAP CER 0.1UF 50V X7R 0603       | 0.04      | 0.4   |
| 3        | LQW18AN8N2D10D     | 490-6914-1-ND        | FIXED IND 8.2NH 800MA 58 MOHM    | 0.18      | 0.54  |
| 10       | GRM1555C1H1R8CA01D | 490-5898-1-ND        | CAP CER 1.8PF 50V NP0 0402       | 0.021     | 0.21  |
| 50       | GRM155R71H103KA88D | 490-4516-1-ND        | CAP CER 10000PF 50V X7R 0402     | 0.0052    | 0.26  |
| 10       | GRM1555C1H2R7BA01D | 490-6229-1-ND        | CAP CER 2.7PF 50V NP0 0402       | 0.027     | 0.27  |
| 10       | GRM155R61A104KA01D | 490-1318-1-ND        | CAP CER 0.1UF 10V X5R 0402       | 0.012     | 0.12  |
| 10       | GRM188R61A225KE34D | 490-1545-1-ND        | CAP CER 2.2UF 10V X5R 0603       | 0.094     | 0.94  |
| 10       | GRM155R71H102KA01D | 490-1303-1-ND        | CAP CER 1000PF 50V X7R 0402      | 0.01      | 0.1   |
| 10       | GRM1555C1H100FA01D | 490-6186-1-ND        | CAP CER 10PF 50V NP0 0402        | 0.044     | 0.44  |
| 4        | GRM155R60J475ME87D | 490-5408-1-ND        | CAP CER 4.7UF 6.3V X5R 0402      | 0.14      | 0.56  |
| 10       | LQG15HN6N8J02D     | 490-1083-1-ND        | FIXED IND 6.8NH 600MA 290 MOHM   | 0.059     | 0.59  |
| 10       | LQG15HS3N3S02D     | 490-2616-1-ND        | FIXED IND 3.3NH 800MA 170 MOHM   | 0.055     | 0.55  |
| 10       | LQG15HS3N6S02D     | 490-6571-1-ND        | FIXED IND 3.6NH 750MA 180 MOHM   | 0.055     | 0.55  |
| 10       | RC0402JR-070RL     | 311-0.0JRCT-ND       | RES SMD 0.0OHM JUMPER 1/16W 0402 | 0.01      | 0.1   |
| 10       | RC0402FR-0749R9L   | 311-49.9LRCT-ND      | RES SMD 49.9 OHM 1% 1/16W 0402   | 0.012     | 0.12  |
| 10       | RC0402FR-073K6L    | 311-3.6KLRCT-ND      | RES SMD 3.6K OHM 1% 1/16W 0402   | 0.012     | 0.12  |
| 2        | RNCF0603BKE172K    | RNCF0603BKE172KCT-ND | RES SMD 172K OHM 0.1% 1/10W 0603 | 0.5       | 1     |
| 25       | ERJ-3EKF1002V      | P10.0KHCT-ND         | RES SMD 10K OHM 1% 1/10W 0603    | 0.0136    | 0.34  |
| 1        | 630-MGA-13316-BLKG | MGA-13316-BLKG       | RF Amplifier 2.2-4 GHz2S LNA     | 5.66      | 5.66  |
| 2        |                    |                      | 2400-2450 MHz 5 Element PCB Yagi | 6         | 12    |
| 20       | Provided from lab  | Provided from lab    | CAP 0.1uF 0603                   |           |       |
| 20       | Provided from lab  | Provided from lab    | CAP 1uF 0603                     |           |       |
| 20       | Provided from lab  | Provided from lab    | RES 220Ω 0603                    |           |       |
| 20       | Provided from lab  | Provided from lab    | RES 220kΩ 0603                   |           |       |
| 20       | Provided from lab  | Provided from lab    | RES 3.6kΩ 0603                   |           |       |
| 20       | Provided from lab  | Provided from lab    | RES 10kΩ 0603                    |           |       |
| 50       | Provided from lab  | Provided from lab    | Pin Headers                      |           |       |
| 3        | Provided from lab  | Provided from lab    | POT                              |           |       |
| 1        | Provided from lab  | Provided from lab    | LM317                            |           |       |
| 1        | Provided from lab  | Provided from lab    | Zener Diode                      |           |       |
| 1        | Provided from lab  | Provided from lab    | TL972                            |           |       |
| 1        | Provided from lab  | Provided from lab    | Teensy                           |           |       |
| 1        | Provided from lab  | Provided from lab    | LTC1563                          |           |       |
| 1        | Provided from lab  | Provided from lab    | MCP4921                          |           |       |
|          |                    |                      | Total Cost                       |           | 54.46 |

## Acknowledgements

Professor Xiaoguang Liu

TAs: Daniel Kuzmenko, Hao Wang, Songjie Bi

Team 3061 (2015-2016)

Sean Huang

## Appendix A - Python Code

```
# -*- coding: utf-8 -*-
#range radar, reading files from a WAV file
# Originially modified by Meng Wei, a summer exchange student
#(UCD GREAT Program, 2014) from Zhejiang University, China,
#from Greg Charvat's matlab code
# Nov. 17th, 2015, modified by Xiaoguang "Leo" Liu,
#lxgliu@ucdavis.edu

import wave
import os
from struct import unpack
import numpy as np
from numpy.fft import fft
import matplotlib.pyplot as plt
from math import log

#constants
c= 3E8 #(m/s) speed of light
Tp = 20E-3 #(s) pulse duration T/2, single frequency sweep
period.
fstart = 2260E6 #(Hz) LFM start frequency
fstop = 2590E6 #(Hz) LFM stop frequency
BW = fstop-fstart #(Hz) transmit bandwidth
trnc_time = 0 #number of seconds to discard at the begining of the
wav file

window = False #whether to apply a Hammng window.

# for debugging purposes
# log file
#logfile = 'log_new.txt'
#logfh = open(logfile,'w')
#logfh.write('start \n')

#read the raw data .wave file here
#get path to the .wav file
#filename = os.getcwd() + '\\running_outside_20ms.wav'
filename = os.getcwd() + '\\range_test2.wav' # The initial 1/6 of
the above wav file. To save time in developing the code
#open .wav file
wavefile = wave.open(filename, "rb")

# number of channels
nchannels = wavefile.getnchannels()

# number of bits per sample
sample_width = wavefile.getsampwidth()

# sampling rate
Fs = wavefile.getframerate()
trnc_smp = int(trnc_time*Fs) # number of samples to discard at the
begining of the wav file

# number of samples per pulse
N = int(Tp*Fs) # number of samples per pulse

# number of frames (total samples)
numframes = wavefile.getnframes()

# trig stores the sampled SYNC signal in the .wav file
#trig = np.zeros([rows,N])
trig = np.zeros([numframes - trnc_smp])
# s stores the sampled radar return signal in the .wav file
#s = np.zeros([rows,N])
s = np.zeros([numframes - trnc_smp])
# v stores fft(s)
#v = np.zeros([rows,N])
v = np.zeros([numframes - trnc_smp])

#read data from wav file

data = wavefile.readframes(numframes)

for j in range(trnc_smp,numframes):
    # get the left (SYNC) channel
    left = data[4*j:4*j+2]
    # get the right (Data) channel
    right = data[4*j+2:4*j+4]
    #.wav file store the sound level information in signed 16-bit
    integers stored in little-endian format
    #The "struct" module provides functions to convert such
    information to python native formats, in this case, integers.

    if len(left) == 2:
        l = unpack('h', left)[0]
    if len(right) == 2:
        r = unpack('h', right)[0]
    #normalize the value to 1 and store them in a two dimensional
    array "s"
    trig[j-trnc_smp] = l/32768.0
    s[j-trnc_smp] = r/32768.0

#trigger at the rising edge of the SYNC signal
trig[trig < 0] = 0;
trig[trig > 0] = 1;

#2D array for coherent processing
s2 = np.zeros([int(len(s)/N),N])

rows = 0;
for j in range(10, len(trig)):
    if trig[j] == 1 and np.mean(trig[j-10:j]) == 0:
        if j+N <= len(trig):
            s2[rows,:]= s[j:j+N]
            rows += 1
```

```

s2 = s2[0:rows,:];

#pulse-to-pulse averaging to eliminate system performance drift
overtime
for i in range(N):
    s2[:,i] = s2[:,i] - np.mean(s2[:,i])

#2pulse cancelation

s3 = s2
for i in range(0, rows-1):
    s3[i,:] = s2[i+1,:] - s2[i,:]

rows = rows-1
s3 = s3[0:rows,:];

#apply a Hamming window to reduce fft sidelobes if
window=True
if window == True:
    for i in range(rows):
        s3[i]=np.multiply(s3[i],np.hamming(N))

#####
# Range-Time-Intensity (RTI) plot
# inverse FFT. By default the ifft operates on the row
v = ifft(s3)

#get magnitude
v = 20*np.log10(np.absolute(v))+1e-12

#only the first half in each row contains unique information
v = v[:,0:int(N/2)]

#normalized with respect to its maximum value so that maximum

```

## Appendix B MATLAB Code

```

%MIT IAP Radar Course 20112.5
%Resource: Build a Small Radar System Capable of Sensing
Range, Doppler,
%and Synthetic Aperture Radar Imaging
%
%Gregory L. Charvat

%Process Range vs. Time Intensity (RTI) plot
tic

clear all;
close all;

% read the raw data .wav file here
% replace with your own .wav file
[Y,FS] = audioread('win3040.wav');
dbv=@(x) 20*log10(abs(x));

%constants

```

```

is 0dB
m=np.max(v)
grid = v
grid=[[x-m for x in y] for y in v]

# maximum range
max_range =c*Fs*Tp/4/BW
# maximum time
max_time = Tp*rows

plt.figure(0)
plt.imshow(grid, extent=[0,max_range,0,max_time],aspect='auto',
cmap=plt.get_cmap('gray'))
plt.colorbar()
plt.clim(0,-100)
plt.xlabel('Range[m]', {'fontsize':20})
plt.ylabel('time [s]', {'fontsize':20})
plt.title('RTI with 2-pulse clutter rejection', {'fontsize':20})
plt.tight_layout()
plt.show()

#plt.subplot(612)
#plt.plot(grid[5])

#plt.subplot(613)
#plt.plot(grid[6])

#plt.subplot(614)
#plt.plot(grid[20])
#
#plt.subplot(615)
#plt.plot(grid[30])

#plt.subplot(616)
#plt.plot(grid[40])

```

```

c = 3E8; %(m/s) speed of light

%radar parameters
Tp = 20E-3; %(s) pulse time
N = Tp*FS; %# of samples per pulse
fstart = 2260E6; %(Hz) LFM start frequency
fstop = 2590E6; %(Hz) LFM stop frequency
BW = fstop-fstart; %(Hz) transmti bandwidth
f = linspace(fstart, fstop, N/2); %instantaneous transmit frequency

%range resolution
rr = c/(2*BW);
max_range = rr*N/2;

%the input appears to be inverted
trig = -1*Y(:,1);
s = -1*Y(:,2);
clear Y;

```



```

%parse the data here by triggering off rising edge of sync pulse
count = 0;
thresh = 0;
start = (trig > thresh);

for ii = 100:(size(start,1)-N)
    if start(ii) == 1 && mean(start(ii-99:ii-1)) == 0
        %start2(ii) = 1;
        count = count + 1;
        sif(count,:) = s(ii:ii+N-1);
        time(count) = ii*1/FS;
    end
end

%check to see if triggering works
% plot(trig,'b');
% hold on; si
% plot(start2,'r');
% hold off;
% grid on;

%subtract the average
ave = mean(sif,1);
for ii = 1:size(sif,1);
    sif(ii,:) = sif(ii,:) - ave;
end

zpad = 8*N/2;

%RTI plot
figure(10);
v = dbv(fft(sif,zpad,2));

```

```

S = v(:,1:size(v,2)/2);
m = max(max(v));
imagesc(linspace(0,max_range,zpad)*0.77,time,S-m,[-80, 0]);
colorbar;
ylabel('time (s)');
xlabel('range (m)');
title('RTI without clutter rejection');
xlim([0, 110])
set(gca, 'YDir', 'normal')
set(gca, 'XTick', 0:10:110)

%2 pulse cancelor RTI plot
figure(20);
sif2 = sif(2:size(sif,1),:)-sif(1:size(sif,1)-1,:);
v = ifft(sif2,zpad,2);
S=v;
R = linspace(0,max_range,zpad);
for ii = 1:size(S,1)
    %S(ii,:) = S(ii,:).*R.^(3/2); %Optional: magnitude scale to range
end

S = dbv(S(:,1:size(v,2)/2));
m = max(max(S));
imagesc(R*0.77,time,S-m,[-80, 0]);
colorbar;
ylabel('time (s)');
xlabel('range (m)');
xlim([0, 110]);
set(gca, 'YDir', 'normal')
set(gca, 'XTick', 0:10:110)
title('RTI with 2-pulse cancelor clutter rejection');
toc

```



