Coffee Can Radar System

Kyle Meza

UNION
COLLEGE
FOUNDED 1795

ECE 499 Capstone Design

Advised by Dr. Pappu & Dr. Silva

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ABSTRACT

Radar systems are used around the world by many industries and governments. For this capstone design project an inexpensive radar system was built and is capable of transmitting and receiving radio signals that can be used to provide Doppler, and ranging information. The goal was to obtain high resolution data by using the Coffee Can Radar system initially built by MIT. This system has been proven to work and will be a great additional piece of demonstration equipment to the Electrical Engineering Department at Union College.

ACKNOWLEDGMENTS

The author would like to formally thank Dr. Chandra Pappu, Dr. James Silva, Dale Coker, and Professor James Hedrick for supporting the work that contributed to this document.

TABLE OF CONTENTS

TABLE OF FIGURES

Figures

Equations

Tables

I. Introduction

Radio detection and ranging (radar) systems are used around the world by many industries and governments. For this capstone design project, an inexpensive radar system was built that is capable of transmitting and receiving radio frequency (RF) signals, from which the velocity and range of a target may be extracted.

The principles of a radar system are depicted in Figure 1 below. An RF signal is generated and emitted from a transmitting antenna. The transmitted signal is then reflected off of a target, and the reflected signal is captured by the receiving antenna. The received signal is then processed with additional hardware and software to estimate the targets range and/or velocity.

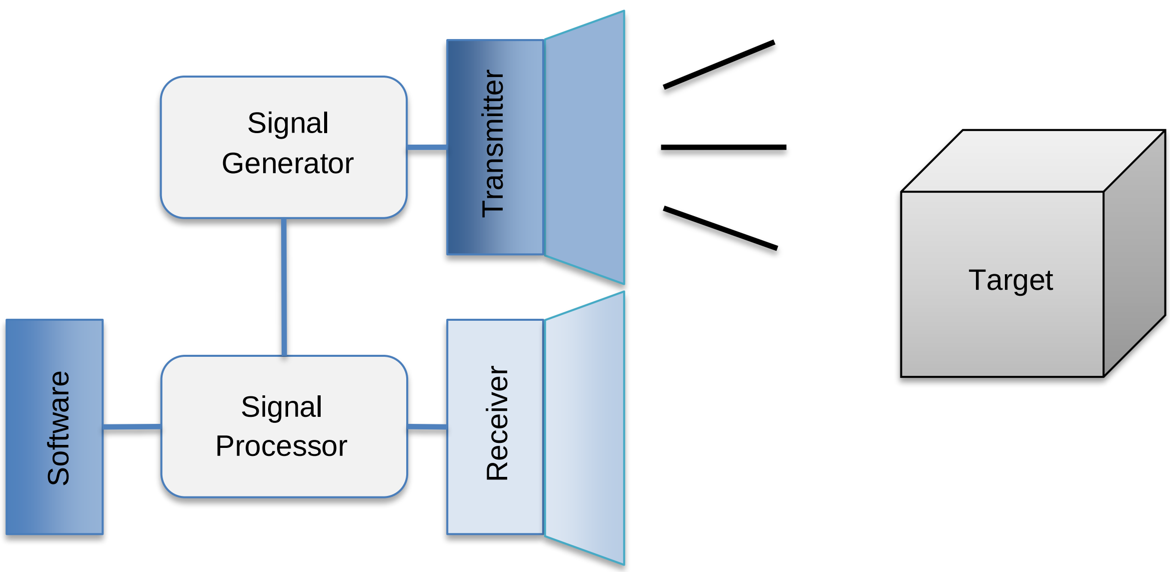


Figure 1: Block Diagram of General Radar System

The history of radar [1] can be traced to the late 1880's, with the discovery by Heinrich Hertz of the electromagnetic spectrum outside of visible light. His experiment showed how electromagnetic signals could be both generated and detected. It was not until the late 1930's that the first practical radar system was developed; only then were the components such as the resonant cavity magnetron and the klystron available that enabled generation of a signal with sufficient energy to be effective for radar [1].

This project afforded the Union College Electrical and Computer Engineering Department (ECE) the opportunity to develop hardware and software in the field of signal processing. A system capable of collecting emitted radio waves and processing the signal into relevant information such as range (distance between target and antenna) was not previously available. Prospective students and local community outreach events were missing a system that could simply but effectively demonstrate the broad and exciting field of signal processing.

The goal of this project was to build a user-friendly, rugged, and portable radar system. The main purpose of the system is to engage prospective students and the surrounding community with a tangible example of signal processing. The radar system needed to be cost-effective to build, easy to maintain, and simple enough for senior-level students to maintain and demonstrate.

II. Background

A conventional radio detection and ranging (radar) system works by emitting an RF signal from an antenna. This signal reflects off a target and is captured by a receiving antenna. The received RF waveform can then be processed to determine the direction, speed, range, and/or altitude of an object.

Key equations

The range is the distance between the radar system and a target. The equation for range is depicted below in Equation 1. The speed of light "c" ($3x10^8$ m/s) is multiplied by the time "t_0" it takes the wave to travel from the radar to the target and back. This is divided by two, to give the range in only one direction. Likewise, the velocity of the target can be determined by using the Doppler frequency f_D and the transmitted signals wavelength (λ), as shown in Equation 2. Both f_D and t_0 can be extracted from the received signal as shown in Equation 3. The received signal contains the Doppler frequency, f_D, in the exponent and the range information in the time delay, t_0.

Equation 1. Target Range $$\frac{ct_0}{2}$$

Equation 2. Target Velocity $$\frac{\lambda F_D}{2}$$

Equation 3. Received Signal $$s(t-\tau)e^{j2\pi(F_c+F_D)t}$$

Project Origin

The coffee can radar system was designed by Dr. Gregory L. Charvat and his colleagues, of the Massachusetts Institute of Technology (MIT). In their words this project was created so students would experience, "the design, fabrication, and test of a laptop-based radar sensor capable of measuring Doppler, range, and forming synthetic aperture radar (SAR) images [2]." The open courseware from MIT has been tested by other colleges such as Queensbury Community College in New York City. IEEE Senior Editor David Schneider also built this system and demonstrated its capability [3].

Radar Applications

Doppler and ranging information is used around the world by numerous industries. Biomedical devices use Doppler in ultrasound equipment, weather stations use Doppler for forecasting, and police use Doppler to determine whether a car is speeding. Likewise, ranging is used by aircraft and ships to determine distances, and by militaries for guided missile launches [4, 5].

Performance

A principal requirement for this system is that it would be a complete implementation of a radar system. Thus, the system must be able to transmit a signal towards a target and capture the signal that is reflected. The reflected signal is then processed to extract range and velocity information.

Geometry & Ergonomics

The goal is that the system would resemble the original system that was built by MIT.

Economic

The cost target for this project was that the materials would cost less than $500. A detailed list of components needed to build the system is shown in Appendix A. Funding was requested through a student research grant which offset the cost of purchasing supplies not owned by Union College.

Safety

A significant requirement for the system is that it must be safe for the operator and audience near the demonstration. The electromagnetic waves generated must not be harmful for human tissue or interfere with biomedical devices and/or other wireless technology. To achieve this the maximum transmit power was limited to 20 mW.

Legal

MIT holds the license for the project. Accordingly, the project information is open source; therefore information for our project must also remain open source [2]. Union College cannot sell or claim this radar system as its intellectual property.

Materials

Key materials for this project include two monopole coffee can antennas, which serve as the transmitter and receiver, and other RF components such as a voltage-controlled-oscillator, an attenuator, low-noise RF amplifiers, an RF signal splitter, and an RF mixer. The goal is that all the materials be readily available.

Fabrication

The system was fabricated in the following steps outlined by MIT's open courseware [2].

Ethical

The main ethical consideration for this project was the proper acknowledgment of MIT and the professors from the Lincoln Lab who first built the system. This design project was shared with the academic world to promote interest in radar systems. My team and

I carefully followed the terms and conditions of use for this project. Doing so ensured that proper attribution is always given to the intellectual property of others. It should be noted that this system can never be used for commercial gain. Part of the legacy of this equipment will be proper explanation of the MIT license for this project, which means that the final product shares the same distribution license as the original design specifications.

Standards

The Institute of Electrical and Electronics Engineers (IEEE) has an ethics standard [6] that was very helpful during construction of the coffee can radar system. Additionally, we readily accepted and sought honest criticism on how the project could be improved.

The IEEE also has a standard [7] that captures the common definitions and terminology used in the radar industry. This standard helped ensure that our terminology complied with that of experts of the field. This consistency assisted in promoting proper understanding of the system.

Lastly, the Occupational Safety and Health Administration (OSHA) published a standard [8] that sets the limits of non-ionizing radiation. The electromagnetic radio waves produced by our source must comply with this standard. To ensure the safety and health of the public, our system must never be able to expose people to waves that are above the energy and power density limits of the OSHA standard.

III. Design Requirements

The overarching design requirement of this system was to replicate MIT's system as closely as possible. The following design requirements were sourced from MIT [2].

The coffee can radar system was developed to be able to work for Doppler and ranging. The Doppler mode is based on transmitting a continuous wave (CW), monotone signal. Velocity information is extracted from the received signal. In the ranging mode, a FMCW (triangular frequency ramp, continuous wave) signal is transmitted; as shown in Table 1. Range information is extracted from the received signal.

Table 1. Design Requirements of System

Frequency Band	2.4-2.5 GHz Industrial, Scientific and Medical Band (ISM)
Maximum Transmit Power	20 mW
FMCW Bandwidth	100 MHz
FMCW Waveform	Triangular Frequency Ramp
Maximum DC Power Consumption	1 Watt
RF Circuit Source	Commercially available
Maximum Cost	$500

IV. Design Alternatives

There were two major parts to the coffee can radar design. The first was the hardware and selection of RF components. The second was the appropriate software. For this capstone project, no design alternatives were considered.

V. Design

The design for the coffee can radar system is described below. Figure 3 depicts the block diagram for the coffee-can radar system. The fundamental purpose of the system was to transmit an FMCW or CW waveform towards the target and capture the returning waveform. Using a mixer, the transmitted waveform is multiplied with the received waveform and later processed in MATLAB to extract information on velocity, or range. Equation 4 shows the mixer output. The computer only receives the low-frequency signal, because the high frequency is filtered out by the low pass filter (LPF)

Equation 4. Mixer Output

$$m(t) = \frac{\cos(4\pi f_C t + 2\pi f_D t) + \cos(2\pi f_D t)}{2}$$

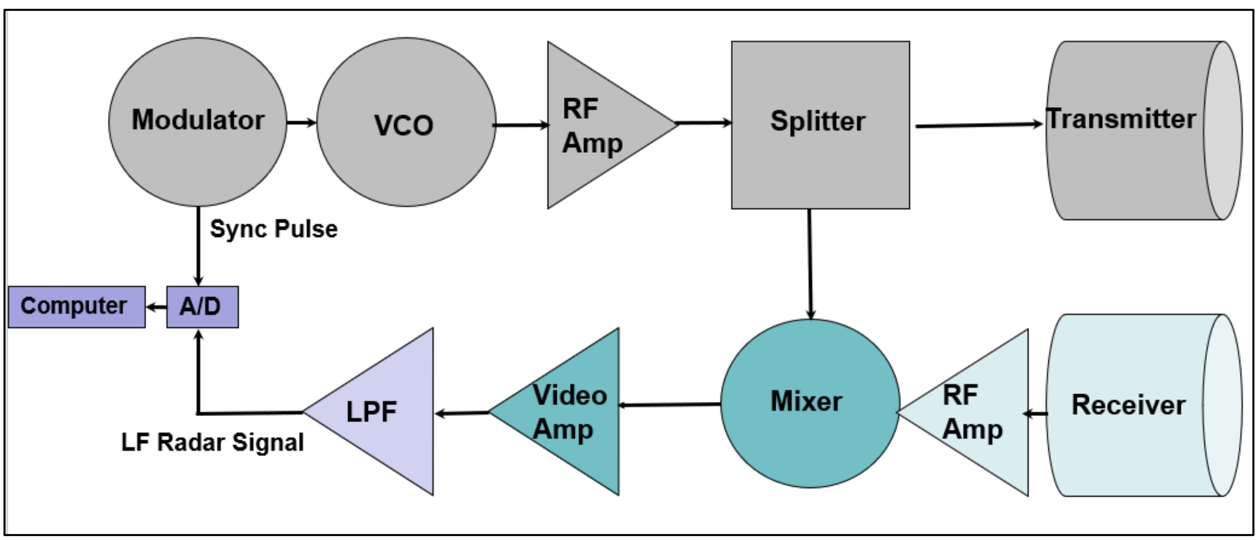


Figure 2. Block Diagram of Coffee-Can Radar System

The block diagram shows the three key parts of this system: the RF electronics (green), audio frequency electronics (blue), and digital signal processing software. The modulator generates the sync-pulse which is used when measuring the range of a target. Note that the sync-pulse occupied the left channel of the audio cable that linked the system to the computer. The modulator also it generates a triangle wave (V-tune) that was tuned to ramp between 2 and 3 volts in 20 ms. This voltage is sent to the voltage-controlled-oscillator (VCO) which in turn produces a 2.4 to 2.5 GHz waveform. This also is how the 100 MHz bandwidth is set. The VCO waveforms is then attenuated by -10 dB before being transmitted towards the target and also sent to the mixer. The received signal immediately sent to a low noise RF amplifier of +18.5 dBm before being mixed with the transmitted signal. The mixer output is then sent through a video amplifier and a 4^{th} order low pass filter before traveling through the right channel of the audio cable into the computer. Figure 3 below shows the layout of the systems analog RF signal chain.

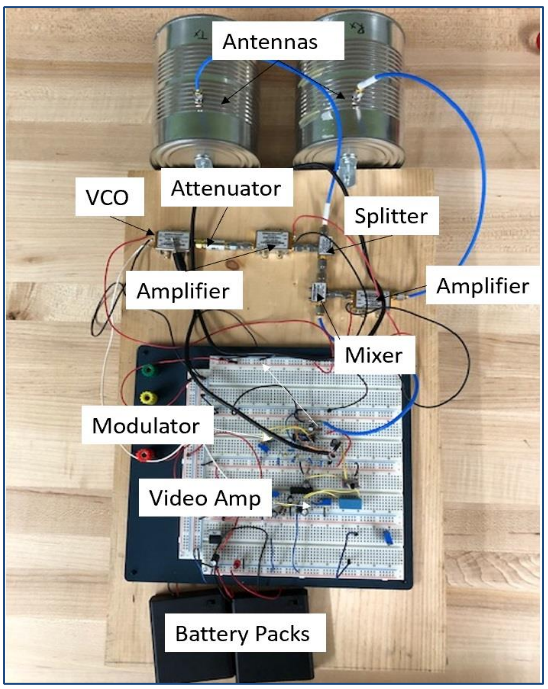


Figure 3. Coffee-Can Radar System Layout

The yellow triangle wave (V-Tune) in Figure 4 below shows the modulator signal that is sent the VCO to generate the transmitted signal. The green signal shows the signal output of the mixer as described in Equation 4. Note that the mixer is output is in the 25 Hz range compared to the GHz RF signal transmitted.

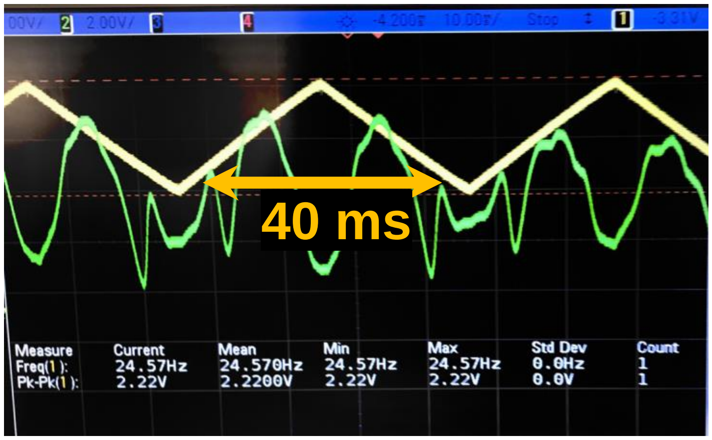


Figure 4. Modulator (V-Tune) Signal to VCO (Yellow) and Mixer Output Signal (Green)

Figure 5 below depicts the two outputs of the modulator, V-tune and the sync-pulse.

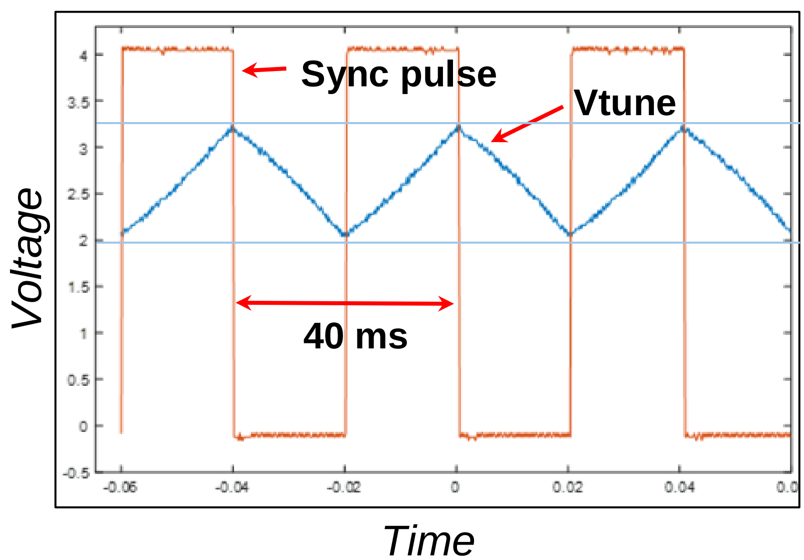


Figure 5. Modulator Signal to VCO (Blue) and Sync Pulse (Orange)

Figure 6 depicts the video amplifier circuit of the system. The amplifier is designed to amplify the output of the mixer before it is sent to the computer. As mentioned, the circuit includes a 15 KHz low pass filter to remove higher frequency harmonics. The three operational amplifiers in series; the first (U1) is the video amplifier and the second and third (U2-U3) comprise a 15 kHz active filter. The operational amplifiers (op-amps) that provide this amplification are powered by a 5 V_{DC} regulated power supply. The fourth op amp (U4) is a voltage follower to provide a low-impedance output to a computer sound card.

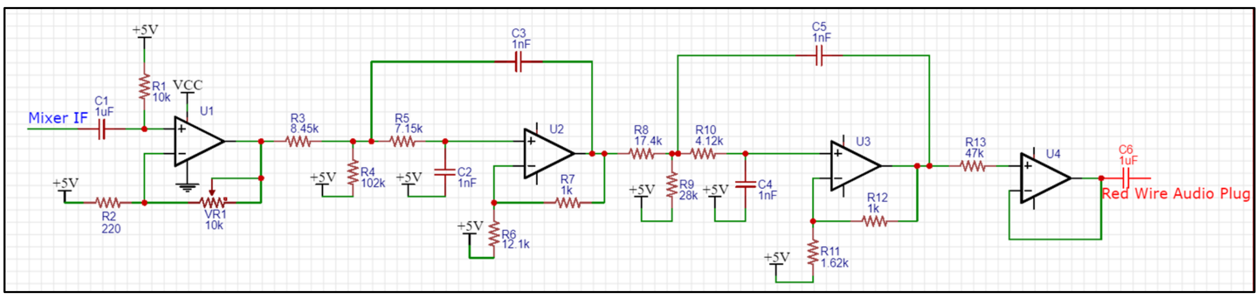


Figure 6. Video Amplifier Circuit

Figure 7 depicts the modulator circuit of the system. The modulator delivers a triangular waveform (V-Tune) to a voltage-controlled oscillator (VCO) as shown in Figures 4 and 5, where V-tune oscillates between 2 and 3 volts over a period of 40 msec. Note that the center frequency of the VCO cannot be changed due to R1 and R2. If these 100 KΩ resistors were switched with a potentiometer the center frequency of the VCO could be changed. The modulator also generates a sync pulse, as shown in Figure 5. This sync pulse is used in the signal processing software.

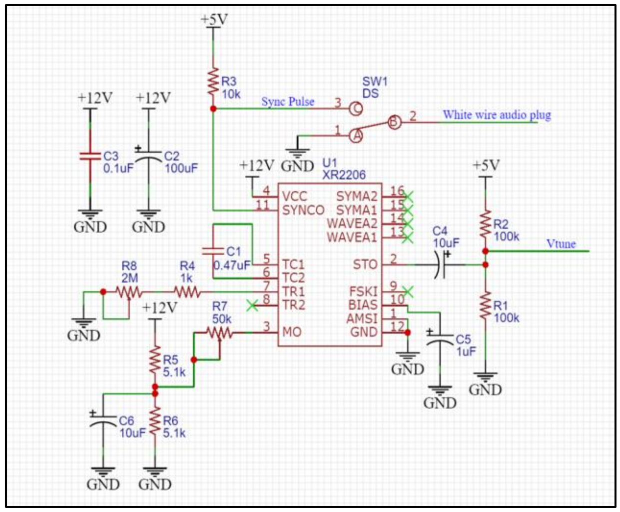


Figure 7. Modulator Circuit

Figure 8 below shows a schematic diagram of the system power supply. The modulator shown in 5 requires both 5 V_{DC} and 12 V_{DC}. The video amplifier/LP filter circuit requires 5 V_{DC}. Accordingly, a 6 V_{DC} battery pack and a 5 V_{DC} voltage regulator (U1) supplies 5 V_{DC}. A second 6 V_{DC} battery pack in series with the first 6 V_{DC} battery pack supplies unregulated 12 V_{DC} power.

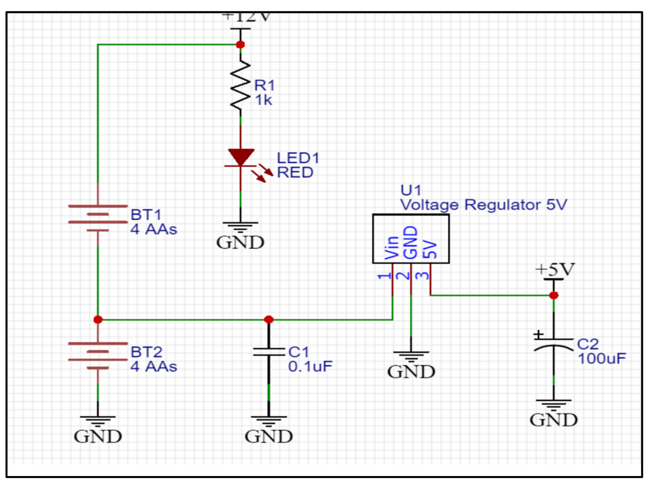


Figure 8. Power Supply Circuit

Following the completion of building the hardware the design requirements were verified by testing each of the components individually and comparing their responses to their respective data sheets. As a system the Doppler and ranging capabilities were tested as follows:

Doppler Effect Testing Plan

As noted above, to measure velocity, a CW RF signal is transmitted. Doppler was tested by biasing the V-tune to fixed DC value. The “Sync Pulse Inhibit” switch is opened. The DC power to the modulator IC is switched off. The transmitter and receiver are oriented towards a fast-moving target, and the reflected LF signal was recorded as an audio .wav file. The recorded audio data was than processed and velocity plotted as a function of time using MATLAB.

Range Measurement Testing Plan

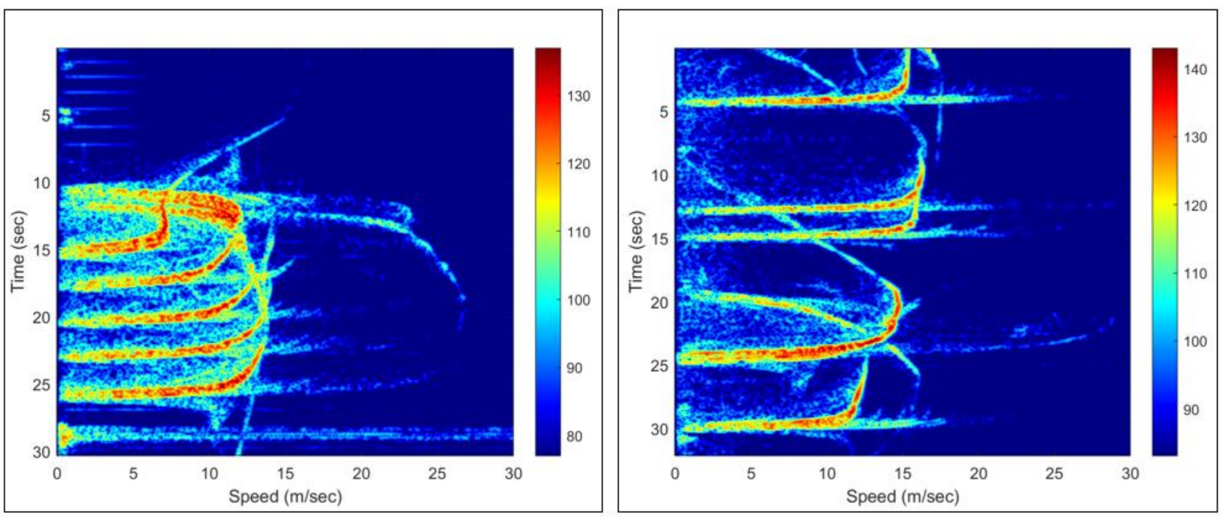
As noted above, for operation in the range mode, an FMCW waveform is transmitted by the radar system. The VCO is driven by the modulator (through V-tune). As shown in figures 4 and 5, the V-tune period is set to 40ms. The magnitude of V-tune was adjusted to enable the VCO to span the desired bandwidth. The radar was then pointed toward a moving target and a .wav file recorded. The data was then processed in MATLAB.

Software Design

The software design is also outlined by MIT [2]. A key part of the design not supported directly by MIT is how to capture a .wav file from the system that can be post processed later. Audacity® was used to record the audio files. This audio files were then processed in MATLAB®. Doppler was achieved mainly by taking the right channel video data and parsing it into 100 ms blocks before having the Fourier transform computed. The log magnitude of the results is plotted as the Doppler-Time-Intensity (DTI). Similarly, range also utilizes the left channel video data which contains the sync-pulse.

Testing Results

The Doppler information extracted from the recorded audio signal is depicted below in Figure 9. The axes for the Doppler-Time-Intensity (DTI) plots are given in time (seconds) verse speed (meters/second). Each of the horizontal lines depict a car driving either away or towards the radar. Thus, for Union Ave, seven cars were driving by below 15 m/s (33.5 MPH). The Nott Street DTI plot shows six cars driving by slightly above 15 m/s. The velocities of the cars as determined by the coffee-can radar match the speed limits of Union Ave and Nott Street.

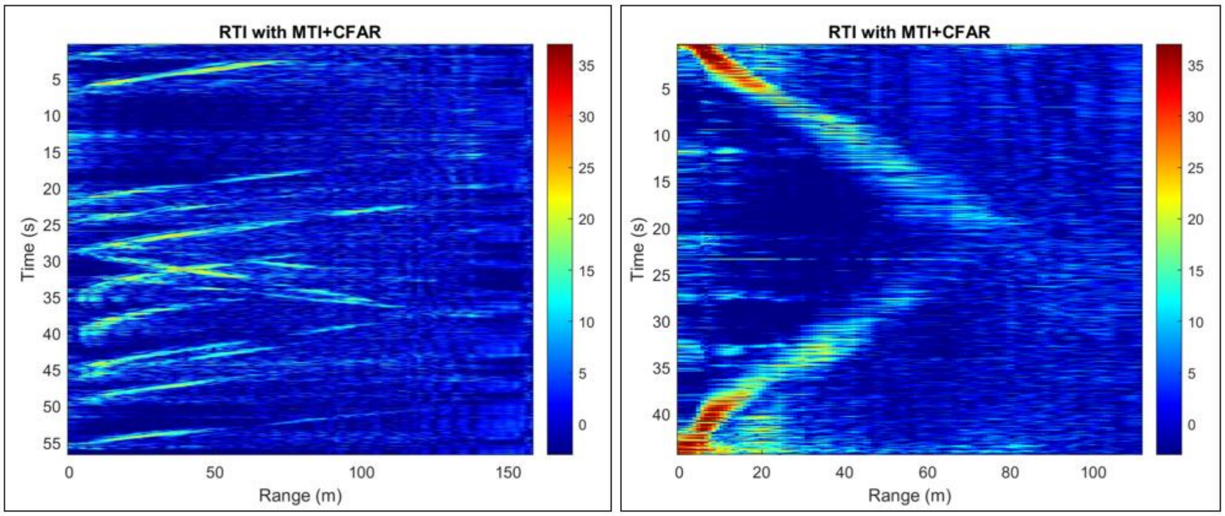


Cars on Union Ave **Cars on Nott Street**

Figure 9. Doppler Test Results

The range information extracted from the recorded audio signal is depicted below in Figure 10. The axes for the Range-Time-Intensity (RTI) with Moving-Target-Indication (MTI) plus Constant-False-Alarm-Rate (CFAR) plots are given in time (seconds) verse range (meters). Each of the horizontal lines depict a car driving either away or towards the radar. Thus, for Nott Street, 10 cars were driving by from 100 meter (109 yards).

Likewise, the, Dale running on the football field, plot shows Dale running 90 yards away from and then back towards the coffee-can radar system. Note that 80 meters is approximately 87.5 yards showing that the system was accurate to within about 2.5 yards.



Cars on Nott Street **Dale Running on Football Field**

Figure 10. Ranging Test Results

A spectrum analyzer was used to measure the spectrum of the transmitted RF signal. The measured bandwidth is depicted below in Figure 11. Note that the measured bandwidth was 140 MHz. However, this value is likely influenced by the location of where the measurement as taken as ambient RF may have influence the reading. Additionally, an electromagnetic field (EMF) detector was used to measure the power of the transmitter which was approximately 19 mW.

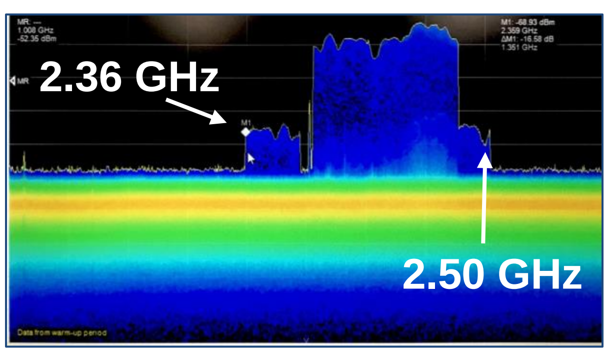


Figure 11. Spectrum of Transmitted Signal

Project Schedule

Table 2. Project Schedule

TASK	Week Number																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Scope Project																				
Order Parts																				
Theoretical Observations																				
Component Verification																				
Antenna & Chirp Tuning																				
Doppler Testing																				
Range Testing																				
Verify Design Requirements																				
Documentation																				
Presentation Preparation																				

VI. Future Work

There are five key goals that should be undertaken in next steps. First, the system should be used to conduct synthetic aperture radar. Second, the systems modulator (V-tune) should be changed to allow the incorporation a chaotic oscillator. Third, further shakedown testing of the range streaming MATLAB® code should be conducted. Fourth, a controlled tests should be conducted to further verify the accuracy of the Doppler live streaming. Additionally, Doppler tests should include testing when the system is in motion and the target is stationary. Lastly, a printed circuit board should be designed and fabricated to replace the proto-board currently used for the system.

VII. Conclusions

The system was successfully built and tested within the 20 weeks allotted for the capstone design. An RF power meter was used to verify that the transmit power was under 20 mW. Additionally, a spectrum analyzer was used to verify that the bandwidth was approximately 100 MHz. Audio .wave files were successfully created using Audacity® and the coffee-can radar system. These audio files can be processed in MATLAB® to extract range and Doppler information. Likewise, the Doppler live stream was successfully deployed on both Union Ave and Nott Street and produced results within the expected values as determined by the speed limits of the roads. Lastly, the system showed that targets with a dynamic range of over 200 meters could be repeatedly detected. The system demonstrates the key radar principles of linear frequency modulation, RF electronics, and antenna design along with signal processing of received waveforms. Lastly, the system was also built under the set budget of $500.

VIII. References

1) The IEEE-Rutgers Center for the History of Electrical Engineering and The Deutsches Museum,“Tracking the History of Radar”; 1994, ISBN: 0-7803-9987-0
2) Charvat, Gregory L., et al. “Build a Small Radar System Capable of Sensing Range, Doppler, and Synthetic Aperture Radar Imaging.” *MIT OpenCourseWare*.

3) Schneider, David. “Coffee-Can Radar.” *IEEE Spectrum: Technology, Engineering, and Science News*, IEEE Spectrum, 1 Nov. 2012, spectrum.ieee.org/geek-life/hands-on/coffeecan-radar.

4) Microwaves and Rf, “Radar Grows From Military Tool to Everyday Use”, Jack Browne, 2015; mwrf.com

5) Stefano Pisa ; Erika Pittella ; Emanuele Piuzzi “A Survey of Radar Systems for Medical Application” IEEE.com

6) “IEEE Code of Ethics.” *IEEE*, www.ieee.org/about/corporate/governance/p7-8.html.

7) https://standards.ieee.org/standard/686-1990.html

8) OSHA Non-ionizing Radiation 39 FR 23502, June 27, 1974, as amended at 61 FR 9236, Mar. 7, 1996

IX. Appendix A. Detailed Parts List

Table 3. Major Component Descriptions and Costs

Callout	Qty/Kit	Part #	Description	Supplier	Supplier Part #	Unit Cost	Subtotal
Radar RF Parts							
OSC1	1	ZX95-2536C+	2315-2536 MC VCO +6 dBm OUT	Mini-Circuits	ZX95-2536C+	$98.95	$98.95
ATT1	1	VAT-3+	3dB SMA M-F attenuator	Mini-Circuits	VAT-3+	$13.95	$13.95
PA1/LNA1	2	ZX60-272LN-S+	Gain 14 dB, NF = 1.2 dB,IP1 = 18.5 dBm	Mini-Circuits	ZX60-272LN-S+	$69.95	$139.90
SPLTR1	1	ZX10-2-42+	1900-4200 Mc, 0.1dB insertion loss	Mini-Circuits	ZX10-2-42+	$34.95	$34.95
MXR1	1	ZX05-43MH-S+	13 dBm LO, RF to LO loss 6.1 dB, IP1 9dBm	Mini-Circuits	ZX05-43MH-S+	$46.45	$46.45
SMA M-M Barrels	4	SM-SM50+	SMA-SMA M-M Barrel	Mini-Circuits	SM-SM50+	$5.95	$23.80
Analog, Power and MISC							
Modulator 1	1	XR-2206	Function Generator Chip	Jameco	34972	$7.95	$7.95
Video Amp 1	1	-	Low-Noise Quad op-amp	Digi-Key	LT1214CN#PBF-ND	$12.37	$12.37
Solderless Breadboard	1	EXP-300E	6.5x1.75" solderless breadboard	Mouser	510-EXP-300E	$7.45	$7.45
Audio Cord	1	172-2236	3.5mm plug to stripped wires	Mouser	172-2236	$3.63	$3.63

Table 4. Component Descriptions and Costs

Callout	Qty.	Part #	Description	Supplier	Supplier Part #	Unit Cost	Subtotal
			Cantennas				
L bracket	2	NA	L-bracket, 7/8", zinc plated	McMaster Carr	1556A24	$0.43	$0.86
SMA F bulkhead	2	901-9889-RFX	SMA bulkhead f Solder cup	Mouser	523-901-9889-RFX	$6.94	$13.88
6-32 screws	1	NA	6-32 machine screw 5/8" length, 100	McMaster Carr	90279A150	$4.64	$4.64
6-32 nuts	1	NA	6-32 hex nuts, pk of 100	McMaster Carr	90480A007	$1.28	$1.28
6-32 lockwashers	1	NA	lock washers for 6-32 screws, 100	McMaster Carr	91102A730	$0.71	$0.71
6" SMA M-M Cables	3	086-12SM+	SMA-SMA M-M 6" Cable	Mini-Circuits	086-12SM+	$12.95	$38.85
			Analog, Power, and Miscellaneous				
Wood Screws	1	NA	brass #2 wood screws 3/8" long, 100	McMaster Carr	98685A225	$5.43	$5.43
Modulator 1	1	XR-2206	Function Generator Chip	Jameco	34972	$7.95	$7.95
Video Amp 1	1	-	Low-Noise Quad op-amp	Digi-Key	LT1214CN#PBF-ND	$12.37	$12.37
Solderless Breadboard	1	EXP-300E	6.5x1.75" solderless breadboard	Mouser	510-EXP-300E	$7.45	$7.45
C1-4	4	SA105A102JAR	1000 pf 5% capacitor	Digi-Key	478-3147-1-ND	$ 0.42	$1.68
R1a_1	10	MFR-25FBF-8K45	8450 ohm 1% resistor	Digi-Key	8.45KXBK-ND	$0.10	$1.00
R1b_1	10	MFR-25FBF-102K	102K ohm 1% resistor	Digi-Key	102KXBK-ND	$0.10	$1.00
R2_1	10	MFR-25FBF-7K15	7150 ohm 1% resistor	Digi-Key	7.15KXBK-ND	$0.10	$1.00
Rf_1_2	10	MFR-25FBF-1K00	1K ohm 1% resistor	Digi-Key	1.00KXBK-ND	$0.10	$1.00
Rg_1	10	MFR-25FBF-12K1	12.1K ohm 1% resistor	Digi-Key	12.1KXBK-ND	$0.10	$1.00
R1a_2	10	MFR-25FBF-17K4	17.4K ohm 1% resistor	Digi-Key	17.4KXBK-ND	$0.10	$1.00

Table 4. Component Descriptions and Costs - Continued

Callout	Qty.	Part #	Description	Supplier	Supplier Part #	Unit Cost	Subtotal
R1b_2	10	MFR-25FBF-28K0	28K ohm 1% resistor	Digi-Key	28.0KXBK-ND	$0.10	$1.00
R2_2	10	MFR-25FBF-4K12	4120 ohm 1%resistor	Digi-Key	4.12KXBK-ND	$0.10	$1.00
Rg_2	10	MFR-25FBF-1K62	1620 ohm 1% resistor	Digi-Key	1.62KXBK-ND	$0.10	$1.00
decoupling cap	3	K104Z15Y5VE5TH5	0.1 uf	Mouser	594-K104Z15Y5VE5TH5	$0.34	$1.02
decoupling cap	3	UVR1E101MED1TD	100 uf	Mouser	647-UVR1E101MED1TD	$0.21	$0.63
trimmer por	3	PV36Y103C01B00	10k	Mouser	81-PV36Y103C01B00	$1.43	$4.29
gain resistor	3	CFP1/4CT52R201J	200 ohm, 5%	Mouser	660-CFP1/4CT52R201J	$0.33	$0.99
Battery pack	2	SBH-341-1AS-R	4xAA battery pack with power switch	Jameco	216187	$2.49	$4.98
5V regulator	2	LM2940CT-5.0/NOPB	5V low dropout regulator	Digi-Key	LM2940CT-5.0-ND	$2.14	$2.14
Audio Cord	2	172-2236	3.5mm plug to stripped wires	Mouser	172-2236	$3.63	$3.63
tuning capacitor	5	FG28X7R1H474KRT00	Multilayer Ceramic Capacitors MLCC - Leaded RAD 50V 0.47uF X7R 10% LS:5mm	Mouser	810-FG28X7R1H474KRT0	$0.31	$1.55
2M trimmer potentiometer	3	PV36W205C01B00	2M trimmer potentiometer	Mouser	81-PV36W205C01B00	$1.50	$4.50
50K trimmer potentiometer	3	PV36W503C01B00	50K trimmer potentiometer	Mouser	81-PV36W503C01B00	$1.50	$4.50
1uF cap	5	UVR1H010MDD1TD	1 uF electrolytic cap	Mouser	647-UVR1H010MDD1TD	$0.22	$1.10
10 uF cap	5	UVR1H100MDD1TA	10 uF electrolytic cap	Mouser	647-UVR1H100MDD1TA	$0.17	$0.85
5.1K resistor	5	MF1/4DCT52R5101F	5.1K resistor	Mouser	660-MF1/4DCT52R5101F	$0.23	$1.15
10K resistor	10	CCF0710K0JKE36	10K resistor	Mouser	71-CCF0710K0JKE36	$0.10	$1.00
LED	3	TLHR5400	Red LED	Mouser	78-TLHR5400	$0.42	$1.26

Table 4. Component Descriptions and Costs - Continued

Callout	Qty.	Part #	Description	Supplier	Supplier Part #	Unit Cost	Subtotal
1K LED resistor	10	CCF071K00JKE36	1K resistor	Mouser	71-CCF071K00JKE36	$0.10	$1.00
100K resistor	10	CCF07100KJKE36	100K resistor	Mouser	71-CCF07100KJKE36	$0.10	$1.00
47K Resistor	24	CCF0747K0JKE36	47K 5% resistor	Mouser	71-CCF0747K0JKE36	$0.10	$2.40
1 uF capacitor unpolarized	4	NA	1 uf film capacitor	Galco	P4675-ND	$1.26	$5.04