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Coffee Can Radar System

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ECE 499 Capstone Design Project

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1. Introduction

A Radio Detection and Ranging ("radar") system detects a target and accurately determines its range and velocity using radio frequency (RF) waves [1]. In the presence of a target, these RF waves are reflected, received, and processed. Until recently, radar systems have been too expensive to implement as undergraduate research projects, primarily because of the cost of the associated RF components. Recently, MIT has developed a low-cost radar system as part of an open-source course [5]. Therefore, one objective of this project is to design and construct a radar system based on the MIT design [5]. A further objective is to develop a system that can calculate target range and velocity in real time from the transmitted and received RF waveforms. For example, the radar system must be able to measure and display the distance (range) of a person moving towards or away from the radar system and estimate and display the person's velocity.

The radar system consists of two antennas, one is used for transmitting the RF waves, and another for receiving them. A signal generator is used at the transmitter to generate and transmit either a monotone or modulated waveform. In the presence of the target, the received waveform is the delayed and Doppler-shifted replica of the transmitted waveform [2]. Both the transmitted and received waveforms are used to identify the target information. In this work, we describe the use of a signal generator to simulate a signal, test the radar system, and tune the RF components for efficient target detection and classification. Signal processing is implemented in MATLAB®. We analyze the transmitted signal bandwidth and perform matched filtering operations. The input to the MATLAB® program is the raw data obtained from the radar system; MATLAB® is used to convert this raw data into information about the range or velocity of the target.

This report provides a brief history of radar and documents our ECE 499 project. This project builds on work reported by other institutions such as the Massachusetts Institute of Technology (MIT) and Worcester Polytechnic Institute that have implemented systems of similar design.

The radar system includes RF components including a voltage-controlled oscillator (VCO), a mixer, a low noise RF amplifier, a splitter, and an attenuator. The system operates in either a continuous wave (CW) monotone mode, which is suitable for measuring the target velocity, or in a continuous wave linear frequency modulated (CWLFM) mode, which is effective for measuring target range. The CWLFM (chirp) signal covers the frequency range of 2.4–2.5 GHz and has a transmit power of about 20 mW.

A key design criterion for this project is that the hardware cost is not to exceed $500.00. The complete parts list and cost breakdown are detailed in the appendix.

2. Background

As mentioned above, the received signal is a delayed replica of the transmitted waveform. This time delay τ is used to determine the range of the target using equation (1).

$$R = \frac{c\tau}{2} \qquad (1)$$

R is the range between the target and the radar, measured in meters, c is the speed of light: 3x 10^8 m/s, and τ is the time delay measured in seconds. Similarly, the received signal is the Doppler-shifted version of the transmitted waveform. This Doppler shift is necessary to estimate the velocity of the target using equation (2).

$$v = \frac{\lambda F_D}{2} \qquad (2)$$

where v is velocity, λ is wavelength of the transmitted waveform, and f_D is the Doppler frequency or Doppler shift. Here wavelength is given as $\lambda = c/f_c$ where f_c is the carrier frequency of the transmitted waveform.

2.1. History and Application of Radar

In 1886, Heinrich Hertz experimented with the theories of Maxwell and found that radio waves can be reflected off "metallic and dielectric bodies" [3]. In June of 1930, the first aircraft was detected using the wave-interference effect [3]. In the 1930s, the first radar was built. Scientists noticed that the signal was reflected as ships passed their radio transmitters [4]. After this discovery, radar quickly found itself into the military during World War II primarily by Britain, Germany and the United States [4]. The Germans used ground-based radar "for air search and height findings so as to perform ground control intercept (GCI)" [3]. On December 7, 1941, the U.S. Army Opana radar site in Oahu, Hawaii detected 353 planes approaching Hawaii, an event known as Pearl Harbor [4]. After World War II, the development of the radar quickly evolved. The United States developed radar systems that could determine the size and weight of an object [4].

Radar has become universal in the 21^{st} century. Radar is used on the ground, in the air, in the ocean, and even in space [3]. Specifically, Radar is applied in the areas of air traffic control, aircraft navigation, ship safety, space, remote sensing, law enforcement, and the military [3]. An example of radar used in law enforcement is police officers monitoring the speeds of automobiles. An example of radar for ship safety is its use to avoid collisions, particularly in limited visibility conditions.

2.2. History of the Project

The coffee can radar system was first introduced by MIT through a class that was offered by the institution. The students learned about electromagnetics and the concepts of radar. The system included ranging, Doppler, and Synthetic Aperture Radar imaging [5]. SAR imaging detects and aims to mirror the object that is in front of the radar system. The course showed how a radar system could be built with metal cans, RF electronic components, and analog circuits [5].

The coffee can radar system has been introduced at other institutions as well, for example WPI. The WPI students used the initial hardware design from MIT to model operation of an “interception-resistant automotive radar” [6]. Students also demonstrated how the radar performance was influenced by the presence of a jammer system [6]. The purpose of the WPI project was to test the performance of an interference radar system in blocking an automobile’s radar signal [6].

2.3. Potential Impacts of Design Requirements

In section 3, the design requirements are listed. A potential impact of the design requirements is economical. This is influenced by the price rise in RF components. The cost of the components is shown in Table 3 and 4 in the Appendix. Another issue with the requirements was the availability of components. For example, there was a problem with the video amplifier IC that was originally chosen by MIT. This specific component was now obsolete. We had to coordinate with the vendor Digi-Key to find a similar video amplifier IC that would perform under the same specifications as the original component.

The last aspect of the project that could impact its viability is the way we build the radar for portability. A protoboard is not ideal for the analog circuitry because wires could move on

the board and connections could become loose. One possible solution to this is to create a PCB for the analog circuit.

2.4. CWLFM Waveform Concept

In the range mode, our radar system uses a CWLFM waveform. Linear frequency modulation is commonly used to generate wideband waveforms. When the bandwidth is increased, the resolution is improved as shown in equation (1). Figure 1 and Figure 2 show the real part of the linear FM and its power spectrum [7].

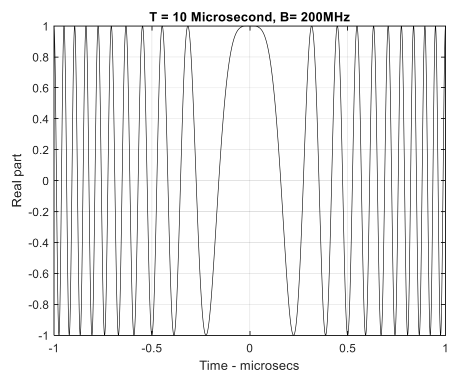

Figure 1: Real Part of CWLFM waveform

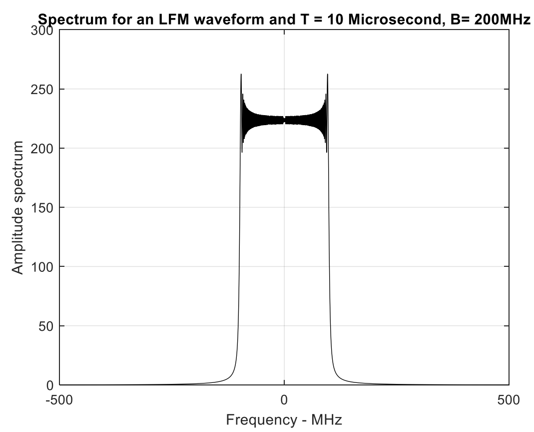

Figure 2: LFM waveform Spectrum

2.5. Key RF Components

The voltage-controlled oscillator (VCO) is a modular RF component that yields a sinusoidal waveform whose frequency depends on the input voltage $V_{in}(t)$. Thus,

$$f(t) = fc + ko * V_{tune}(t) \quad (3)$$

where f_c equals the base frequency (Vin=0) of 2257.4MHz at 25°C and K_o equals the tuning sensitivity of 70MHz/V [8]. V_{tune} represents the input to the VCO and is a triangular wave generated by the modulator circuit (also referred to as ramp generator).

Using a Tektronix RSA5100 series spectrum analyzer and a DC voltage source, we measured the VCO frequency as a function of V_{tune}, as shown in Table 1. With the corresponding V_{tune}, we get a frequency range that spans between 2.4 - 2.5 GHz.

Table 1. VCO Characteristics

V_{tune}, volts	Output frequency, GHz
2.000	2.39125
2.067	2.40000
2.500	2.43076
3.000	2.46775
3.450	2.50000
3.500	2.50350
4.000	2.53725
4.500	2.56800

Another key RF component is the mixer. A mixer is used to multiply two signals. For example, if one input is $A\cos(f_1t)$ and other is $B\cos(f_2t)$, then its output is $AB\cos(f_1t)\cos(f_2t)$, which is equivalent to the expression shown in equation 4:

$$\left(\frac{AB}{2}\right)\{\cos\left((f1 + f2)t\right) + \cos\left((f1 - f2)t\right)\} \quad (4)$$

For this radar application, the mixer multiplies the transmitted signal f_1 and the received signal f_2 to yield a signal that contains f1 + f2 (~ 4.8 – 5 GHz) and f1-f2 (an audio-frequency component that contains the range or Doppler information). The favorable part of the signal for the radar system is f1-f2. This signal is around 25 Hz. Specifically, this signal is the difference between the transmitted and the received signal. This difference is used in MATLAB® to calculate the change in range or velocity of a target. This mixing concept is discussed further in section 6.2.

The last key components are the antennas. Two metal cans must be a part of the antennas due to their cylindrical shape. Both cans will have holes cut into them to then place monopole wires inside. The metal cans act as an open-ended cylindrical waveguide antenna [5]. We placed the monopoles at the top of the antenna can. The construction of the antennas is discussed further in section 5.6.

3. Design Requirements

This section provides the goals for the components and the limitations we have with this project.

Table 2. Overall Design Limitations and Requirements

Requirement	Approach
1. Cost	Use metal cans with wires as monopole antennas, AA batteries for power supply, and wooden base to minimize cost.
2. Power & Portability	Use AA batteries to allow easy maintenance of power supply. All components are light weight, allowing the system to be very portable.

3. Software	Use MATLAB® to enable either live streaming or running a saved .wav file for range and Doppler.
4. Performance	Use CWLFM waveform and a sync pulse to obtain range information. Use DC voltage and no sync pulse to obtain Doppler information.

3.1. Power and Portability

The radar system is powered by two battery packs, each filled with 4 AA batteries. Combining two packs of batteries provides the circuit with 5 V for the RF components, with the application of a 5 V regulator, and 12 V for the VCC of the video amplifier. The system must have a wooden platform as a base. The radar system must be light in weight so that it is portable. Also, the RF components are easy to implement on a wooden board because they can be screwed on and put together by SMA-SMA connection.

3.2. Software

The system must detect both Range and the Doppler. The radar hardware provides raw data, which is processed on the MATLAB® platform that consists of ranging and Doppler files. For ranging, the system should be able to live stream the target range in real time. The system should also be able to provide range information using saved data (i.e. the recorded .wav file). The same two options should be implemented to process Doppler information.

3.3. Performance

In the ranging mode, the system transmits a CWLFM waveform using the VCO and ramp generator [5]. The system must receive the reflected signal and calculate and display the target

range information [5]. The CWLFM frequency range is 2.4 – 2.5 GHz. All RF components were readily available for this frequency range.

4. Design Alternatives

The following design alternatives were considered:

- One alternative is interface between the radar system and the computer. Modern laptops such as the Microsoft Surface do not have a microphone input jack. The microphone input to a desktop computer has a low input impedance (ca. 600 Ω), which causes serious loading of the analog signals from the radar system due to the 47 kΩ series resistor in series with the radar lowpass filter output (see section 5.4). One alternative we tested was to use an external sound card as an analog to digital (A/D) converter; the sound card plugs into a standard USB input. The soundcard input impedance is 27kΩ, which avoids the loading problem.
- Another alternative is to introduce a voltage follower circuit between the active lowpass filter and the analog output. This modification, in addition to the external USB sound card, alleviated the analog signal loading problem.
- The last alternative is to add a 10V regulator to what is currently the 12V power supply to avoid drifting in the modulator circuit.

5. Final Design and Implementation

5.1. Functional blocks

Figure 3 represents the functional block diagram of our proposed radar system. The target is assumed to be in the line-of-sight of the radar system. In the presence of the target, the

transmitted signal is intercepted by the object and reflected from back to the radar system. The received data is provided to the computer to obtain the information about the object. Based on which MATLAB® code is running, the system can measure how far the object is from the system (range) or how fast the object is going (Doppler).

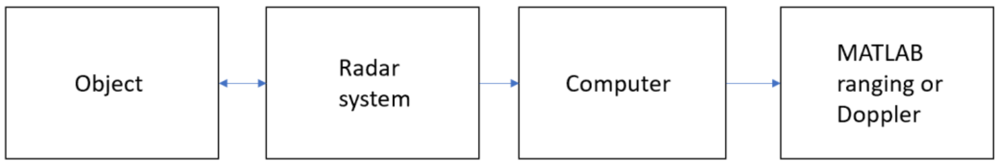

Figure 3: Functional Block Diagram

5.2. Block Diagram

Figure 4 is the overall block diagram of the radar system. In the range mode, the modulator generates a sync pulse that is sent to one channel of the sound card A/D converter to be used by the software to identify the beginning of a frequency ramp. The modulator also generates a symmetrical triangular wave (V_{tune}), which serves as input to the VCO. The VCO output, a 2.4-2.5 GHz waveform, is then amplified by the power amplifier and is split by the splitter. One output of the splitter is sent to the transmitter antenna and the other output acts as input to the the mixer. The mixer multiplies the transmitted signal and the amplified received signal. The mixer output goes into the video amplifier where it passes through a gain stage, a two-stage 15kHz low pass filter (LPF), and a voltage follower. The voltage follower output is sent to the second channel of the sound card A/D converter. The A/D converter sends the data to the computer to perform additional signal processing using MATLAB®.

In the Doppler mode, the modulator is disabled, and a DC voltage (set by a voltage divider from the 5V power supply) is connected to the VCO, which generates a monotone signal (ca. 2.45 GHz).

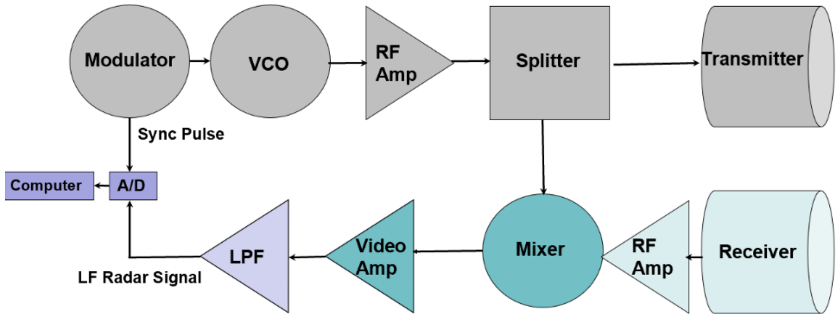

Figure 4: Block Diagram of Overall System

5.3. Power Supply

Figure 5 shows a schematic diagram for the power supply. The 2 battery packs are placed in series to create 12V to supply the voltage to the video amplifier (Vcc). An LED indicates whether or not the battery packs are ON. A voltage regulator is used to regulate the voltage to 5V for the required for RF components and ICs.

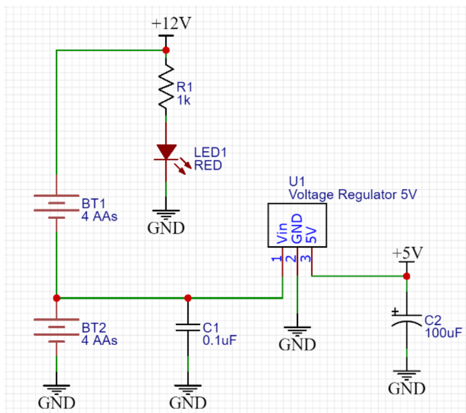

Figure 5: Power Supply Schematic Diagram

5.4. Video Amplifier and Low Pass Filter

Figure 6 shows a schematic diagram of the video amplifier and a LPF circuit. The first amplifier (U1) has an adjustable gain using a potentiometer. The second (U2) and third (U3) stages comprise an LPF with a 15kHz corner frequency. The last amplifier (U4) is a voltage follower to introduce a high input impedance and a low output impedance. Capacitor C_1 acts as a DC blocker. Resistors R_1, R_2, R_4, R_6, R_9, and R_{11} are bias resistors required for current limiting.

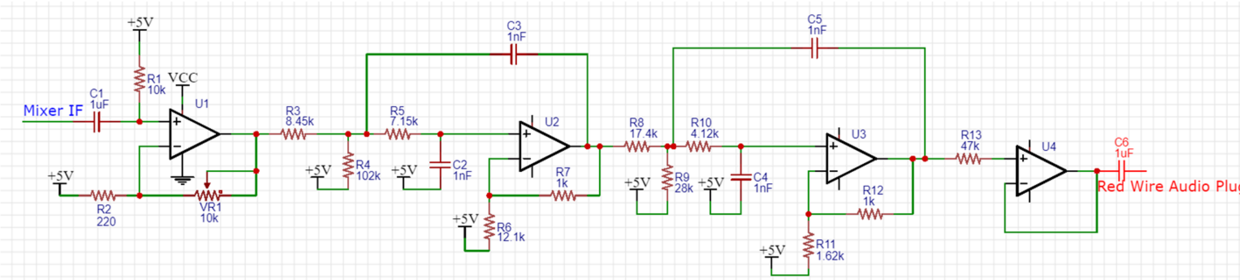

Figure 6: Video Amplifier Circuit

5.5. Modulator

As noted above, in the range mode, the modulator circuit, shown schematically in Figure 7, generates a triangular wave, which is sent to the VCO. The modulator also generates a sync pulse that is sent to the A/D converter through switch SW1. In the range mode, switch SW1 is in the “up” position (pins B and C are connected); in the Doppler mode, switch SW1 is in the “down” position (pins A and B are connected). Figure 11 shows an example of the modulator output. The period of the ramp signal is 40ms, and its voltage varies between 2 and 3V. At pin 11 of the modulator IC (XR2206), the square wave sync pulse is produced. The modulator output, V_{tune}, is generated at pin 2 through a polarized capacitor as a DC blocker and a voltage divider. V_{tune} is used to modulate and generate the CWLFM signal. Variable resistor R7 is used to adjust

the period of the triangular waveform (chirp rate) and variable resistor R7 is used to adjust the frequency span.

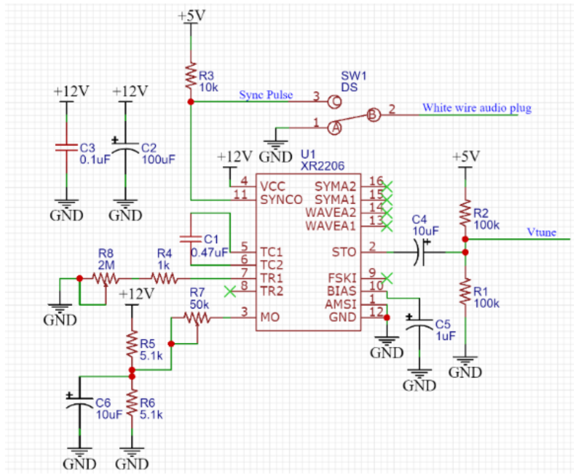

Figure 7: Modulator Circuit

5.6. Cost and Construction of the Radar System

The cost of the components is summarized in the Appendix (section 11.1). The goal of this project is to successfully construct a low-cost radar system. The construction of the RF components in the radar system is shown in the Appendix (section 11. 2). The video amplifier and the modulator circuit were built on the solderless breadboard and then placed on the wooden platform. The buses on the breadboard are ground, +12 V and +5 V respectively. A coaxial cable from the mixer output was connected to capacitor C_1 in the video amplifier circuit shown in Figure 6.

Figure 8 shows the transmitting and receiving antennas. The metal cans were attached to the platform using L-brackets. In this figure, the right can is the transmitter and the left can is the receiver. The transmitter is connected to the splitter with the coaxial cable, and the receiver is connected to the second amplifier with another coaxial cable. Each coaxial cable is connected to

an antenna by an SMA bulkhead connector. This figure also shows the two leads inside the cans; these leads are the monopole antennas. The holes in the cans for the monopoles were made at 4.6 cm from the backwalls of the cans. The length of the monopole is decided based on the reflection coefficient. The specification for the reflection coefficient is that it should be less than -10 dB at our selected 2.4-2.5 GHz. Each monopole antenna was cut to a length of 3.5cm to minimize the reflection coefficient of the antenna. Figure 9 shows the assembled RF components and the completed radar system.

Figure 8: Monopole Antennas

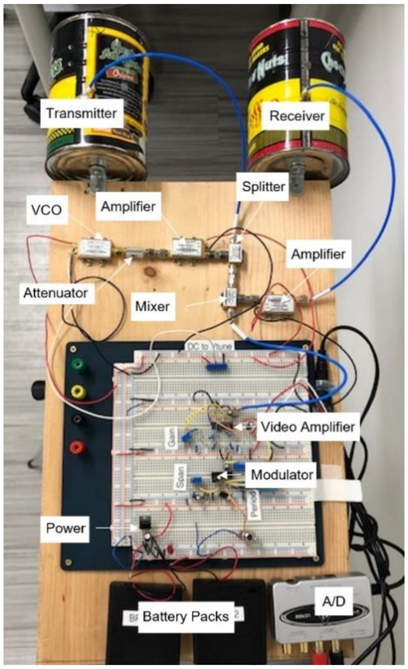

Figure 9: Layout of the Radar System

6. Calibration and Testing

The VCO and the amplifier were characterized using a spectrum analyzer and DC voltage source as described in section 2.5. The modulator and the video amplifier circuits on the solderless breadboard were tested using an oscilloscope. We adjusted potentiometers R7 and R8 to ensure they could change the period and the amplitude of V_{tune}.

6.1. Voltage Controlled Oscillator (VCO)

Figure 10 shows the triangular wave, V_{tune}, that drives the voltage controlled oscillator. When the slope of the triangular wave is positive, the frequency of the CWLFM waveform increases with time. At the positive peak, the frequency will be highest. When the slope is negative , the frequency decreases with time. At the negative peak, the frequency will be the lowest.

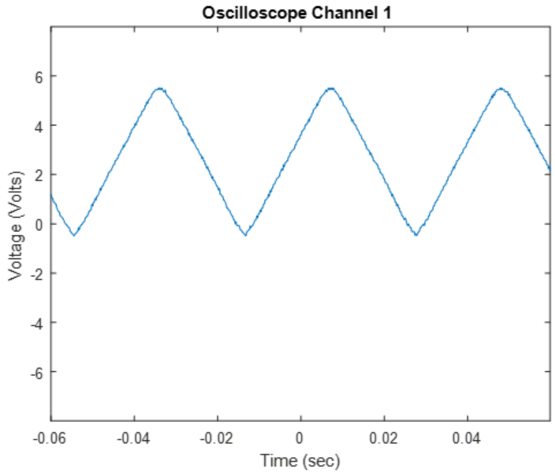

Figure 10: Vtune into the VCO

Figure 11 shows the V_{tune} and the sync pulse, which are generated by the modulator. V_{tune} was tuned to a period of 40 ms and an amplitude of 2-3V ($1V_{pp}$). Table 1 above shows the measured frequency as a function of V_{tune}.

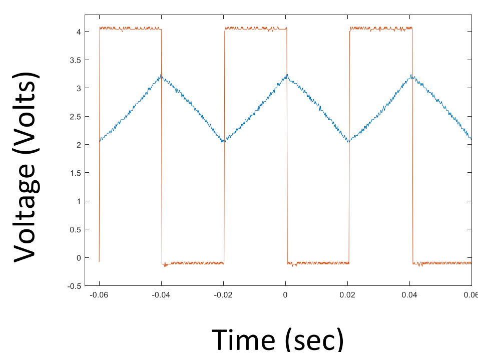

Figure 11: Vtune and the Sync waveforms

6.2. Mixer

The mixer multiplies the transmitted signal and the received signals. The mixer output consists of the sum and difference frequency components of the transmitted and received signals. Using the LPF, the sum component is filtered out while difference component is preserved. The LPF is the input to the video amplifier. Figure 12 shows an example of how the mixer behaves

under the Doppler conditions. The transmitted signal is 2.40 GHz and the received signal 2.4 GHz + 75 Hz. The output of the signal is the 75 Hz which is equivalent to a speed of at about 4.7 m/s.

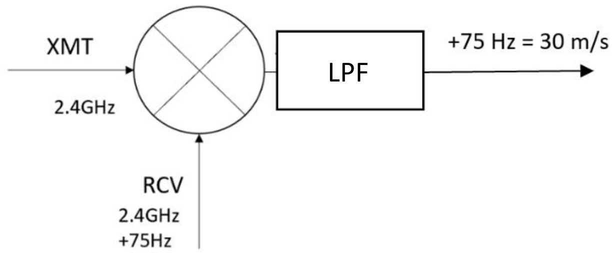

Figure 12: Mixer Behavior under Doppler Conditions

Figure 13 shows the behavior of the mixer in the range operating mode. In this case, V_{tune} is a triangular wave.

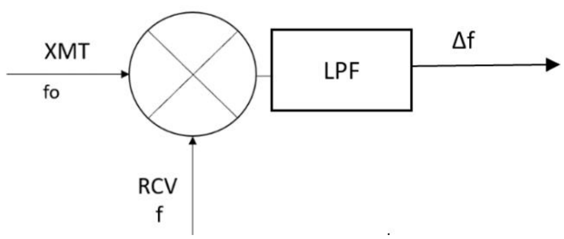

Figure 13: Mixer Behavior under Range Conditions

The transmitter baseline frequency f_o and the instantaneous phase and instantaneous frequency f, are given in equations 5 and 6, respectively.

$$\Theta = 2\pi f_o t + 2\pi k t \tau \qquad (5)$$

$$f = \frac{1}{2\pi}\frac{d\Theta}{dt} = fo + k\tau \qquad (6)$$

where k is the chirp rate, which is equal to $\frac{0.1GHz}{20msec}$.

The output signal frequency is given by equation 7 below:

$$\Delta f = k\tau \qquad (7)$$

$$\text{Thus, } \tau = \Delta f / k$$

and the range can be calculated from the delay, τ, as shown in Equation 1.

6.3. Video Amplifier

The video amplifier gain was adjusted using a function generator as the input. In Figure 14, the blue color plot is the input of the system with a peak-to-peak voltage of $1.12V_{pp}$. The input frequency was 5kHz. The red color plot is the output with a peak-peak voltage of $0.920V_{pp}$.

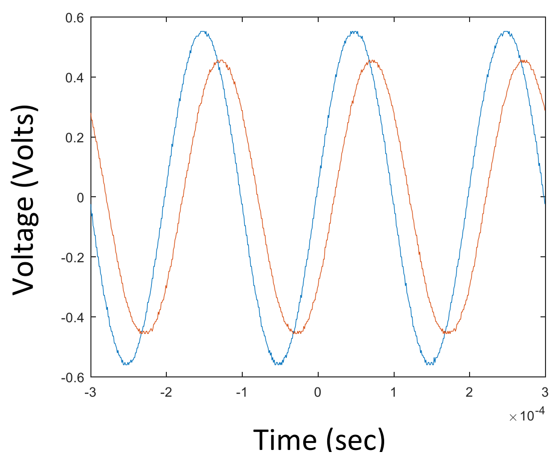

Figure 14: Input (blue) and Output (red) of Video Amplifier

Figure 15 is the same as Figure 14; however, in Figure 15, the output is clipping. This figure shows how the amplifier gain can affect the linearity of the system. The output here is $1.03V_{pp}$.

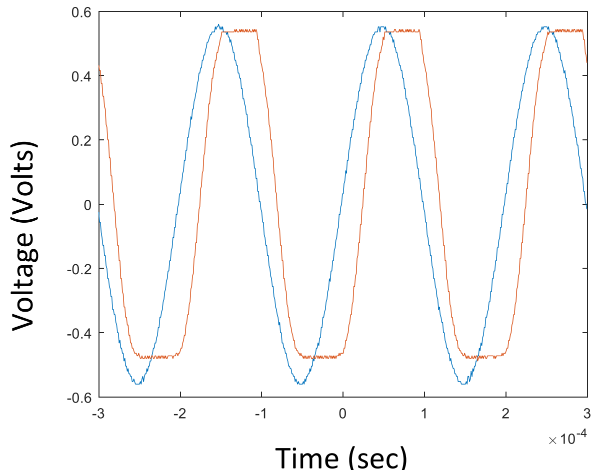

Figure 15: Video Amplifier Clipping (input: blue, output: red)

The input of the video amplifier was changed to 15 kHz. This is to simulate the purpose of the video amplifier. The first video amplifier output is fed through a fourth order 15 kHz ant-aliasing filter [5]. As shown in Figure 16, the input amplitude was 1.12 V_{pp}.

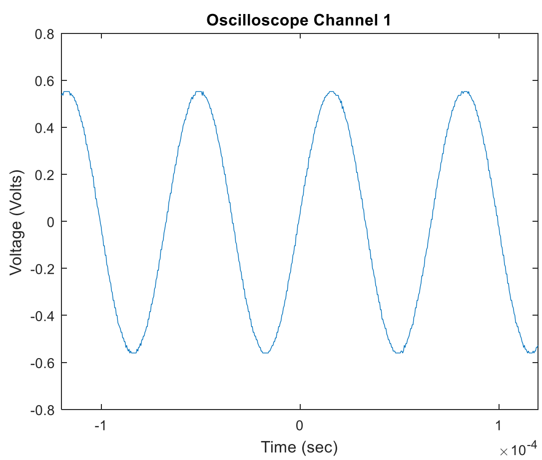

Figure 16: Input at 15kHz

Figure 17 shows the output of the video amplifier. The output was at 9.4 V_{pp} at 15 kHz. There was significant clipping. Figure 18 is the output of the amplifier without clipping at 15 kHz and the amplitude was 7.20 V_{pp}. The potentiometer was adjusted until the output was unclipped.

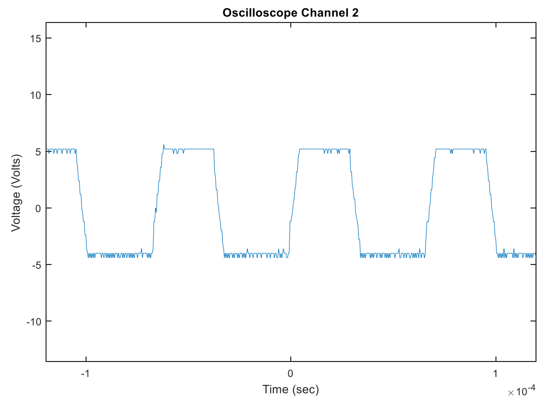

Figure 17: Clipped output of the first amplifier (U1 in Figure 6)

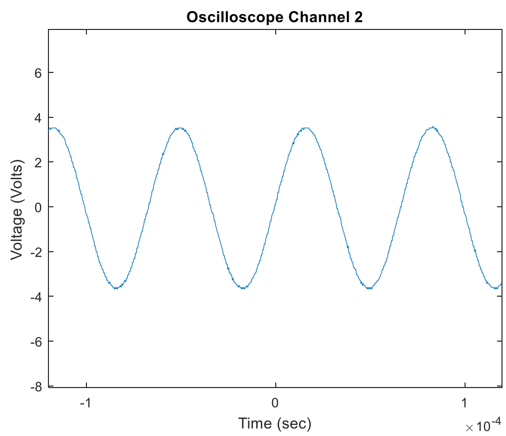

Figure 18: Output at the first amplifier (U1) after gain adjustment

6.4. Radar Response

After the video amplifier adjustments were completed, the coaxial cable was plugged back into the circuit. Figure 19 shows the output of the circuit when an object is placed 1 foot away from the antennas. Figure 20 shows the output when the object is 2 feet away from the antennas.

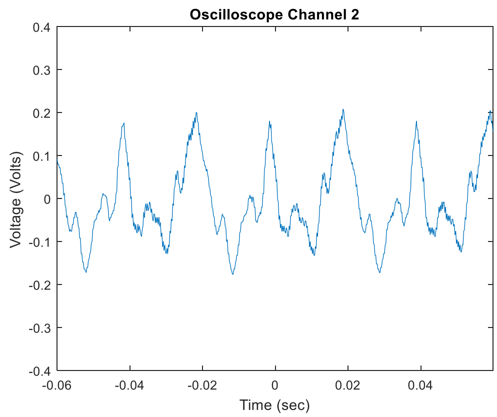

Figure 19: Output with a Ruler a foot away

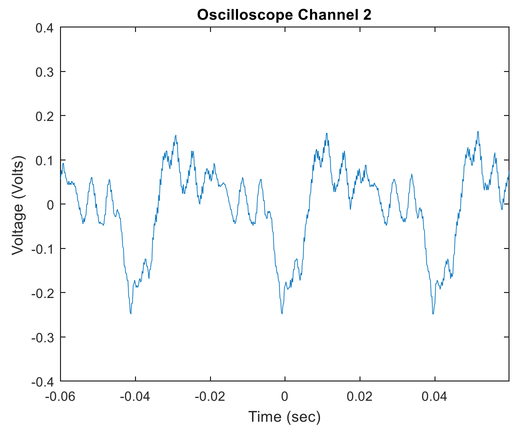

Figure 20: Output with a ruler 2 feet away

Figure 21 shows the spectrum of the transmitted waveform. The spectrum spans a total of 140 MHz from 2.36 GHz to 2.50 GHz. We also observed that the bandwidth changes as a function of the amplitude of the triangular wave connected to the VCO, as expected.

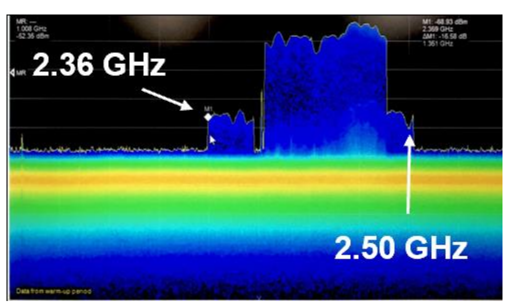

Figure 21: Spectrum of the Radar System

7. Collection of Data and MATLAB® Results

The audio files in .wav format were collected through the Audacity application, which reads in the left and right channels from soundcard A/D converter. For the ranging mode, the signals comprise a sync pulse (left channel) and the output from the LPF (right channel). For the Doppler mode, the sync pulse is grounded (zero volts), and right channel contains the low-frequency Doppler waveform. Audacity records the data and converts the data into a .wav file for processing by the MATLAB® code. The Doppler live streaming is performed straight through the MATLAB® code.

7.1. Range .wav File Results

Figure 22 shows an example of the information recorded by the Audacity application during the ranging mode of operation. This figure shows the data collected on Nott Street. The top waveform is the sync pulse and the bottom waveform is the low-frequency output from the video amplifier/lowpass filter.

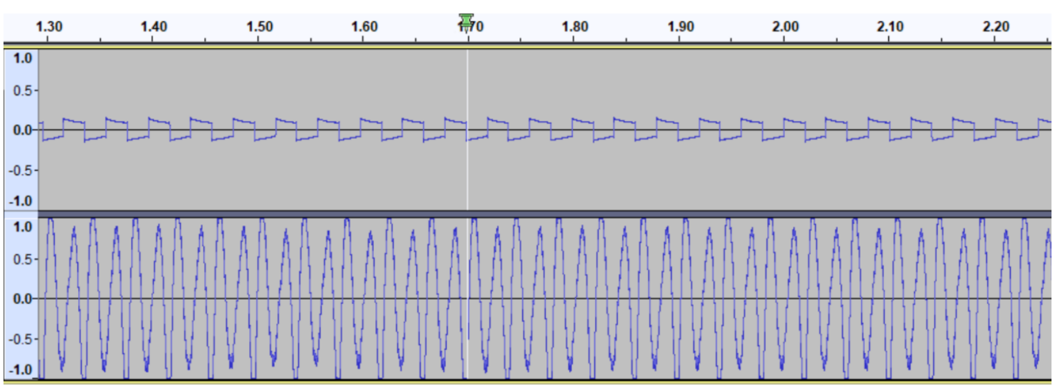

Figure 22: Range Data using Audacity (Nott Street)

Figure 23 shows the MATLAB®-processed range data of the traffic movement on Nott Street. The lines with the positive slopes indicate cars that are driving *towards* the radar

antennas; the lines with negative slopes indicate cars that are driving *away* from the radar antennas. It should be observed that as time progresses the range changes. The color bar on the right indicates the signal intensity, which corresponds to the target size (radar cross-section) and range.

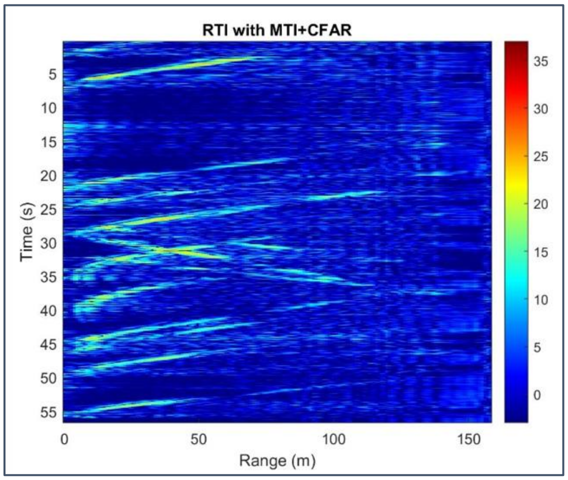

Figure 23: Range Plot for Cars on Nott Street

Figure 24 shows another example of the range test conducted at the Union College football field. This figure shows the measured range vs. time for an individual running away from and towards the radar antennas. Again, the negative slope shows that the target is running away from the radar. Thus, at time 0 seconds, the initial range is recorded as 0 meters and at time 20 seconds the recorded range is approximately 80 meters. The positive slope represents the target returning towards the radar system. For the return trip, the initial range (at time 20 seconds) is 80 meters; at 45 seconds the range is 0 meters, which shows that the target approached the radar system. It is noted that the radar system was placed at 10-yard line and the maximum range target completed was a 100-yard line.

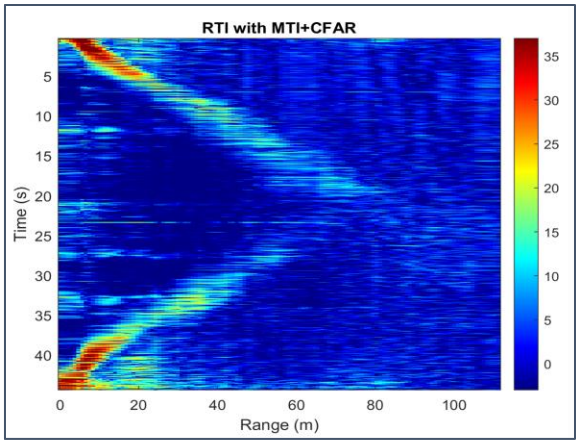

Figure 24: Range plot for target running on Union College football field

7.2. Doppler .wav File Results

Figure 25 shows an example of Doppler data we recorded from cars moving on a street. The left channel, which is on the upper half of the figure, is a straight line because V_{tune} is connected to a DC voltage and the sync pulse and modulator are disabled. The bottom half of the figure shows the Doppler data we recorded for a target in motion.

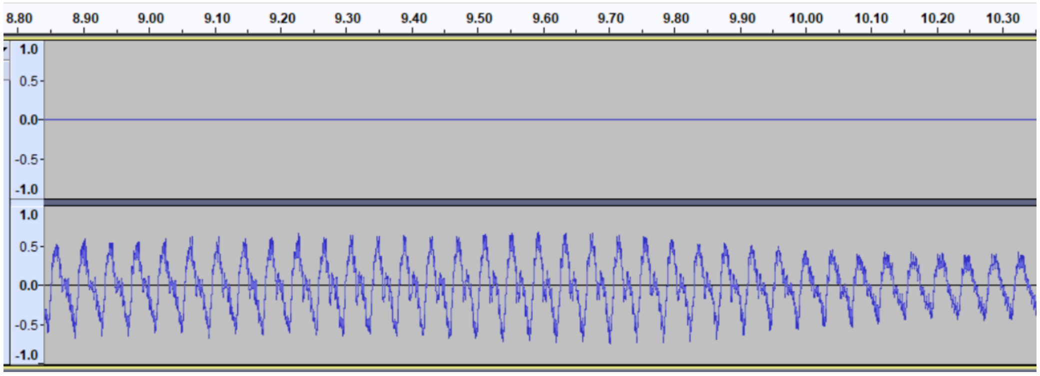

Figure 25: Doppler data recorded using Audacity

Figure 26 shows Doppler data collected during a test on Union Avenue in Schenectady. This figure shows that for most of the targets, the speed was in the range of 12-15 m/s (27-34 mph). These values are consistent with the 30-mph speed limit. Figure 27 shows the Doppler plot

for data collected on Nott Street in Schenectady. Here the range of target speeds was 13-16 m/sec (29-36 mph), compared with a 30-mph speed limit. These figures display velocity versus time. At time 0 seconds, the initial velocity is recorded as 0 meters per second. The red represents high signal intensity. This represents a car going by the radar system. The signals that curve up at their respective speeds are the vehicles that are coming towards the radar system. The signals that curve down show the vehicles that are driving away from the radar system. When the red curve peaks, this represents the max velocity that the radar collects from that respective target.

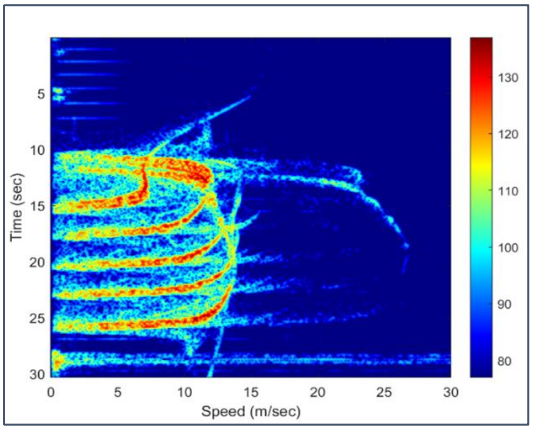

Figure 26: Doppler plot of cars on Union Avenue

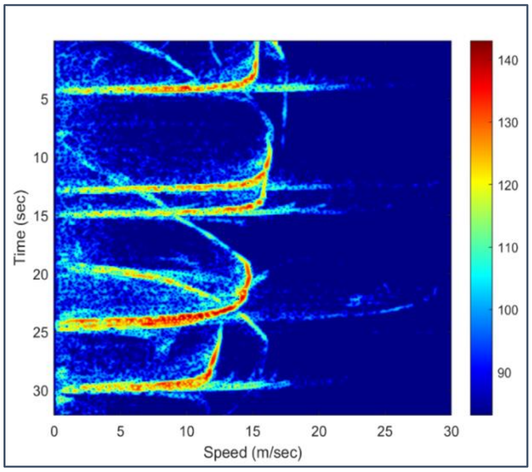

Figure 27: Doppler plot of cars on Nott Street

7.3. Doppler Live Streaming

Figure 28 shows an example of a Doppler live streaming plot. This figure shows the speed versus time graph. The more defined lines in signal intensity show cars that are coming towards the radar system. The faded lines represent the cars driving away from the radar system. The speeds of the vehicles are converted in the MATLAB® code and the current speed title above the plot in this figure constantly changes with the speeds of the respective targets. This figure shows an instance of a vehicle going 35.95-mph on Nott street. As mentioned earlier, this accurately compares with the 30-mph speed limit.

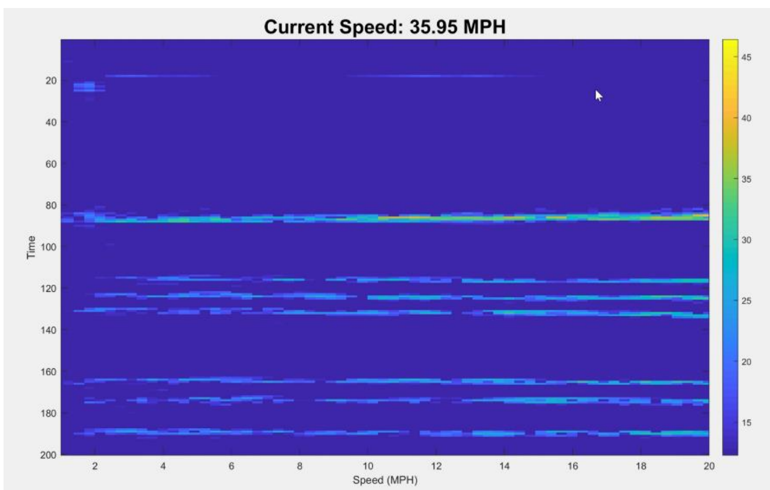

Figure 28: Plot of Doppler live streaming

8. User's Manual

This section is the user's manual for the operation and the maintenance of the coffee can radar system. It provides the necessary steps to successfully perform the tests for Doppler live streaming, range .wav extraction, and Doppler .wav extraction.

8.1. Doppler Live Streaming Test

To perform the Doppler live streaming test, the radar system needs to be set for the correct hardware configuration. The sync pulse switch needs to be switched to ground and V_{tune} of the VCO needs to be connected to a DC voltage source. When the radar is tracking moving targets, live streaming data are used to run the MATLAB® code to acquire the velocity of the target, as shown in section 7.3.

8.2. Doppler .wav Data Acquisition and Analysis

The Doppler test is identical to the Doppler live streaming in terms of the hardware configuration. The sync pulse needs to be turned off and V_{tune} needs to be connected to a DC voltage source. However, to collect a .wav file, the data needs to be collected using the Audacity application. When the radar system is in the tracking mode, we record the received signal through Audacity. The recorded .wav file from Audacity is saved and inputted into the MATLAB® code. The MATLAB® code displays the velocity versus time graph, as shown in section 7.2.

8.3. Range .wav Data Acquisition and Analysis

To test the radar system in the range mode of operation, the hardware configuration needs to be set up as follows. The sync pulse needs to be turned on and the VCO V_{tune} input needs to be connected to the modulator chip at the positive polarity end of C4. When the radar system is in the tracking mode, we record the received signal through Audacity. The recorded .wav file from Audacity is saved and inputted into the MATLAB® code. The MATLAB® code displays the range versus time graph, as shown in section 7.1.

9. Future Work and Conclusions

The coffee can radar system was successfully implemented, and the cost was under budget. The radar system can transmit and receive modulated waveforms. The received signal is processed to obtain the target range and velocity information. Future work includes perfecting the live streaming of the range, SAR imaging, and PCB implementation. The live streaming of the range can be improved by configuring the correct gain in the video amplifier to speed up the MATLAB® live streaming. SAR imaging would include additional hardware and MATLAB® code. Lastly, neatening the protoboard and ultimately PCB implementation will make the components more secure and the overall system more robust. This development could open more opportunities for testing such as putting our radar system on a vehicle and seeing the range and Doppler results of targets.

10. References

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[2] “Function of Radar Transmitter.” *Bohat ALA*, 12 Dec. 2018, bohatala.com/function-of-radar-transmitter/.

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[8] https://www.minicircuits.com/pdfs/ZX95-2536C+.pdf

11. Appendix

11.1. Components and Cost

Table 3 and Table 4 show the expenses of our coffee can radar system. All parts have been ordered and placed into our radar system.

Table 3. Major Component Descriptions and Costs

Callout	Qty/Kit	Part #	Description	Supplier	Suplier 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
Soldrless 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, pk of 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, pk of 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, pk 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

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

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

11.2. Constructing the RF components for the Radar System

The voltage-controlled oscillator is shown in Figure 29. The bracket on the back of the RF component was taken off to enable the component to lay flat on the board. The VCO was then screwed onto the board.

Figure 29: VCO (voltage controlled oscillator)

Figure 30 shows the attachment of the attenuator to the VCO. An SMA barrel was used to connect the attenuator and the amplifier as shown in Figure 30 and Figure 31. The back bracket of the amplifier was taken off and the component was screwed into the wood.

Figure 30: Attenuator

Figure 31: First Amplifier

An SMA barrel was used to connect the number 2 output of the splitter to the mixer as shown in Figure 32 and Figure 33.

Figure 32: Splitter

Figure 33: Mixer

An SMA barrel connects the mixer to the last amplifier shown in Figure 34.

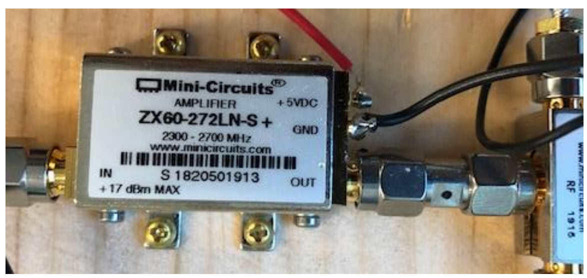

Figure 34: Second Amplifier