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The limitations of a continuous wave Doppler radar for vehicle speed measurement and enforcement

Johann Ruben van Tonder
22569596

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Supervisor: Dr W. Steyn

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22569596	
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Voorletters en van / Initials and surname	Datum / Date

Abstract

English

Afrikaans

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Nomenclature

Variables and functions

E	Electric
H	Magnetic
B	Magnetic Flux Density
μ	Permeability
ϵ	Permittivity
R	Range
G	Gain
V	Voltage
I	Current
P	Power
P_t	Transmitter Power
P_d	Power Density
P_r	Received power
σ	Radar Cross section
λ	Wavelength
A_e	Receive Aperture
τ	Dwell Time
c	Speed of light
f	Frequency
τ_p	Pulse width
t_i	Measurement Time
I_r	Reflected Intensity
I_i	Incident Intensity
w	Angular Frequency
ϕ	Phase

Variables and functions

f_o	Generated Frequency
f_d	Doppler Frequency
v	Vehicle Velocity
N_f	Fast Fourier Transform Size
B	Bandwidth
S_r	Range Resolution
P_o	Input Power
U	Radiation Intensity
N	Sample Size

Acronyms and abbreviations

RADAR	Radio Detection and Ranging
CSIR	Council for Scientific and Industrial Research
PBY	Patrol Bomber Y
CW	Continuous Wave
FMCW	Frequency Modulated Continuous Wave
RCS	Radar Cross Section
SNR	Signal to noise ratio
NBF	Narrow band filter
FFT	Fast Fourier transform
DFT	Discrete Fourier transform
STFT	Short time Fourier transform
RC	Resistor and Capacitor
ADC	Analog to Digital Converter
AGC	Automatic Gain Control
RMS	Root Mean Squared
GNSS	Global Navigation Satellite System
NMEA	National Marine Electronic Association
PC	Personal Computer
OP-AMP	Operational Amplifier
DC	Direct Current
AC	Alternating Current
TE	Transverse Electric
TM	Transverse Magnetic

Chapter 1

Introduction

1.1. Background

The traditional way of measuring vehicle speeds is done with the well-known phenomenon called the Doppler effect. Doppler radars were invented in the second world war, by John L. Barker Sr. and Ben Midlock [1]. They were tasked with solving the problem of terrestrial landing gear damage on the now legendary aircraft the PBY Catalina [2]. Barker and Midlock attached a Doppler radar unit, made out of coffee cans soldered shut to act as microwave resonators, to the end of the runway to measure the sink rate of landing PBYs. The radar gun was later used in 1947 by the Connecticut State Police in Glastonbury, Connecticut. After two years of testing and surveying in 1949, the state police began issuing speed tickets. Over the years the use of Doppler radar guns has come under some scrutiny. In 1987, the CSIR did their independent case study [3] on the validity of Doppler radars for vehicle speed measurements. The case study reported that there are several limitations in vehicle speed measurements, but most importantly the limitation that posed the greatest threat is identifying which vehicle is supplying the measurement. Knowing these limitations might limit the error in vehicle speed measurements and improve accuracy. Establishing how accurate Doppler radars are in vehicle speed measurements might give rise to a change in how vehicle speed is enforced. The goal is to increase safety on roads and limit accidents while making sure the right person is punished for speeding. Below are the operation parameter prescribed by law when using Continuous-Wave(CW) Doppler radars to measure vehicle speed in South Africa [4],

- No metal road signs or vertical flat surfaces larger than 1 meter in vertical height within 15° on either side of the aiming direction, within a distance of 200 m of the antenna.
- No signals received and processed from vehicles more than 500 meters away
- No other moving vehicle other than the measured vehicle within 600 meters from the radar in the direction of operation
- The vehicle's speed should be tracked for 3 s for a valid reading to be possible

1.2. Problem Statement

The objective of the report is to determine the limitations of a CW Doppler radar in vehicle speed measurement and if the prescribed operating laws are sufficient in mitigating these limitations.

1.3. Objectives

1. Identify the possible limitations of CW Doppler radars in vehicle speed measurements
2. Develop hardware for a CW Doppler radar that can perform up to 80 m
3. Develop software capable of calculating the speed of targets
4. Develop software capable of tracking a vehicle
5. The radar should be able to distinguish between a vehicle and clutter
6. Test the theorized limitations of CW Doppler limitations in vehicle speed measurements
7. Determine whether the laws and regulations are satisfactory in limiting possible errors and limitations

1.4. Summary of Work

Research was conducted to first understand how radars work. A thorough understanding was gathered how the radar equation is formulated and how CW Doppler radar differs from other radars. After establishing how a CW Doppler radar is capable of measuring a vehicles speed. The limitations of a CW Doppler radar in vehicle speed measurement was formulated with the knowledge obtained and further research.

To practically test the limitations a CW Doppler radar in vehicle speed measurement, a radar was built. The radar was built with a combination of self designed hardware and sensor integration. The accompanying radar software was designed in Matlab, this was also where all the data processing was done. The radar was tested against GPS speed data to estimate its accuracy before testing the identified limitations. The limitations was then tested and then represented in such a way to clearly indicate where a CW Doppler radar performs accurately and where not. Lastly a comparison was made between the identified and tested limitations, and the operating laws of a CW Doppler radar.

The conclusion was drawn that although a CW Doppler radar is capable of accurately measuring the speed of a vehicle, its accuracy is limited to only one vehicle moving in its

range. There are many cases where a CW Doppler radar is unable to determine a specific vehicle's speed. The biggest limitation of a CW Doppler radar comes down to its inability to determine which vehicle is traveling at which measured speed, in the case that two or more vehicles are in range. The operating laws mitigate these limitations to some extent but fail to completely resolve them.

1.5. Scope

The project scope is to determine the limitations of a CW Doppler radar in vehicle speed measurement. The project does not entail the design of a CW Doppler radar and/or how design choices might affect the radar. This project rather focused on building a suitable radar that would demonstrate the limitations of a CW Doppler radar in vehicle speed measurement. A moving CW Doppler radar is not considered in this report.

1.6. Format of Report

- **Chapter 1** introduces important information used to formulate the problem. The objectives for the report are mentioned followed by a reflection on what objectives were successfully executed. The chapter then discusses the scope of work that was not considered and what important limitations were not included in the report.
- **Chapter 2** discusses other notable work on Doppler radars and their application to vehicle speed measurements. This is also where I pointed out how my report differs from previous work.
- **Chapter 3** starts with the introduction to radar physics and what concepts allow radars to work. I then go on to explain the important fundamentals of radars that a reader of this report should be familiar with and how a CW Doppler radar is capable of measuring a vehicle's speed.
- **Chapter 4** formulates the limitations of CW Doppler radars in vehicle speed measurement.
- **Chapter 5** is where I discuss how I built a CW Doppler radar that I used to test the formulated limitations. This includes the hardware and software design.
- **Chapter 6** starts with a formulation of how I tested the CW Doppler radar. I then discuss how the tests were constructed to test the limitations formulated in Chapter 5. The results from the test are discussed and compared to the limitations.
- **Chapter 7** concludes the report and points to possible future work.

Chapter 2

Literature Review

2.1. Proposed Doppler Radar Solutions

A proposed solution to the problem of vehicle identification was developed by Neil Cameron Martin [5] published in 1987, where the proposed system shown in Figure 2.1, indicates the use of two sources to measure and compare their results. For example, source one only measures vehicle speeds of B and C and source two only measures vehicle speeds of A and C. The configuration will allow you to determine which vehicle is travelling at what speed. The thesis concluded that the system improved the reliability of identifying which vehicle is travelling at what speed. Unfortunately, this system has not been adopted into law enforcement speed regulations. Leaving the case study of the CSIR still at the heart of the problem. This might be due to the complex real-time processing required at the time to successfully implement the system.

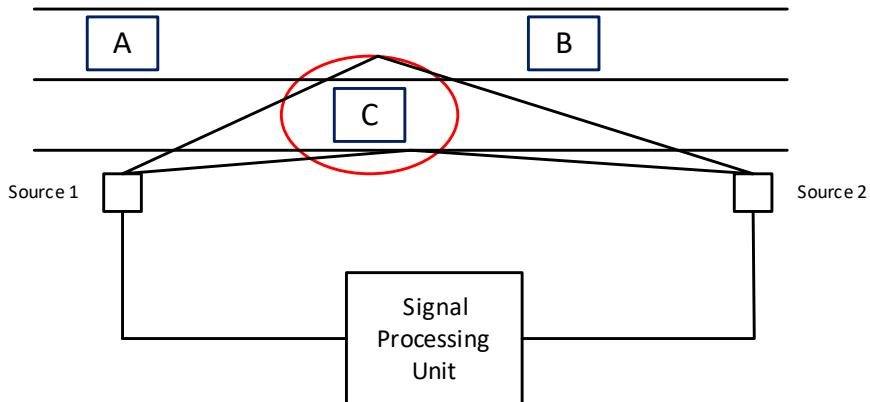


Figure 2.1: Proposed Doppler speed Measurement Configuration

Other noteworthy work was done by Nguyen Giang Lam [6]. Nguyen focussed on developing a Doppler radar with an HB100 X-band sensor [7]. To quite some success Nguyen developed the sensor with an ESP-32 microcontroller module. The developed system was capable of measuring speeds close to the speed measured from the vehicle, shown in Table 2.1, but the measurement was only attained from a distance of 15 m. Nguyen's work focused on building a functional Doppler radar and he did not focus on the limitations of a Doppler radar.

Table 2.1: Accuracy Comparison from HB100 Sensor

Speed from the car	Speed from the HB100 Sensor
0 Km/h	0 Km/h
10 Km/h	11 Km/h
17 Km/h	16 Km/h
20 Km/h	20 Km/h
25 Km/h	24 Km/h
30 Km/h	31 Km/h
35 Km/h	35 Km/h

Apart from the CSIR case study, which is only referenced in Neil Cameron Martin's masters dissertation, there is very little information on how big an influence certain limitations of a Doppler radar have on vehicle speed measurements. In my project, I will aim to adapt the system design by Nguyen to measure vehicles from as far as 80 m and instead of real-time processing I will instead focus on recording data and then applying different processing methods to illustrate the formulated limitations, that is discussed in Chapter 4.

Chapter 3

Radar Physics

3.1. Electromagnetic Wave Propagation

The principle that allows radars to work stems from Maxwell's equation. Maxwell derived his electromagnetic wave equation from the corrected Ampère's circuit law shown in equation 3.1 and 3.2. Faraday's law of induction is shown in equation 3.3 and 3.4.

$$\nabla \cdot E = 0 \quad (3.1) \qquad \nabla \times E = -\frac{\partial B}{\partial t} \quad (3.2)$$

$$\nabla \cdot B = 0 \quad (3.3) \qquad \nabla \times B = \mu\epsilon \frac{\partial E}{\partial t} \quad (3.4)$$

Maxwell derivation is today replaced by combining Ampère's and Faraday's to obtain the electromagnetic wave equation in a vacuum shown in equation 3.5 and 3.6, known as the wave equation.

$$\frac{1}{\sqrt{\mu\epsilon}} \frac{\partial^2 E}{\partial t^2} - \nabla^2 E = 0 \quad (3.5) \qquad \frac{1}{\sqrt{\mu\epsilon}} \frac{\partial^2 B}{\partial t^2} - \nabla^2 B = 0 \quad (3.6)$$

The electromagnetic waveform is generated by a periodic change in the current inside an antenna. The waveform that is generated from the antenna is indicated in Figure 3.1, the blue waveform is the E-field, which is perpendicular to the red waveform, which is the H-field. The waveform propagates in the z-direction.

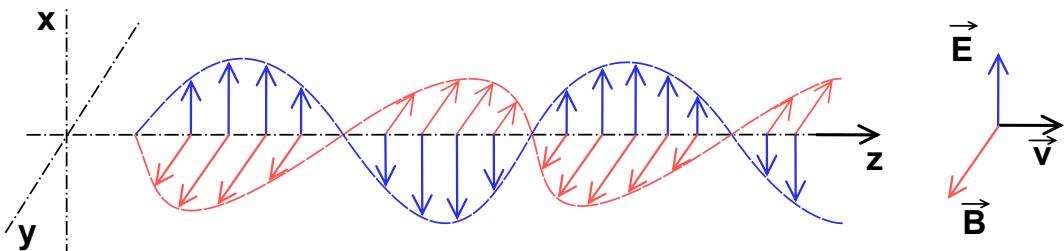


Figure 3.1: Electromagnetic Waveform

Consider the basic radar illustrated in Figure 3.2, it is an antenna transmitting an electromagnetic wave, the waveform then propagates through the air until it reaches a target. A portion of the transmitted energy is intercepted by the target and is scattered, some of it in the direction of the radar, where it is collected by the receiving antenna.

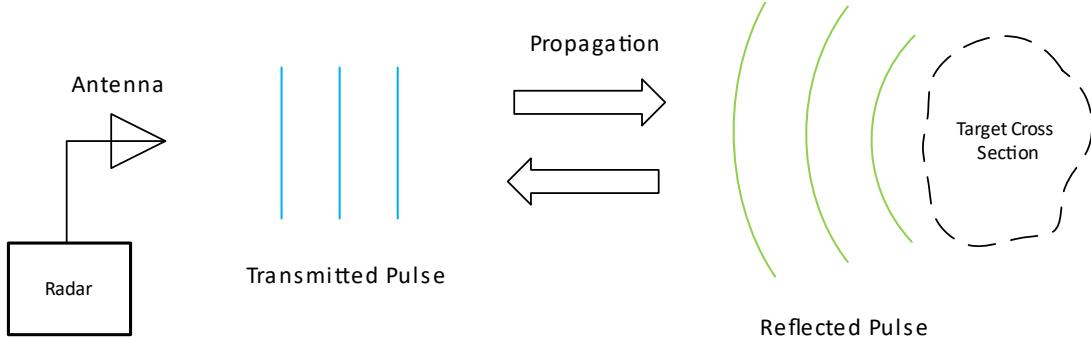


Figure 3.2: A Basic Radar

3.2. Radar Equation

The radar equation relates the range of radar to the characteristics of the transmitter, receiver, target and environment [8]. Understanding the radar equation not only gives you a means for determining the maximum distance from the radar to the target but can also serve as a tool for understanding radar operation and radar design. If the power of the radar transmitter is denoted by P_t , and if an isotropic antenna [9], one which radiates uniformly in all directions, is used. The power density P_d at a distance R from the radar is equal to the transmitter power divided by the surface area $4\pi R^2$ of an imaginary sphere of radius R , the power density is given by

$$P_d = \frac{P_t}{4\pi R^2} \quad (3.7)$$

When the radar employs a directive antenna to channel or direct the radiated P_t into some particular direction. The gain G of an antenna is a measure of the increased power radiated in the direction of the target as compared with the power that would have been radiated from an isotropic antenna. This means P_d at the target from an antenna with transmitting gain G is

$$P_d = \frac{P_t G}{4\pi R^2} \quad (3.8)$$

A portion of the radiated power is intercepted by the target and reradiated in various directions. The measure of the amount of incident power intercepted by the target and reradiated back towards the radar is denoted by the radar cross section σ , and is defined by the relation

$$P_d = \frac{P_t G}{4\pi R^2} \frac{\sigma}{4\pi R^2} \quad (3.9)$$

The radar cross-section σ has units of area. It is a characteristic of the particular target and is a measure of its size as seen by the radar. The radar antenna captures a portion of the echo power. If the effect is denoted by A_e , the power P_r , received by the radar is

$$P_r = \frac{P_t G A_e \sigma}{(4\pi)^2 R^4} \quad (3.10)$$

The maximum range of the radar R_{max} is the distance beyond which the target cannot be detected. It occurs when the received signal power P_r , just equals the minimum detectable signal S_{min} . Therefore

$$R_{max} = \left(\frac{P_t G A_e \sigma}{(4\pi)^2 S_{min}} \right)^{\frac{1}{4}} \quad (3.11)$$

Antenna theory gives the relationship between the transmitting gain and the receiving effective area of an antenna as

$$G = \frac{4\pi A_e}{\lambda^2} \quad (3.12)$$

Generally, radars use the same antenna for transmitting and receiving by substituting equation 3.12 into equation 3.11, resulting in

$$R_{max} = \left(\frac{P_t (A_e)^2 \sigma}{4\pi (\lambda)^2 S_{min}} \right)^{\frac{1}{4}} \quad (3.13)$$

3.3. Radar Frequencies

Radars conventionally operate at frequencies from 220 MHz to 35 GHz. These are not limits but rather standards proposed by the International Telecommunications Union [10]. Early in the development of radar, a letter code such as S, X, L, etc., was employed to designate radar frequency bands. The original purpose was to safeguard military secrecy, and the designation was maintained. The frequency band of importance for a Doppler radar are referred to as the Microwave region. The Microwave region ranges from 300MHz to about 36 GHz. Table 3.1 shows the designated bands inside the Microwave region.

Table 3.1: Standard Microwave Frequency letter-band nomenclature

Band Designation	Nominal Frequency range (GHz)
<i>UHF</i>	0.3-1
<i>L</i>	1-2
<i>S</i>	2-4
<i>C</i>	4-8
<i>X</i>	8-12
<i>K_u</i>	12-18
<i>K</i>	18-27

Doppler radars are operated in the *X*-band region, this is mainly due to law enforcement from the mid-1950s [11]. The reason behind using *X*-band as opposed to *K*-band or *K_u*-band is due to *X*-band being less affected by poor weather conditions. There are however disadvantages when using *X*-band over *K*-band, *X*-band requires a larger antenna and is easy for radar detectors to pick up at long distances. The operating frequency is related to the wavelength as shown below

$$\lambda = \frac{c}{f} \quad (3.14)$$

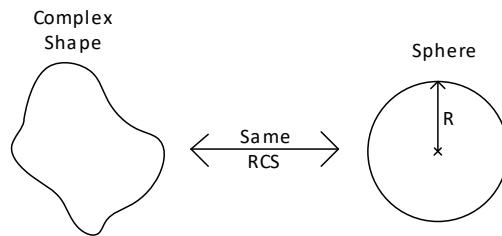
The higher the frequency, the smaller the wavelength. Meaning the radar will be able to measure smaller details the higher its operating frequency is.

3.4. Radar Cross Section

The radar cross-section (RCS) [12], is a measure of the reflectivity of an object and is formulated as

$$\sigma = \lim_{R \rightarrow \infty} 4\pi R^2 \frac{I_r}{I_i} \quad (3.15)$$

where I_r is the reflected intensity and I_i is the incident intensity. The $4\pi R^2$, comes from the assumption, that the radar cross-section is assumed to take the shape of a sphere, this assumption is illustrated below

**Figure 3.3:** Equivalent Sphere shape

Most of the incident energy is scattered and only a small fraction is reflected on the radar. Larger objects usually, but not always, have larger reflections and a longer radar

detection range R . The object parameters that influence the RCS are size, shape and reflectivity [13]. Flat surfaces reflect energy better than contoured shapes. Edges with diameters on the order of a wavelength of the radar frequency tend to be good reflectors. All metals and alloys are excellent reflectors at all frequencies. Metal screens with gaps spacing less than a quarter wavelength are as reflective as solid surfaces. Composites, fibreglass and plastic are bad reflectors at microwave frequencies.

3.5. CW Doppler Radar

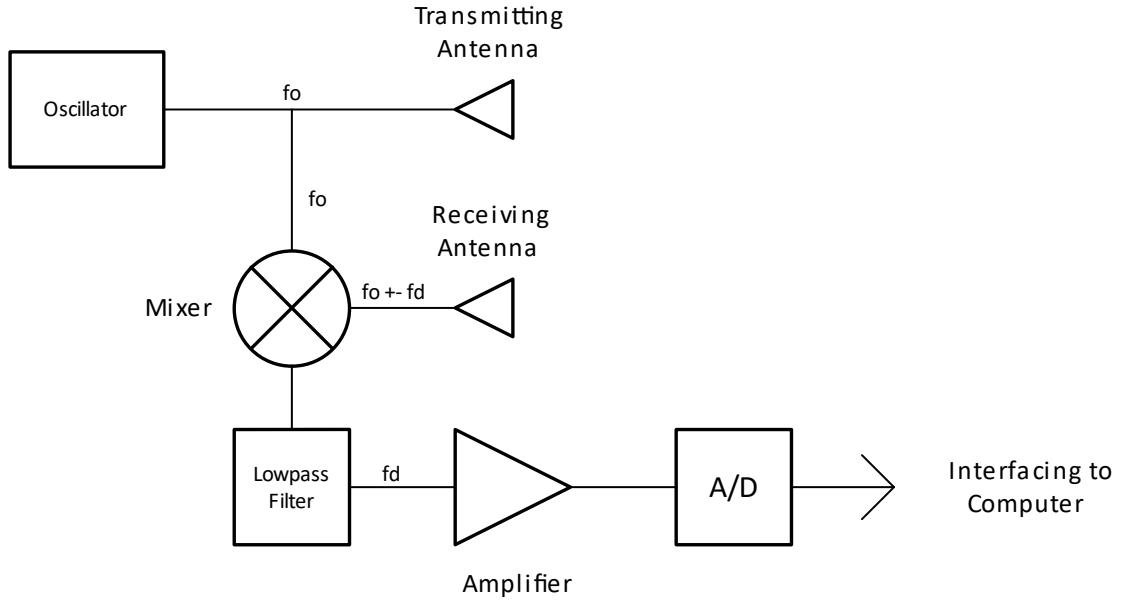
It is well known in the fields of optics and acoustics that if either the source of oscillation or the observer of the oscillation is in motion, an apparent frequency shift will result. This is known as the Doppler Effect and is the basis of CW Doppler Radar [8]. If the distance between the radar and target is R , the total number of wavelengths λ contained in the two-way path between the radar and target is $\frac{2R}{\lambda}$. Since one wavelength corresponds to an angular excursion of 2π radians, the total angular excursion ϕ made by the electromagnetic wave during its transit to and from the target is $\frac{4\pi R}{\lambda}$ radians. If the target is in motion, R and the phase ϕ are continually changing. A change in ϕ with respect to time is equal to a frequency. This is the Doppler angular frequency ω , given by equation 3.16

$$2\pi f_d = \omega = \frac{4\pi \partial R}{\partial t} = \frac{4\pi v}{\lambda} \quad (3.16)$$

where f_d = Doppler frequency shift and v = relative velocity of target with respect to radar. The Doppler frequency shift is given by equation 3.17

$$f_d = \frac{2v}{\lambda} = \frac{2vf_o}{c} \quad (3.17)$$

where c is the speed of light in a vacuum. Consider the CW Doppler radar as illustrated in Figure 3.4. The oscillator generates a continuous frequency f_o , which is transmitted by the antenna. If the target is in motion with velocity v , relative to the radar, the received signal will be shifted in frequency from the transmitted frequency f_o , by an amount $\pm f_d$, given by equation 3.17. The plus sign associated with the Doppler frequency applies if the distance between the radar and target decreases. The minus sign applies if the distance is increasing. The received echo signal at frequency $f_o \pm f_d$, enters the radar via the antenna and is heterodyned in the mixer, with the transmitted signal f_o to produce a Doppler beat note of frequency f_d . This is illustrated in Figure 3.5, note that the sign of f_d is lost in the process.

**Figure 3.4:** CW Doppler Radar

The resulting Doppler frequency obtained from the mixer is then passed through a lowpass filter, to filter out all the frequency components above f_d . The signal is then amplified before its sampled by an analogue-to-digital converter and then passed on to the computer interface for signal processing and analysis.

**Figure 3.5:** Result of Frequency Mix

3.6. Frequency Resolution

Doppler frequency resolution is the ability to distinguish between two objects travelling at different speeds, but at the same distance from the radar. Frequency resolution is inversely related to the dwell time, the time an antenna spends on a target. The greater the dwell time the finer the frequency resolution

$$\Delta f_D = \frac{1}{\tau} \quad (3.18)$$

We can also estimate the Doppler accuracy as, where SNR is the signal to noise ratio

$$\delta f_D = \frac{\Delta f_D}{t\sqrt{2SNR}} \quad (3.19)$$

To plot the spectrum of the sampled signal individual narrow band filters(NBF) must be as narrow as possible in bandwidth to allow accurate Doppler measurements and minimize the amount of noise power. In theory, the operating bandwidth of a CW Doppler radar is infinitesimal. However systems with infinitesimal bandwidths cannot physically exist and thus, the bandwidth of CW Doppler radars is assumed to correspond to that of a gated CW waveform.

An NBF bank can be implemented using a Fast Fourier Transform(FFT). If the Doppler filter bank is implemented using FFT of size N_f , and if the individual NBF bandwidth is Δf_D , then the effective radar Doppler bandwidth is

$$B = N_f \Delta f_D \quad (3.20)$$

The table 3.2 below indicates the Doppler shift as a function of velocity and frequency [14].

Table 3.2: Doppler Shift as a Function of Velocity and Frequency

<i>f</i>		Doppler Shift f_D (Hz)	
Band	Frequency (GHz)	1 m/s	1km/h
<i>L</i>	1	6.67	1.85
<i>S</i>	3	20	5.55
<i>C</i>	5	33.3	9.25
<i>X</i>	10	66.7	18.53
<i>K_u</i>	16	107	29.72
<i>K_a</i>	35	233	64.72

3.7. Range Resolution

The range resolution of a radar is its ability to distinguish between two or more targets on the same bearing, the angle measured relative to a hypothetical north, but at different ranges [15]. The degree of range resolution depends on the width of the transmitted pulse τ_p , the types and sizes of targets, and the efficiency of the receiver. Pulse width τ_p is the primary factor in range resolution. The simplified theoretical range resolution can be calculated from

$$S_r = \frac{c\tau_p}{2} \quad (3.21)$$

An unmodulated CW Doppler radar does not have range resolution. To acquire range resolution some sort of timing mark must be applied to a CW carrier if the range is to be measured. The timing mark permits the time of transmission and the time of return to be recognized. The more distinct the mark, the broader the transmitted spectrum will be. This follows from the properties of the Fourier transform,

$$\mathfrak{F}(h(t)) = \int_{-\infty}^{\infty} h(t) e^{-j2\pi f_t t} dt \quad (3.22)$$

therefore a finite spectrum must be transmitted if transmit time or range is to be measured. The spectrum of a CW transmission can be broadened by the application of modulation either amplitude, frequency or phase. A widely used technique is to frequency-modulate the carrier resulting in a Frequency Modulated Continuous-Wave(FMCW).

3.8. Radar Clutter

Land clutter is difficult to quantify and classify. The clutter is widely dependent on the type of terrain, as described by its roughness and dielectric properties. Buildings, towers, and other structures give more intense echo signals than forests and vegetation because of the presence of flat reflecting surfaces. Land clutter will mostly affect the targets with small radar cross-sections, like motorcycles. Birds flying past a radar are also seen as a type of clutter.

3.9. Antenna Parameters

The purpose of the antenna is to act as a transducer between free-space propagation and guided-wave (transmission-line) propagation. The function of the antenna during transmission is to concentrate the radiated energy into a shaped beam which points in the desired direction in space. On reception, the antenna collects the energy contained in the echo signal and delivers it to the receiver. Antenna design and theory are very complex. To understand the application of an antenna in radars there are two pieces of theory to understand, namely Gain and Directivity.

Gain is a measure of the ability of the antenna to direct the power delivered to the input into radiation in a particular direction. Gain is measured at the peak radiation intensity. Consider the power density radiated by an isotropic antenna at a distance R and input power P_t :

$$P_d = \frac{P_0}{4\pi R^2} \quad (3.23)$$

As isotropic antenna radiates equally in all directions and the power density P_d is found by dividing the radiated power by the area of the sphere with radius R . The isotropic

radiator is considered to be 100% efficient. The gain of a real antenna increases the power density in the direction of the peak radiation.

$$P_d = \frac{P_t G}{4\pi R^2} \quad (3.24)$$

Directivity is a measure of the concentration of the radiation in the direction of the maximum radiation. Directivity is the maximum radiation intensity over the average radiation intensity:

$$\text{Directivity} = \frac{U_{max}}{U_{avg}} \quad (3.25)$$

Directivity and gain differ only by efficiency, but the directivity is easily estimated from patterns. Gain, directivity times efficiency, must be measured. The average radiation intensity can be found from a surface integral on the radiation sphere of the radiation intensity divided by 4π , the area of a sphere in steradians.

$$U_{avg} = \frac{1}{4\pi} \int_0^{2\pi} \int_0^\pi U(\theta, \phi) \sin\theta d\theta d\phi \quad (3.26)$$

Chapter 4

Limitations of a CW Doppler radar in Vehicle Speed Measurement

4.1. Cosine Effect

The incorrect Doppler frequency is measured from the radar when the vehicle is not travelling directly towards the radar, this is illustrated in figure 4.1. The phenomenon is called the Cosine Effect because the measured speed is directly related to the cosine angle between the radar and the vehicle's direction of travel. The cosine angle is calculated by the equation below,

$$\beta = \tan^{-1}\left(\frac{d}{R}\right) \quad (4.1)$$

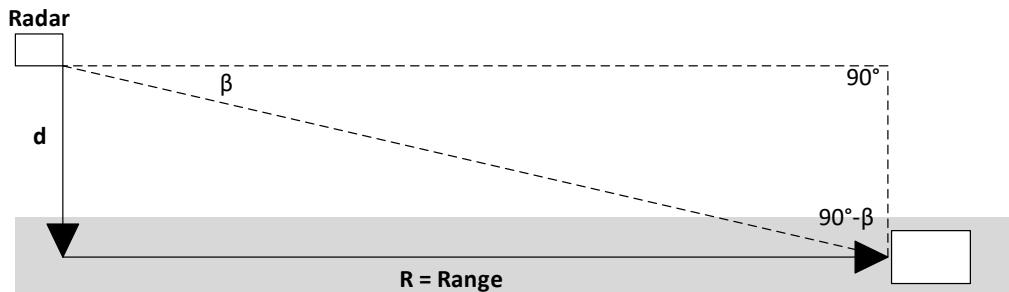


Figure 4.1: Cosine Angle β

The error in speed measurement is calculated in equation 4.2, where β is the incident angle, R target range to radar and d is the antenna distance to the middle of the target lane. As the target lane becomes curved or the radar is placed in the air the change in angle is too great for the radar to give an accurate result. Below is the equation for correcting the cosine error,

$$V_m = V_o \cos(\beta) = V_o \frac{R}{(R^2 + d^2)^{0.5}} \quad (4.2)$$

V_m is the measured speed and V_o the actual speed. As highlighted in section 3.7 the CW Doppler radar cannot determine how far away a target is from the radar. There

are some software techniques you can apply, but their accuracy is questionable. The measured speed will always be less than the actual speed and thus care should be taken when enforcing minimum speed limits.

4.2. Accuracy and Acceleration Limits

Under ideal conditions, most speed measurement radars should have an accurate reading of about ± 1 km/h. A very important part of radar is to discriminate between different frequency components in a signal, in a short period. Radars are capable of extracting frequency from the measured values of an Analog-To-Digital Conversion(ADC) by a Discrete Fourier Transform(DFT) analysis of nonstationary signals. Nonstationary signals are signals that differ in frequency over time. To differentiate between frequency components a short period of the signal is used to calculate the frequency spectrum, hence the name Short Time Fourier Transform(STFT). The sample taken in the time domain has a trade-off in the frequency domain. To understand this trade-off you need to understand how the DFT works. The equation below shows how the DFT is calculated.

$$H[k] = \sum_{n=0}^{N-1} h[n]e^{-j2\pi kn/N} \quad (4.3)$$

The DFT takes a finite amount of samples, N , to calculate the frequency spectrum of discrete signal h . To increase the resolution in the frequency domain one can decrease the sampling frequency or increase frame size. To increase the resolution in the time domain you can increase the sampling frequency or decrease the frame size. Both methods have trade-offs, by increasing the frequency resolution you are decreasing the time resolution. To visualize the effect the results of a DFT are represented in a spectrogram, which has time displayed on the horizontal axis, frequency on the vertical axis and spectral magnitude displayed on the third axis by colour. Figure 4.2 illustrates the trade-off between time and frequency, the first graph highlights how to differentiate between frequency components you will lose the ability in the time domain. The right-sided graph demonstrates the opposite, to differentiate in time you lose the ability to differentiate in the frequency domain.

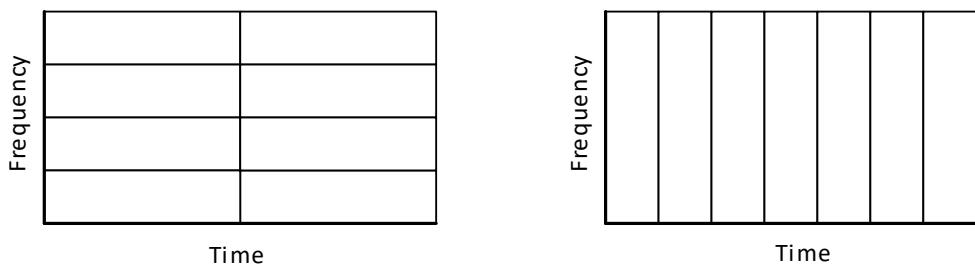


Figure 4.2: Frequency Versus Time Resolution

4.3. Object Identification

A CW Doppler radar uses the frequency spectrum to identify objects. As shown in Table 3.2, the frequency shift measured is a direct indication of how fast an object is moving. This is a very sound method and is capable of very accurate measurements. There is a problem nonetheless, how does the radar identify which object is travelling at what speed? For the case of a CW Doppler radar which does not have range resolution, discussed in section 3.7. A CW Doppler radar cannot distinguish between multiple vehicles/objects travelling at different speeds, both in the range of the radar. Due to Automatic Gain Control(AGC), discussed in section 5.1.3, being applied to the measured signal frequencies. The assumption of the closest object will generate the strongest signal is not true.

In Table 4.1 the estimate of vehicle RCS is illustrated. For motorists their RCS is relatively small, the motorcycle RCS normalised to a full-size pickup is 0.05 m^2 . This means that a motorcycle is very likely to be mistaken for a more distant vehicle. Figure 4.3, illustrates this phenomenon.

Table 4.1: Estimates of vehicle RCS

Vehicle Type	Radar Cross Section
Recreation Vehicle	400 m^2
Full Size Pickup	200 m^2
Large Car	120 m^2
Medium Size Car	60 m^2
Small Car	30 m^2
Motorcycle	10 m^2
Bicycle	5 m^2

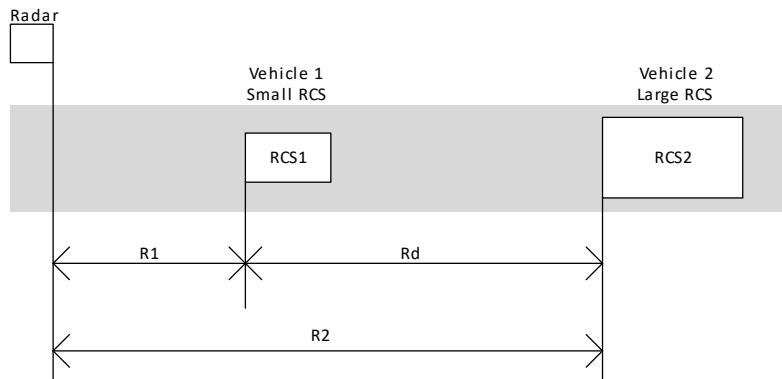


Figure 4.3: Vehicle Ranges for Equal Echo Power

The distance from the radar to the vehicle where the reflected power of vehicle two is equal to the reflected power of vehicle one, can be calculated by

$$R2 = R1 \left(\frac{\sigma_2}{\sigma_1} \right)^{\frac{1}{4}} \quad (4.4)$$

The equation can be written in terms if the distance between the two vehicles Rd ,

$$Rd = R1 \left[\left(\frac{\sigma_2}{\sigma_1} \right)^{\frac{1}{4}} - 1 \right] \quad (4.5)$$

Not only will the radar struggle to distinguish the travelling speeds of multiple vehicles in its range but it would also not be able to detect what the object is, that recorded the speed measurement. For instance, birds flying past the radar may cause false speed readings. This is not a likely phenomenon if it is just one bird due to a bird's RCS being usually around 0.1 m^2 . But when a swarm of birds fly past a radar it will cause the radar to have a false reading.

4.4. Antenna Sidelobes

An Antenna radiation pattern is a visual representation of the radiation emission from an antenna. Figure 4.4 illustrates how this can be plotted in polar coordinates. The main lobe is directed in the direction of the intended measurement. The side lobes are relatively small compared to the main lobe. This specific antenna's radiation pattern is very good to measure only in one direction/lane. This is not always the case, some antennas might have very big side lobes. This will cause the radar to measure unintended objects that are not in the direction of measurement. Attention should be applied to the antenna radiation pattern when operating the radar.

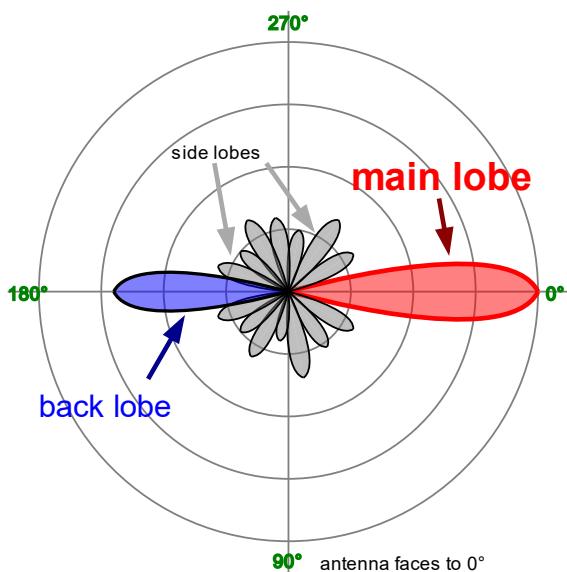


Figure 4.4: Antenna Radiation Pattern

Looking at the antenna radiation pattern of the HB100 sensor shown in figure E.1, the

antenna is not very directional. When applying AGC to the received signals, it further complicates the process. This adds to the confusion of not knowing what object is reflecting the signal. Combining antenna radiation, side lobes, and AGC. It can compromise the credibility of a radar. It is important to know the radiation pattern of your radar for both the transmitting and receiving antenna otherwise, you will not have accurate readings.

4.5. Multiple Path Reflection

The transmitted signal does not always take a direct path from radar to target and back. Any metal object, which is a good reflector, may lead to another path of reflection for the radar to measure. The radar is not capable of detecting how a signal has travelled from and back to the radar. A common object like an overhead or off-road highway sign can cause signals to reflect in multiple ways. Figure 4.5 shows two reflection paths the radar will measure when an overhead sign is placed on a highway.

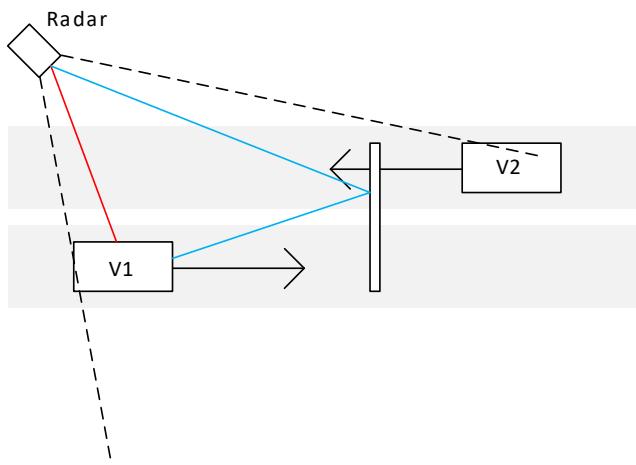


Figure 4.5: Multiple Reflections

The above illustration is just one example. There are more examples that are not as easy to quantify.

4.6. Radar Receiver Saturation

Strong echoes from larger vehicles close to the radar will reduce the radar detection range. The receiver will saturate and will not be able to measure any other vehicles in the radar range. Strong signals that saturate the radar receiver's low noise amplifier or mixer will produce cross-modulation products. Cross modulation, also known as intermodulation, is the amplitude modulation of signals containing two or more different frequencies. The intermodulation between frequency components will result in additional components at frequencies that are not just at harmonic frequencies but also the sum and difference

frequencies of multiples of those frequencies. Figure 4.6 illustrates how intermodulation can result in distortion and how this might saturate the radar receiver.

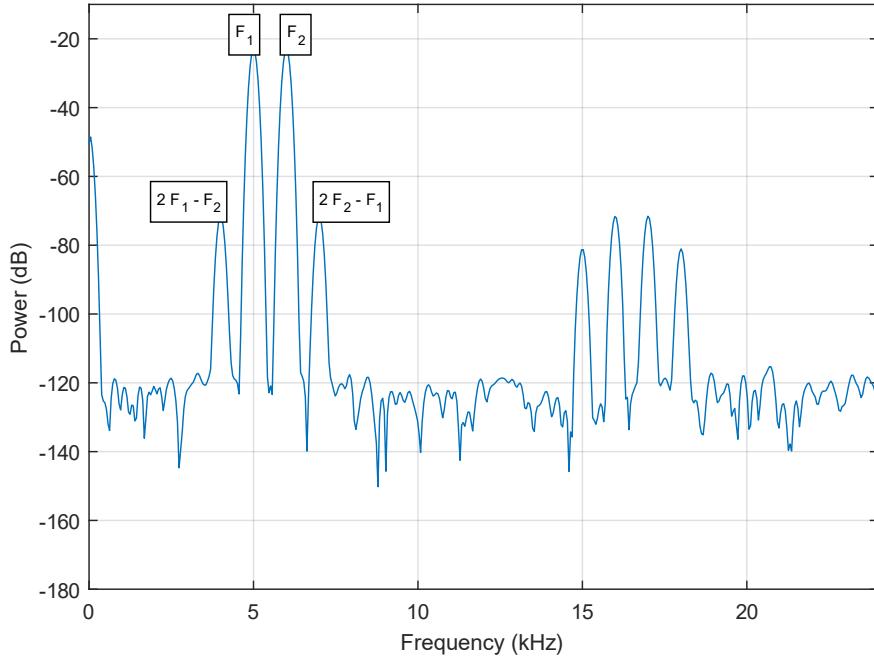


Figure 4.6: Intermodulation Distortion

To combat this some radars are equipped with AGC, to protect the receiver from signal saturation. The AGC reduces radar sensitivity but as mentioned in section 4.4 causes other problems to arise.

Chapter 5

Doppler Radar

5.1. System Design

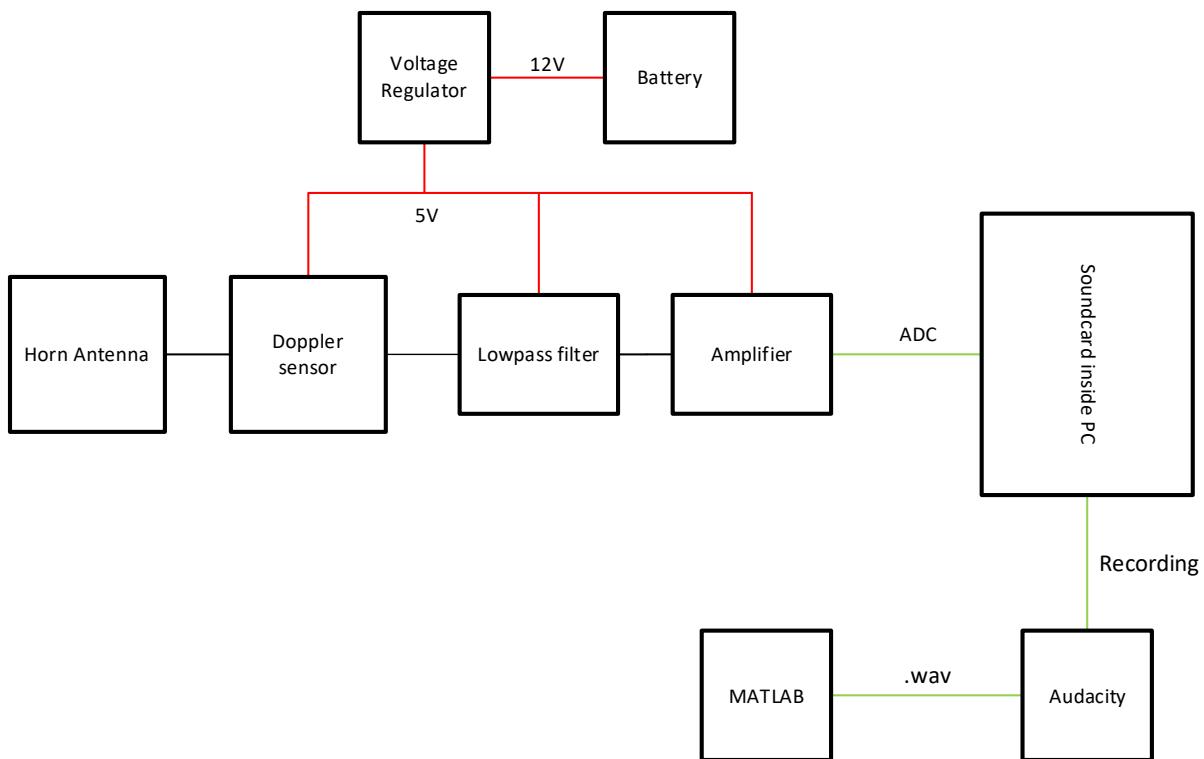


Figure 5.1: System Diagram of Project

5.1.1. Doppler Sensor

The HB100 sensor will be used for sensing the Doppler frequency. The sensor operates at 10.525 GHz and is designed for velocity measuring. The sensor includes an oscillator, mixer, transmit and receive antenna. The sensor can be operated in CW or FMCW mode. The radiation pattern of HB100 is illustrated in Figure E.1. The sensor requires a lowpass filter and amplifier before it can be sampled for analysis, this is discussed in Section 5.1.3. Another option was to build a sensor from individual components, but this is not within the scope of the project, due to its complexity.

5.1.2. Antenna

The patch antenna on the HB100 sensor is shown in Figure E.3. A horn antenna will be used to focus the radiation and increase the gain. The increase in antenna gain will increase the range of the CW Doppler radar. The horn antenna was designed in CST and is illustrated in figure E.4 and E.5.

5.1.3. Lowpass Filter and Amplifier

The lowpass filter will be a second-order RC circuit, due to its simplicity. Active filters were considered but did not provide any advantage over a passive filter. The amplification of the sensor output proved to be a bit more tedious. Due to little information available on the HB100 sensor and the uncertainty of the output voltage. The only information about output levels, were that it is in the range of a few mV [16]. The amplification will be done with Operation Amplifier(op-amp), another form of amplification is AGC. AGC is when the different frequency components will be amplified and attenuated depending on their amplitude, with the goal to have all the components at the same amplitude. This will deter components that might over saturate a radar but will add complexity when determining what signal is closest to the radar. AGC was considered but the required hardware was not available. The amplification will be tested and adapted as needed to sufficiently amplify the signal. To protect the soundcard of the laptop which has ADC voltage limits of 1 V_{rms} , the output signal needs to be clipped through a diode clipper circuit at 1 V.

5.1.4. Voltage Regulator

The choice of power supply is a linear voltage regulator. Another considered option was a switched-mode power supply. Switched mode power supply has a couple of advantages over linear voltage regulators, but it produces significantly more noise compared to linear voltage regulators. The noise might affect the HB100 sensor and due to the advantages of switched mode not being utilized in my project, I decided to go with linear voltage regulators.

5.1.5. Soundcard

The soundcard inside a PC will be used to sample the Doppler sensor. The soundcard is capable of sampling at a range of frequencies from 8 kHz to 44 kHz. The Doppler frequency that I expect to sample will not exceed 3 kHz. The input limit is around 1 V_{rms} and thus the amplification is designed with this limitation taken into account.

5.1.6. Software

The sampled signal from the soundcard will be recorded in Audacity [17], which is open-source audio software. The recorded file will then be exported as a .wav file and further analyzed in MATLAB. In MATLAB the radar software algorithms will be coded to determine vehicle speed, noise levels and to track a vehicle. A GPS unit will be placed inside the car used for testing the system, which will help with calibrating the system and used for comparison in non-ideal conditions. The GPS unit is a Ublox, GNSS smart board [18], with an external antenna to improve accuracy illustrated in C.2. The NMEA data strings that will be recorded in the Ublox software, will be copied to a text file and the speed extracted in MATLAB.

5.2. Detailed Design

5.2.1. Filter

Due to the low Doppler frequency expected to be measured from the HB100 sensor, a second-order RC filter will result in good attenuation at higher frequencies. The cut-off frequency is calculated by equation 5.1. The Doppler frequency will not exceed 3 kHz. The second-order RC filter has a gain of 0.707^n , where n equals the number of stages. The gain will therefore be 0.5 and thus this should be considered when designing the amplifier. The values of the resistors and capacitors are chosen to be equal, $R_1=R_2$ and $C_1=C_2$. The capacitor value is chosen to be 10 nF and the resistors value 1 k Ω , due to availability of components. The -3 dB cut-off frequency is calculated to be 15 kHz.

$$f_c = \frac{1}{2\pi\sqrt{R_1C_1R_2C_2}} \quad (5.1)$$

As the filter stage and therefore the roll-off slope increases, the low pass filters -3 dB corner frequency point and its pass band frequency changes from its original calculated value above by an amount determined by the following equation

$$f_{-3dB} = f_c\sqrt{2^{\frac{1}{n}} - 1} \quad (5.2)$$

The newly calculated cut-off frequency is $f_c = 10.243$ kHz. The new cut-off frequency still satisfy the 3 kHz requirement. The filter circuit is illustrated in figure 5.2.

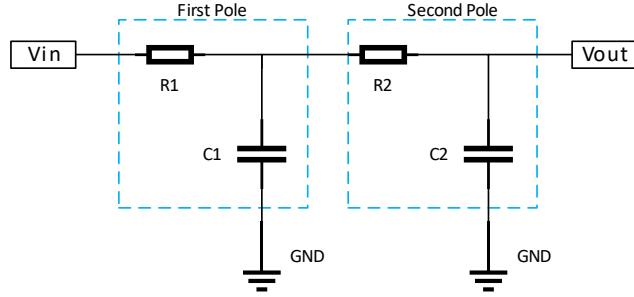


Figure 5.2: Filter Circuit

5.2.2. Amplifier

The amplification of the output from the Doppler sensor, needs to be both variable and stay within 1 V_{rms} swing. The best method of amplification is to make use of a differential amplifier. The differential op-amp gain equation is shown below

$$V_{\text{OUT}} = \frac{R_3}{R_2} \times (V_b - V_a) \quad (5.3)$$

The amplifier is illustrated in figure 5.3, resistor R3 will be a rheostat and R2's size is $1 \text{ k}\Omega$. Thus a variable resistor that ranges up to around $470 \text{ k}\Omega$ is used to allow for a gain of up to 470. Extracted from the datasheet of the op-amp, MCP602 [19], the gain versus frequency plot is illustrated in figure C.1. The gain settles at 60 dB, which equals a gain of 1000, then starts to fall off at 1 MHz. The expected frequency should range from 1 to 3000 Hz, so the gain specifications can be met with one op-amp.

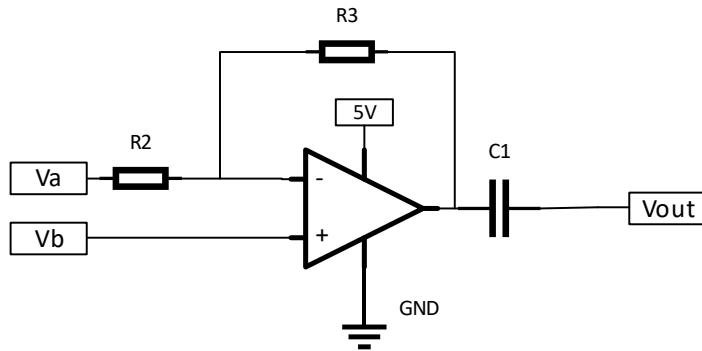


Figure 5.3: Amplifier Circuit

The voltage labels V_a and V_b , will both be centred around 2.5 V to give optimal swing on the output of the op-amp. The output will also swing around 2.5 V. The common mode input limits of the MCP602 op-amp ranges from $V_{ss}-0.3$ to $V_{DD}-1.2$, with $V_{ss}=0$ and $V_{DD}=5$, the limits ranges from -0.3 to 3.8 . Therefore 2.5 V safely lies between the common mode voltage limits. The circuit required to produce voltage V_a is illustrated in 5.4, a decoupling capacitor is placed between the output voltage from the filter and

the 2.5 V DC voltage that the AC will swing around. The voltage node between the two resistors is calculated by the equation below

$$V_{ref} = 5 \times \frac{R1}{2 \times R1} = \frac{5}{2} \quad (5.4)$$

the value of $R1$ does not matter as long as the resistors are equal in size. The values are thus chosen to limit current and are $100\text{ k}\Omega$. A voltage follower is added between V_{ref} and V_b reference to stabilize the 2.5 V as the output swings, illustrated in figure 5.5. Voltages V_a and V_b are attached to the same labels in the circuit illustrated in figure 5.3.

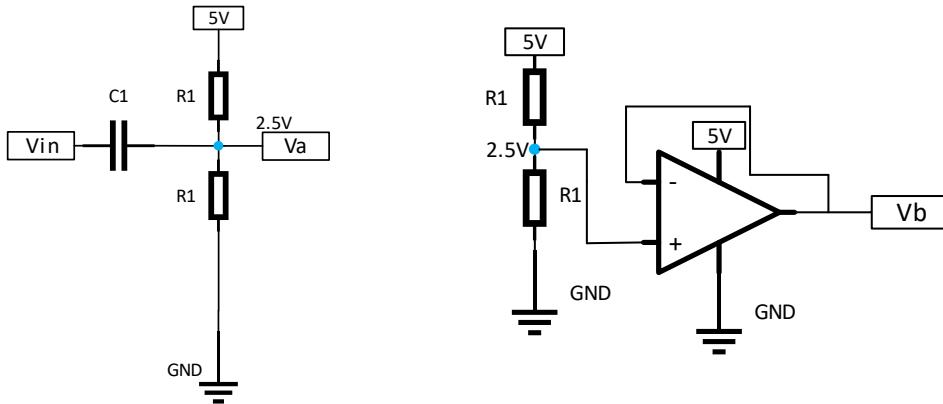


Figure 5.4: Voltage Swing Circuit

Figure 5.5: Voltage Reference Circuit

5.2.3. Voltage Regulator

The regulator circuit for generating 5 V is illustrated in figure 5.6. Capacitor C_1 is placed to help with input stability and C_2 is placed to help with the transient response. It is important to use a low noise voltage regulator to limit noise in the circuit, therefore a LM7805 regulator is used [20]. The input voltage will be 9 V coming from an alkaline battery [21]. The expected output current will not exceed 200 mA. The power dissipated by the voltage regulator is 1 W and therefore there is no need for a heat sink or to do thermal calculations.

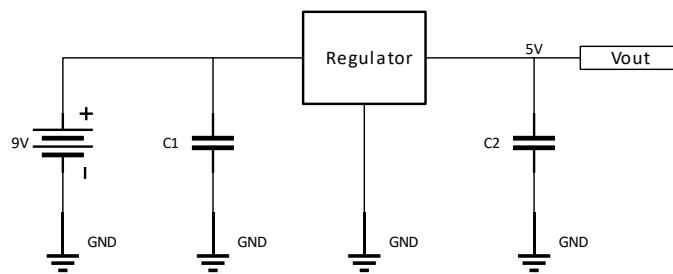


Figure 5.6: Voltage Regulator Circuit

5.2.4. Clipper

The clipper circuit is designed to limit the voltage swings at $\pm 1V$. This is achieved with a diode clipper circuit illustrated in figure 5.7. Two diodes are both placed with different polarity facing V_{in} , this will clip the voltage level at the forward voltage drop of the diodes. After testing different diodes the forward voltages were around 0.56 V. To satisfy the $1V_{rms}$ four diodes are needed in the circuit with two of them having the same polarity. This limits the voltage swings at $\pm 1.12V$ resulting in an RMS value of $0.79V_{rms}$. A decoupling capacitor is placed between the output of the clipper circuit and the ADC sampling point to further block any DC voltage.

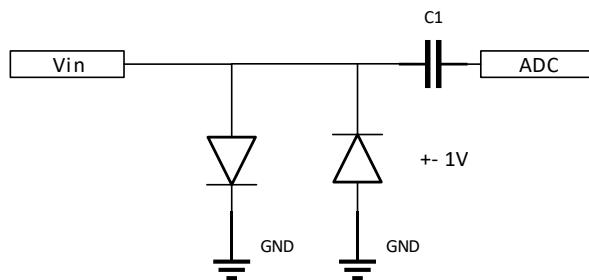


Figure 5.7: Diode Clipper Circuit

5.2.5. Antenna

To increase the range of the radar, a horn antenna is used to increase the gain G of the antenna. Noting equation 3.11, the range will increase relative to the gain increase of the order $G^{1/4}$. Together with the increased gain the horn antenna aims to focus the radiation pattern of the radar to a narrower beam.

The first part of a horn antenna is a waveguide. The waveguide act as a feed for the signal propagating from the patch antenna into the horn [22]. Figure 5.8 illustrates the shape of a rectangular waveguide. The main modes of propagation in the waveguide is either Transverse Electric Mode(TE mode) or Transverse Magnetic Mode(TM mode). There are infinite TE_{mn} modes, with $m \neq n$.

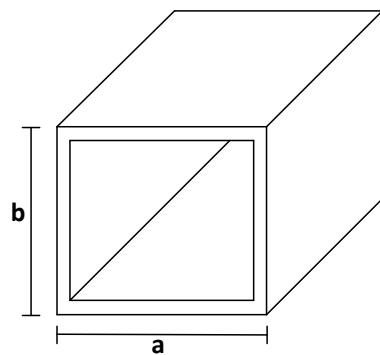


Figure 5.8: Rectangular Waveguide

The width a and height b parameters is used for designing the cut off frequency of the TE_{mn} mode in the waveguide. The equation for calculating the cut off frequency is shown below,

$$f_{cmn} = \frac{c}{2\pi} \sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2} \quad (5.5)$$

Considering TE_{10} mode as the dominate mode and $a \geq b$, the equation is simplified to

$$f_{c10} = \frac{c}{2a} \quad (5.6)$$

The micro strip lines, on the HB100 feeding the patch antenna, also transmits EM waves and this causes the waveguide not to work if they are inside the rectangular waveguide. The lines also cause surface waves, illustrated in figure C.5, that affects the waveguide. The waveguide is therefore designed not to include the micro strip lines and where the waveguide is to be right above the micro strip line a cut out is made so that the surface waves does not affect it. The designed waveguide is shown in figure E.6 with a cut off frequency of 7.5 GHz.

Figure 5.9 illustrates the geometry of a horn antenna. W is the width of a rectangular aperture, and a is the radius of a circular aperture. The distance from the junction of the projected sides to the aperture is the slant radius R .

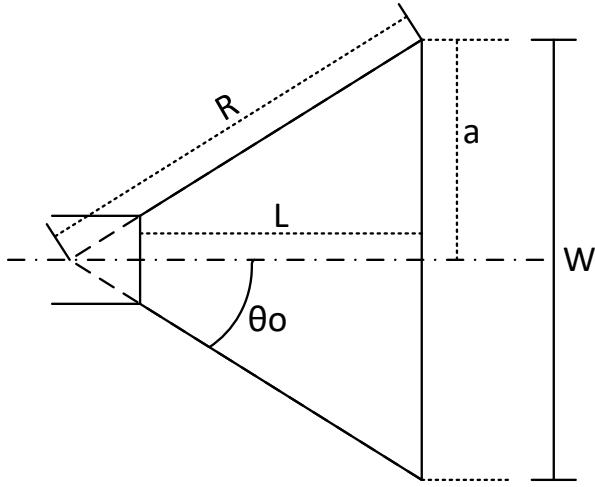


Figure 5.9: Horn Geometry

The dimensionless constant S [23] is represented by

$$S = \frac{W^2}{8\lambda R} = \frac{a^2}{2\lambda R} \quad (5.7)$$

Figure C.3 relates the relative field strength to the length of the horn antenna. The relative field strength graph is used to design the the size of the sidelobes of the radiation pattern. Different models were designed in CST with taking into account what the manufacturing capabilities available. The final model is illustrated in figure E.1, with the radiation pattern is illustrated in figure E.2.

5.2.6. Software

The common signal processing technique used in radars is to determine the strongest frequency component in a short period, through an STFT [24]. This frequency component is then converted to speed. The speed calculation is designed to imitate that of real radar processing. The algorithm takes as inputs the recorded file, sampling rate, frame size, overlap and size. The algorithm is illustrated in algorithm 4.1. The output of the file will be an array with the speeds measured from the strongest frequency component of the signal in that short period.

The SNR level is calculated dynamically on each iteration of an STFT. This dynamically changes the level of the SNR, which leads to a better estimate of targets. This also improves the speed algorithms capability when the radar is placed in different measurement locations. This is also the standard calibration, to determine the SNR of the location, when a permanent radar is installed in the field. The SNR algorithm is illustrated in algorithm 4.2.

Algorithm 4.3 is the tracking of a vehicle algorithm. This entails establishing a vehicle and tracking its speed for as long as it is in range of the radar. The algorithm will assume only one vehicle will be in the range of the radar or in other words only try to track one vehicle. The STFT time period is used to determine the assumed maximum change in speed a vehicle can exercise. This speed variation is then used to set up bin ranges in the frequency domain. When the following STFT is calculated and a target is identified within these limits the new target frequency is used to update the bin ranges. This process repeats until the target falls outside of the range of the bins, meaning the target is out of range or possibly not the same vehicle. The measurable change in the speed of a vehicle is directly proportional to how long the period is used to calculate the STFT. The equation below relates the measured frequency to speed,

$$\text{Speed} = \frac{\text{Frequency}}{19.49} \quad (5.8)$$

Assume the fastest change in speed of a vehicle in a second is 9 km/h. The speed change per second should be scaled as the size of the DFT changes, the relationship between DFT and time is shown below,

$$(1 - \text{overlap}) \times \frac{\text{length}}{F_s} \times 9 = \frac{\text{Frequency}}{19.49} \quad (5.9)$$

Equation 5.10 relating the measured frequency to the index of the DFT.

$$\text{Frequency} = \frac{k \times F_s}{DFT_{length}} \quad (5.10)$$

Substituting equation 5.10 into equation 5.9 and simplifying it, relates the DFT index to speed change. The bin range k for speed change is shown below,

$$k = \left(\frac{\text{length}}{F_s}\right)^2 \times 175.41 \quad (5.11)$$

Chapter 6

Results

6.1. Radar and Setup



Figure 6.1: Side View of Radar



Figure 6.2: Back View of Radar

Illustrated above is the structure and hardware of the radar. The radar is built around a wooden structure that imitates that of a real radar speed trap. The radar will be placed next to a road located at 3 m from the center. The radar will be pointed at the oncoming motors. The motor used for testing will be a Nissan X-trail, that will be put on cruise control. Inside the car the GPS unit will be placed that will also log the NMEA data of the vehicle for speed comparison. The setup is illustrated in figure 6.3.

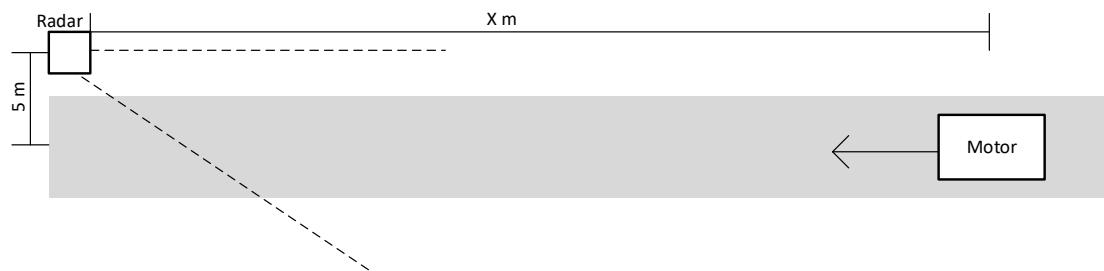


Figure 6.3: Radar Setup

6.2. Radar Results

The radar hardware designed in Chapter 5, was simulated in LTSpice and the radar software was simulated in Matlab. The circuits and results are illustrated in Appendix F.

To accurately test the radar in its entirety, the measured speed of the radar is compared with the GPS speed measured from the Ublox GPS module. The spectrogram, illustrated in figure 6.4, clearly indicates the measured vehicle in a yellow line. The recording is imported into Matlab where the vehicles speed is measured. The radar speed is compared to the GPS speed in figure 6.5. The radar is capable of accurately measuring the speed of a vehicle and is similar to that of the GPS. From this measurement the radars maximum range is calculated to be $R_{max} = 85.7m$.

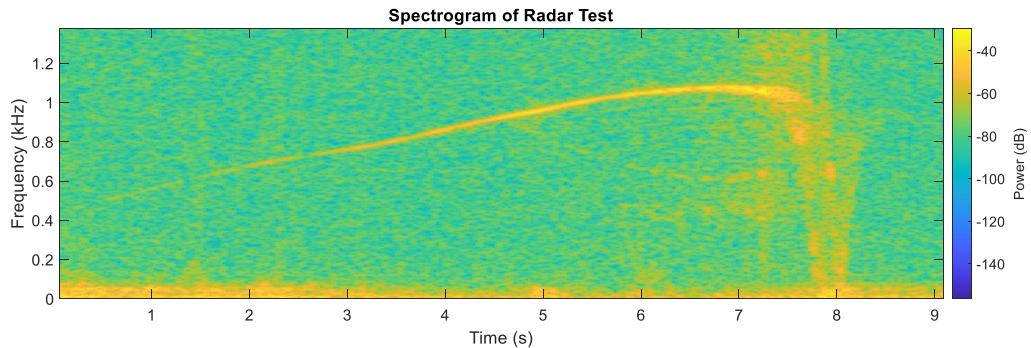


Figure 6.4: Measured Spectrogram of Vehicle

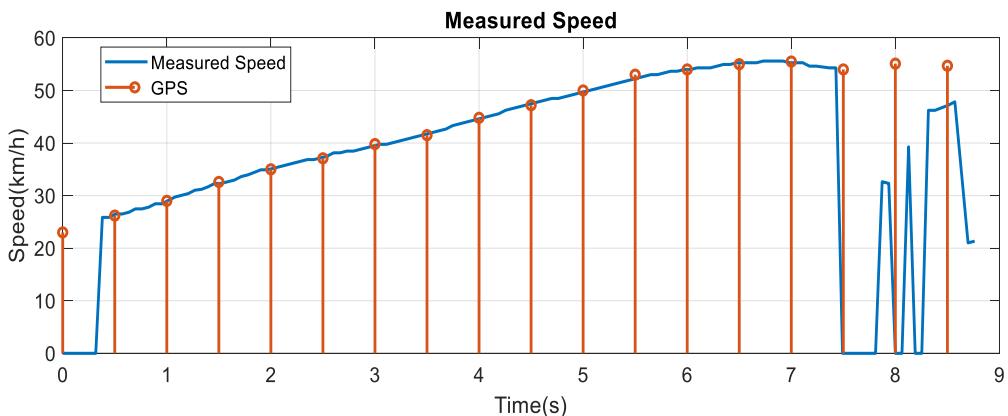


Figure 6.5: Speed Measured from Radar and GPS

6.3. Results of Limitations

6.3.1. Results of Cosine Effect

Section 4.1 explains the cosine effect. As concluded in that section, the measured speed will always be less than the real speed of a vehicle. In two cases where d is equal to 3 m and 6 m. The actual measured speed by the radar is shown in blue. By knowing the maximum distance from which a vehicle is visible to the radar. Software can be used to estimate and correct the cosine error. The corrected cosine error for both distances d are illustrated in the figure below. Note that when the vehicle is within 3 to 5 m of the radar, the speed of the vehicle is no longer measurable due to saturation. Consequently the cosine error gives false corrections. This phenomenon is discussed in section 6.3.6.

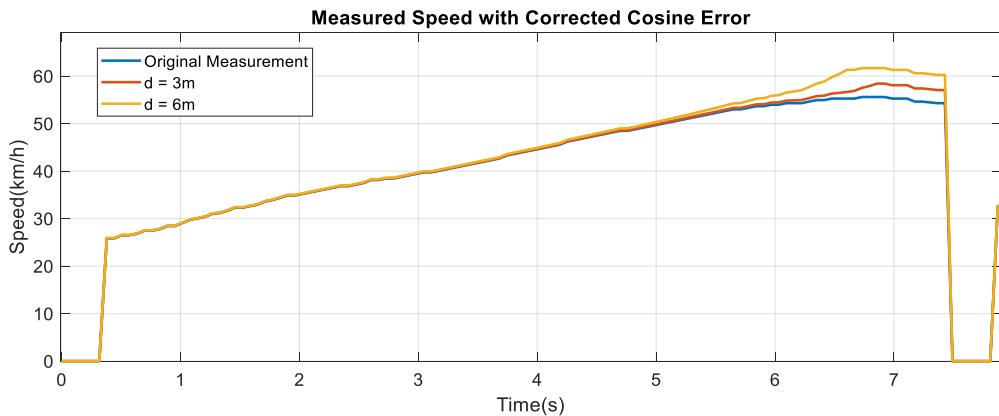


Figure 6.6: Cosine Error on Vehicle Speed

Despite that the cosine error is capable of being corrected. The operation and setup of a radar is very important. The radar is not capable of determining in what lane the vehicle will be travelling. This will mean that the radar cannot correct the cosine error on more than one lane at a time. The cosine error can only be corrected where the distance d will remain the same for all vehicles passing by the radar. Multiple lane application will result in erroneous measurements. When the vehicle is limited to traveling in one lane at a fixed distance d , the cosine error might be small enough for most of the distance it is measured, that no correction is needed. For the speed measurement illustrated in figure 6.6, the cosine error is only visible once the vehicle is within 10 to 20m of the radar.

6.3.2. Results of Accuracy and Acceleration Limits

The configuration of the DFT sample size is important for the accuracy of a radar as mentioned in Section 4.2. To illustrate this phenomenon Figure 6.7 is an indication of a correctly set up DFT. The measurement is of a vehicle accelerating past the radar. The

radar accurately calculates the acceleration of the vehicle without too many calculations. The accompanying spectrogram is shown in figure G.1.

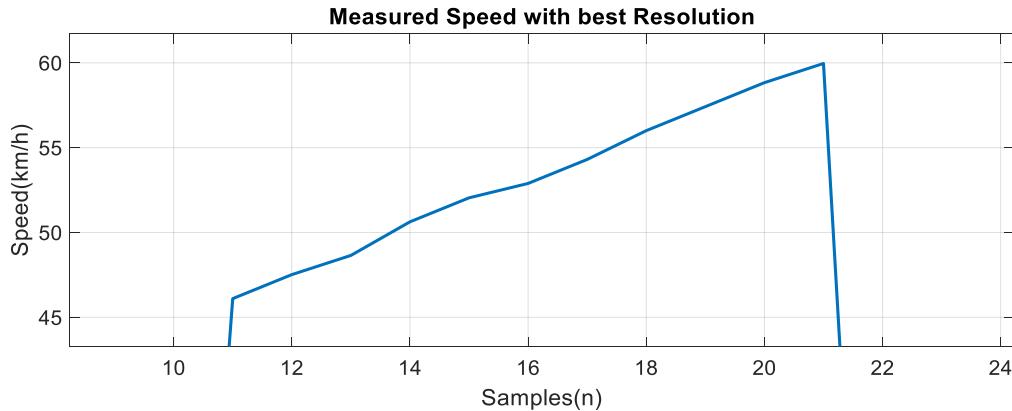


Figure 6.7: Measured Speed with best combination of Time and Frequency Differentiation

When the DFT sample size is set too big. The radar is incapable of calculating the change in speed. This is illustrated in figure 6.8. The measured speed is not an accurate estimate of the accelerating vehicle. The change in speed per sample is around 4 km/h which does not satisfy the required accuracy for a radar. The accompanying spectrogram, illustrated in figure G.2, clearly indicates how the radar is capable of differentiating between frequency components, but unable to differentiate in time.

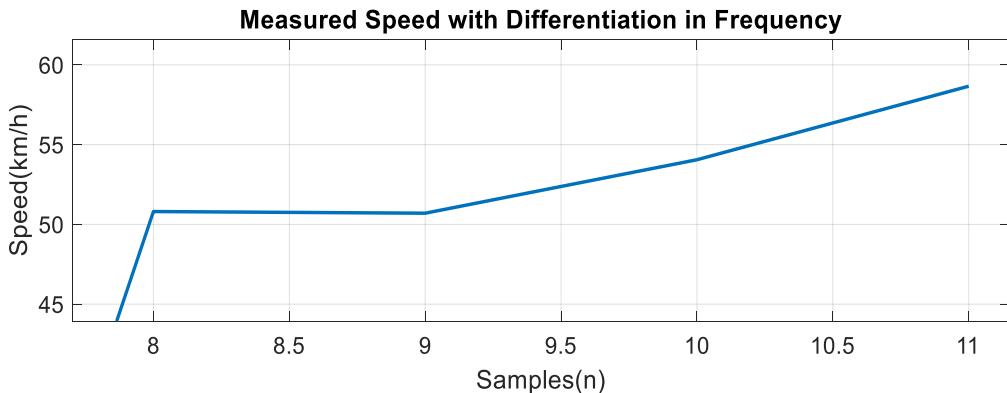


Figure 6.8: Measured Speed with Differentiation in Frequency

If the DFT sample size is too small. The radar is measuring the acceleration accurately but there are too many measurements. This will require powerful processing which is unnecessary. Some of the measurements recorded the same speed as the previous measurement. In comparison to figure 6.7, which requires 10 samples, figure 6.9 calculates 25 samples. The accompanying spectrogram is shown in figure G.3. The spectrogram is a clear indication of how the frequency differentiation is lost when time differentiation is prioritised.

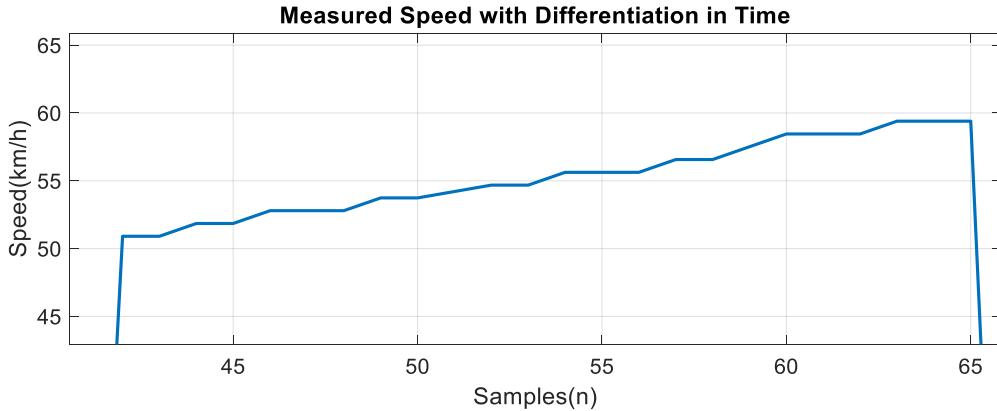


Figure 6.9: Measured Speed with Differentiation in Time

The table below concludes the differences between sampling sizes. As the sample size decreases the accuracy increases and vice versa.

Table 6.1: Comparison between Sample Sizes

	Best Resolution	Frequency Resolution	Time Resolution
Frame Size(s)	0.1224	0.0289	0.5442
Acceleration(km/h)	1.4	0.33	3.5

6.3.3. Results of Object Identification

To illustrate the effect of a vehicles RCS, the maximum measurable distance is compared to each other. The bigger the RCS the further the vehicle will be picked up by the radar. The spectrogram of the large vehicle is shown below and the maximum measurable distance is 60m. In comparison the spectrogram of the small vehicle is illustrated in figure 6.11, where the maximum measurable distance is merely 30m. This relates the large vehicles RCS to be double that of the small vehicles RCS.

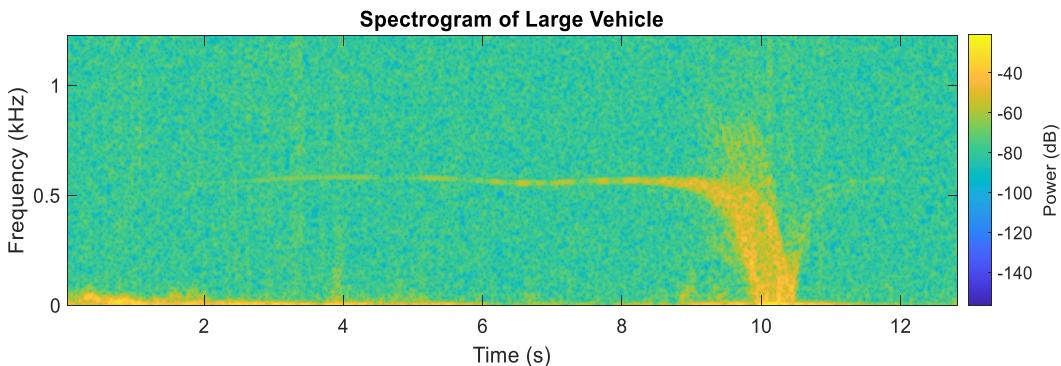


Figure 6.10: Spectrogram of Large Vehicle

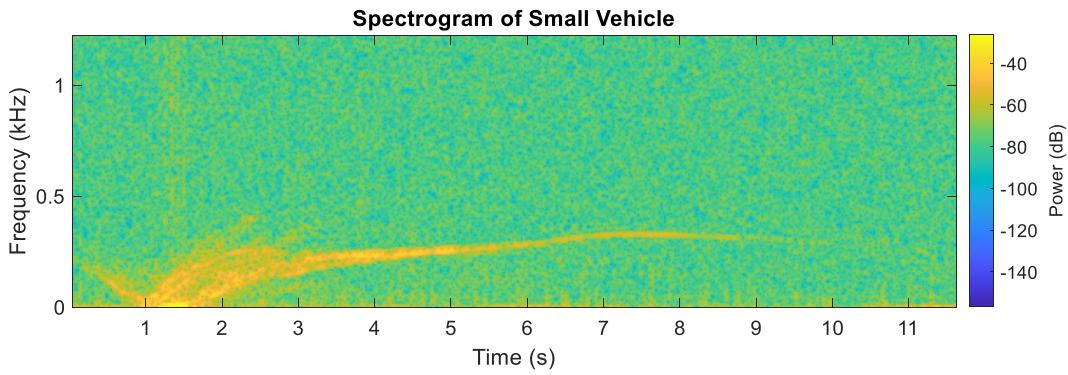


Figure 6.11: Spectrogram of Small Vehicle

To demonstrate the inability for the radar to differentiate between two vehicles. The Spectrogram illustrated in figure 6.12, shows two vehicles approaching from opposite directions. The radar is incapable of determining which direction the vehicles are travelling in and which signal is associated with which vehicle. The tracked speed of the vehicle is shown in figure 6.13, the radar is only capable of tracking one vehicle.

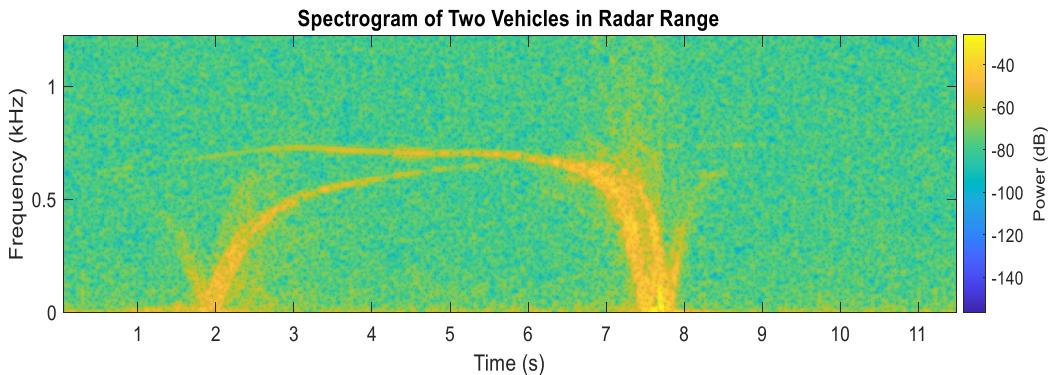


Figure 6.12: Spectrogram of Two vehicles in Radar Range

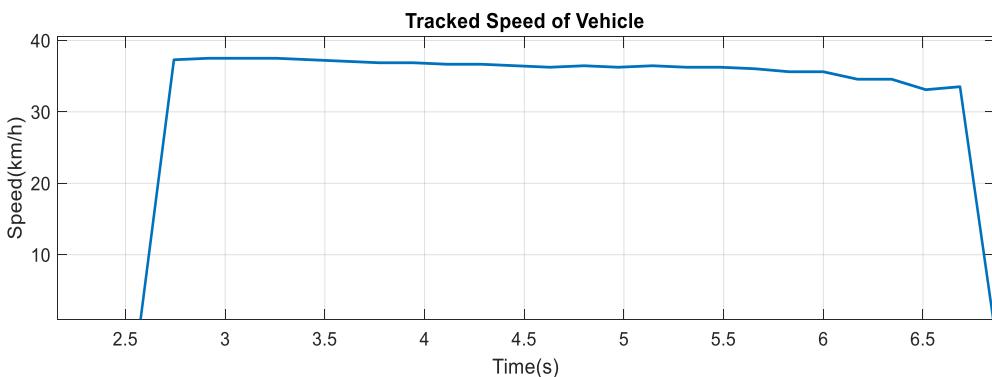


Figure 6.13: Tracked Speed of Vehicle

6.3.4. Results of Antenna Sidelobes

To demonstrate the effect of antenna sidelobes, the radar will be rotated from north to indicate the importance radiation and radar setup can have on the readings. Table 6.2

indicates the radars measurable range before and after adding the horn antenna. As the radar is rotated the HB100 Antenna still has good range while the Horn antenna which has a more directed radiation pattern loses most of its ability to measure a vehicle. Figure 6.14 illustrates how radiation patterns of the HB100 and horn antenna differs.

Table 6.2: Measurable Distance of Radar

Degrees West of North	HB100 Antenna	Horn Antenna
0°	62m	85.7m
30°	52m	32m
60°	30m	21m

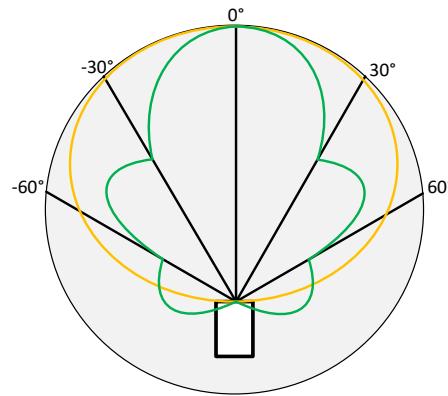


Figure 6.14: Comparison of Radiation Patterns between HB100 and Horn Antenna

6.3.5. Results of Multiple Path Reflection

A radar signal reflects entirely when it is incident on a metal surface. This results in multiple paths for the radar to measure a vehicle, when such a metal surface is nearby. To demonstrate this effect a metal surface was created by covering a piece of wood with foil. The self made "billboard" is illustrated in Figure C.4. The setup is illustrated below, the red lines indicates the radar is measuring the reflection from the "billboard". The blue line shows when the radar measures the vehicle and then the blue striped line is to indicate when the radar is incapable of measuring the vehicle.

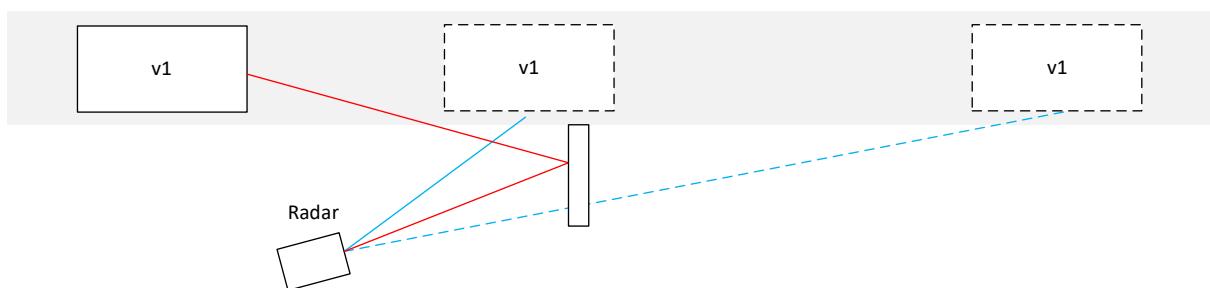


Figure 6.15: Multiple Path Reflection Setup

The measured spectrogram is illustrated in Figure 6.16. It indicates the vehicle is measured while it is still traveling behind the radar. The vehicle then passes by the radar, where saturation occurs and then the vehicle passes behind the "billboard", where the radar does not detect the vehicle. Once the vehicle is far enough away from the radar. The radar is then able to measure the vehicle again.

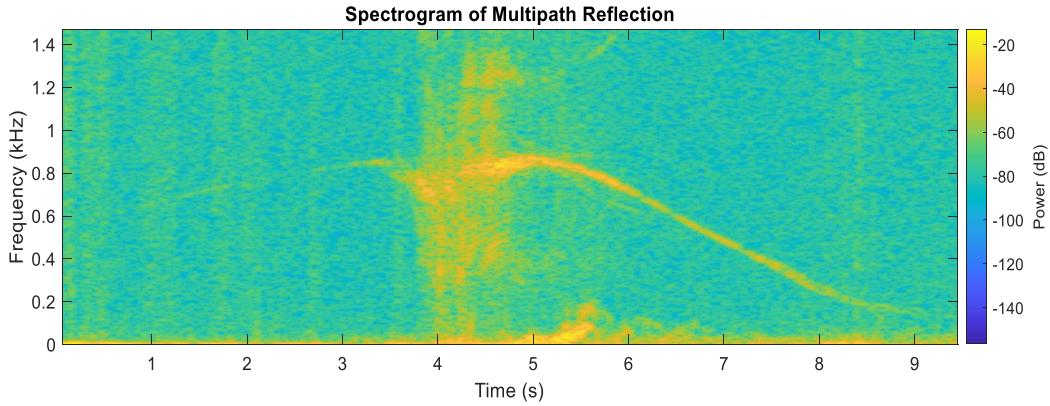


Figure 6.16: Spectrogram of Multiple Path Reflection

The radars tracking ability is shown in figure 6.17. It is clear that the radar is capable of tracking the vehicles reflection from the "billboard". It also indicates when the vehicle has passed the "billboard" and is tracked again.

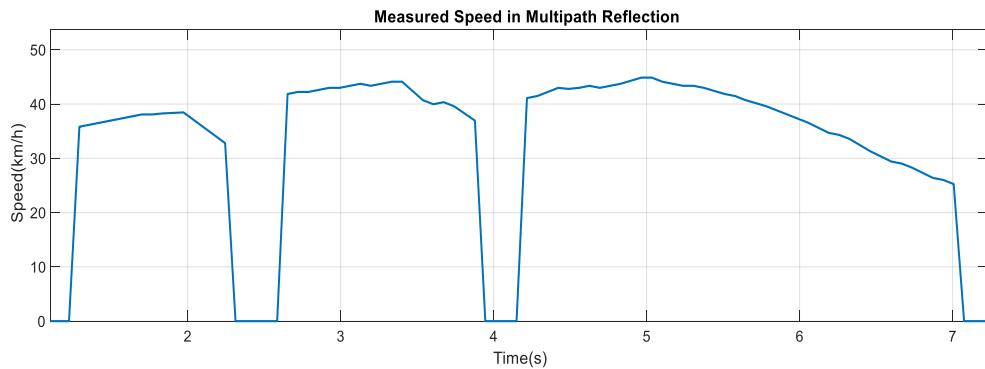


Figure 6.17: Tracked Speed of Multiple Path Reflection

6.3.6. Results of Radar Receiver Saturation

As discussed in Section 4.6, the radar is subject to saturation whenever a vehicle drives closely by the radar. This will cause a moment where the radar will be blind to any other moving vehicles in the range. Depending on how the radar is set up. If vehicles are coming from the opposite direction the radar is pointing in. This will cause the radar to unexpectedly lose its visibility. Figure 6.18 illustrates the spectrogram of two vehicles, one moving towards the radar from the direction it is pointing in and one vehicle moving in the opposite direction. The distortion causes the radar to lose track of the first vehicle for

a moment. The radar is then locked on to the second vehicle until the first vehicle passes by the radar and the phenomenon occurs again.

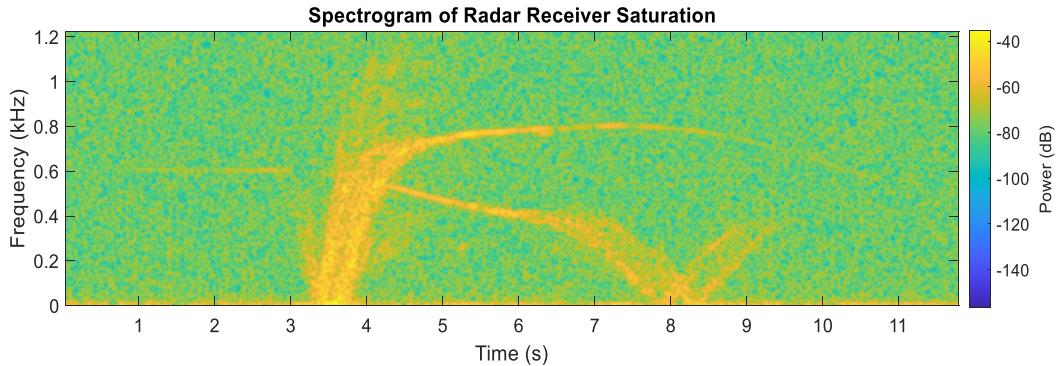


Figure 6.18: Spectrogram of Radar Receiver Saturation

The tracking software applied is shown in figure 6.19. The graph clearly illustrates when there is a vehicle passing by the radar and where the radar is and is not capable of tracking a vehicle.

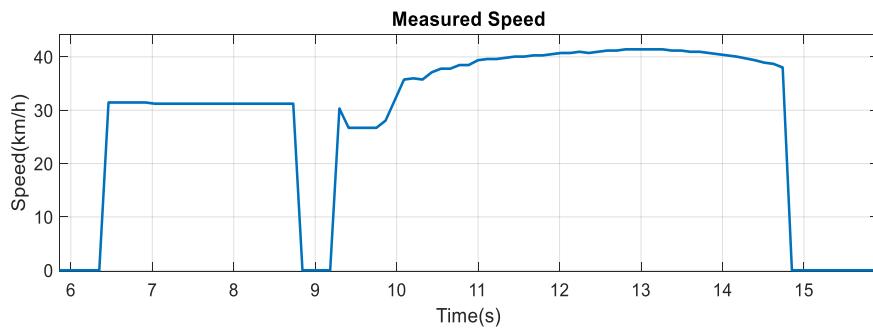


Figure 6.19: Speed tracking when Saturation occurs

An extreme case of receiver saturation is illustrated in figure 6.20. The second and third harmonics are clearly visible from the measurement and this is due to the saturation of the mixer.

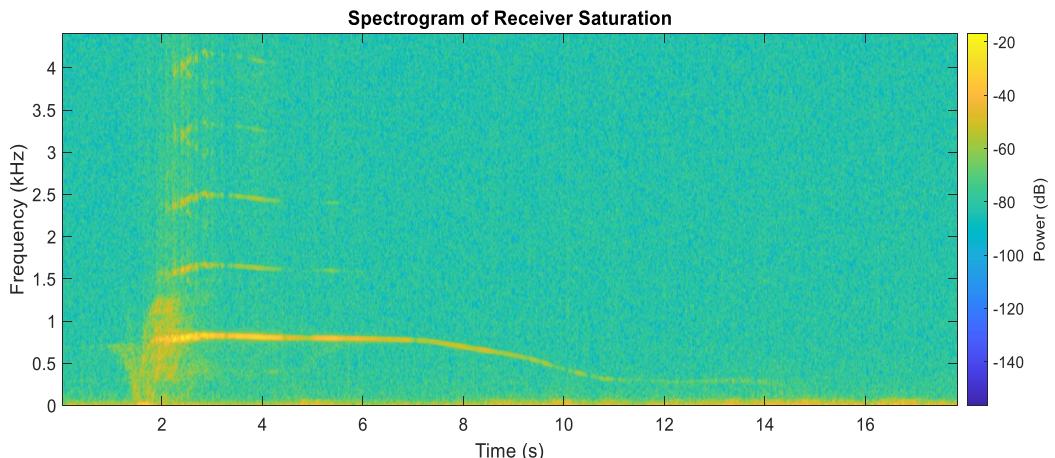


Figure 6.20: Extreme Receiver Saturation

Chapter 7

Conclusion

7.1. Objectives

Below are discussed to what degree each objective was achieved. The objectives are only represented through enumeration for further detail refer back to Section 1.3

1. After a thorough literature study, there were six limitations identified for a CW Doppler radar in vehicle speed measurements.
2. The CW Doppler radar is capable of measuring vehicles up to 85m, subjective to a vehicles RCS. The biggest car was a Nissan X-trail, if for instance a truck was used it would have been measured from further away.
3. The developed software is capable of accurately measuring a vehicles speed. It was compared to GPS speed data.
4. The developed software is capable of tracking a vehicle in the measurable range of the radar.
5. The radar is capable of clearly distinguishing between a vehicle and clutter.
6. All the limitations were tested and their results were illustrated in Section 6.2.

7.2. Operations

The only objective yet to be discussed is the one of how the limitations relate to the specified laws of operation for a CW Doppler Radar. To determine whether the laws are adequate in limiting the errors of the limitations, the laws first need to be related to the built radars specifications.

- No metal road signs or vertical flat surfaces larger than 1 meter in vertical height within 15° on either side of the aiming direction, within a distance of 30 m of the antenna.
- No signals received and processed from vehicles more than 70 meters away

- No other moving vehicle other than the measured vehicle within 84 metres from the radar in the direction of operation
- The vehicle's speed should be tracked for 0.5 s for a valid reading to be possible

Considering these laws, a clear picture is drawn under which circumstances the radar is acceptable and under which it ultimately fails to give accurate readings. The radar is only capable of measuring a vehicles in one lane and not possible on multiple lanes. The reason for this is due to cosine effect alongside receiver saturation, highlighted in subsections 6.3.1 and 6.3.6. The cosine error is not capable of being correcting when vehicles are capable of traveling at different distances d from the radar. When there are two opposite traveling roads, the receiver saturation my blind the radar unexpectedly.

The limitations of accuracy and acceleration is not specified in the operations. This is due to it being determined when building the radar and not when operating it. To counter this the radars should be subject to strict verification before it is installed or approved for use. As indicated in subsection 6.3.2, the vehicles acceleration is very dependent on the sample size.

The operator should be knowledgeable on the radars radiation pattern to correctly operate it. As shown in subsection 6.3.4, the radars measuring capabilities is greatly subjective to its positioning of the antenna. The radar might measure unintended vehicles or even miss vehicles completely if incorrectly installed.

A CW Doppler radar is capable of accurately measuring a vehicles speed. They are however subject to many limitations. These limitations are significant enough to warrant the use of other methods to enforce speed measurements.

7.3. Future Work

Possible future work can be a limitation study on a FMCW Doppler radar and its limitations to vehicle measurement and enforcement. The FMCW Doppler radar can then be compared to the limitations identified in this report. FMCW Doppler radars are very popular in vehicle measurement and it would be very significant to see how FMCW Doppler radars solve many of the issues related to CW Doppler radars.

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Appendix A

Project Planning Schedule

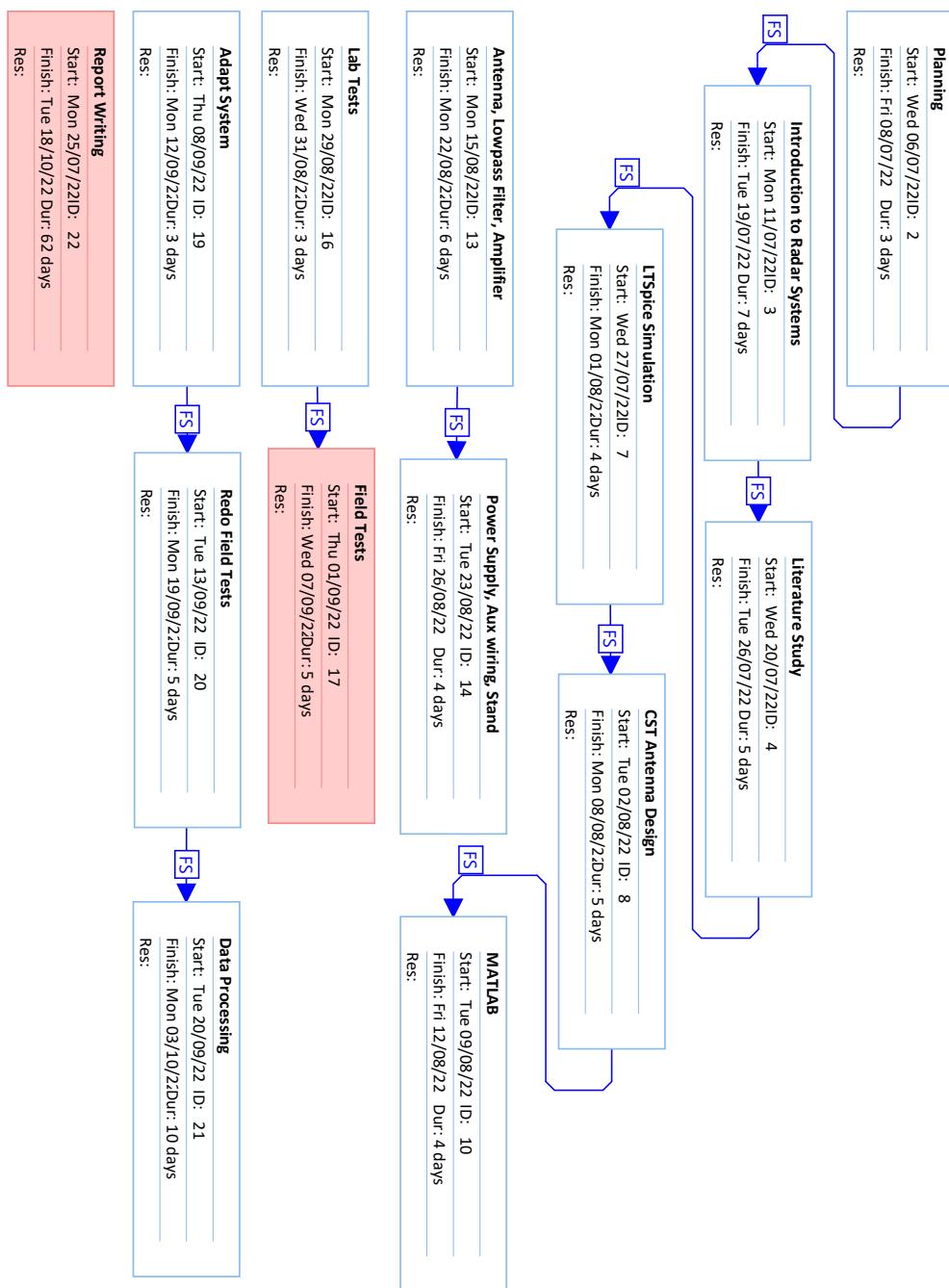


Figure A.1: Tracking Gantt Chart used for Project Planning

Appendix B

Outcomes Compliance

GA 1. Problem Solving: Identify, formulate, analyse and solve complex engineering problems creatively and innovatively.

The problem, "What are the limitations of a CW Doppler Radar", was under specified and required intensive literature study on radars. It contained three sub-problems, formulation of the limitations of a CW Doppler Radar, building a Radar and testing the radar and its limitations. The solution required information from a wide variety of sources and are complex and also required originality.

GA 2. Application of Scientific and Engineering knowledge: Apply knowledge of mathematics, natural sciences, engineering fundamentals and an engineering speciality to solve complex engineering problems.

The scientific and engineering knowledge that I required and acquired to solve the problem range from electromagnetics, signal processing, electronic design and applied mathematics. For electromagnetics I attained knowledge on wave propagation, waveguides and antenna theory. The signal processing is mainly applied to a radars processing techniques like speed extraction and vehicle tracking. Electronic design was used in designing the radar hardware and conditioning the signals accordingly. Then the applied mathematics relates to the combining of all of the above in a working radar and formulating the limitations.

GA 3. Engineering Design: Perform creative, procedural and non-procedural design and synthesis of components, systems, engineering works, products or processes.

I successfully applied engineering design to three domains. The first is to design a radar that consists of modules, electronic components and antennas. The second engineering design was to design software capable of performing the necessary task of a Doppler radar and to be able to illustrate the limitations. The last engineering design was in the form of tests, that would prove the radar is performing accurate and to test the theorized limitations.

GA 4. Investigations, experiments and data analysis: Demonstrate competence to design and conduct investigations and experiments.

My first steps in investigating the problem was to do a literature study on radars and specifically CW Doppler Radars. As I progressed with the project I also had to investigate radar software techniques and radar limitations. The experiments were exercised across multiple software and lab tools. For instance I tested my hardware in both LTSpice and with lab tools, like an oscilloscope and signal generator. Matlab was used to experiment with software techniques, where I simulated a radar signal to test my software. CST was used to test and experiment with antenna designs. Data analysis was done in Matlab, where I made use of a combination of generated graphs and spectrograms.

GA 5. Engineering methods, skills and tools, including Information Technology: Demonstrate competence to use appropriate engineering methods, skills and tools, including those based on information technology.

A combination of engineering tools, the like of LTSpice, Matlab and CST were used. LTSpice was used for electronic circuit design. Matlab was used for software design, testing and data analysis. CST was used in antenna design and experimentation. Furthermore Python was used for extracting GPS speed from NMEA data, which was acquired from a Ublox GPS module. Version controlled was done through GitHub and lastly the report was constructed in Latex.

GA 6. Professional and technical communication. Demonstrate competence to communicate effectively, both orally and in writing, with engineering audiences and the community at large.

The project includes a written report and an oral presentation. These demonstrate competence to communicate effectively, both orally and in writing.

GA 8. Individual work: Demonstrate competence to work effectively as an individual.

I took primary responsibility for successful completion of all aspects of the projects.

GA 9. Independent Learning Ability: Demonstrate competence to engage in independent learning through well-developed learning skills.

I completed a MIT Lincoln Laboratory, course on Radar Systems that formed a basis for my knowledge on radars. I then studied complementary work, consisting of articles, a honours thesis and two master thesis's. The bulk of the information I learned came from textbooks, namely Introduction to Radar Systems, by Merrill L. Skolnik and Modern Antenna Design by Thomas A. Milligan.

Appendix C

Figures

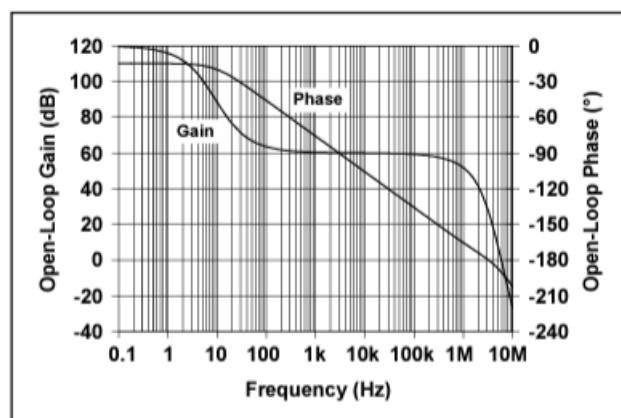


Figure C.1: Gain versus Frequency plot of MCP602 op-amp



Figure C.2: Ublox GPS Module and Antenna

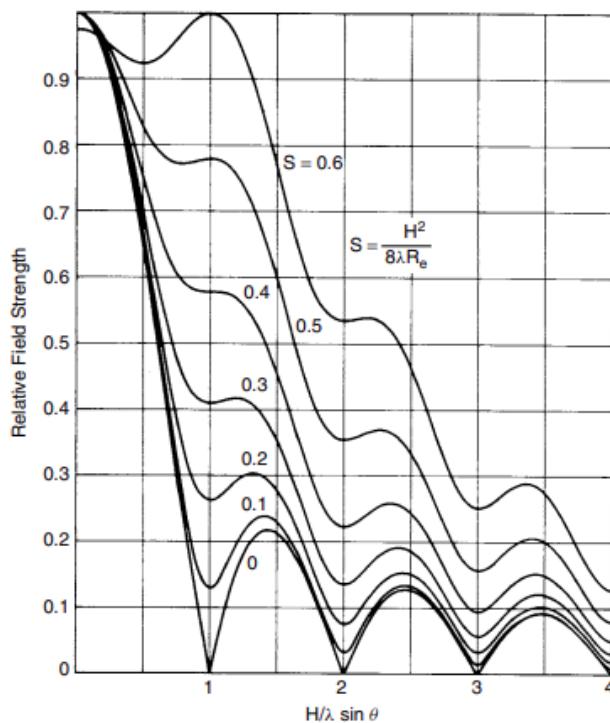


Figure C.3: Relative Field Strength Graph



Figure C.4: Homemade Billboard

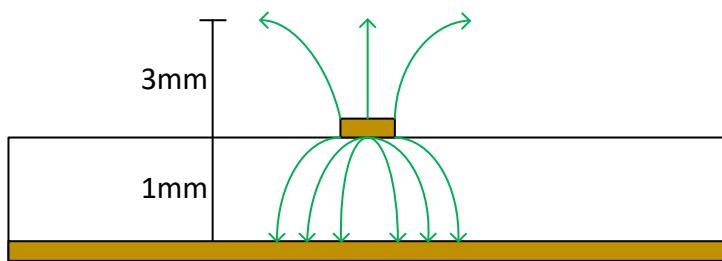


Figure C.5: Surface waves on micro strip copper line

Appendix D

Radar Software

Algorithm 4.1: Speed

input Recording, Sampling Rate, Frame Size, Signal-to-Noise Ratio
for $n = 0$ to $frames$ **do**
 Calculate FFT of sample
 Calculate maximum frequency component
 Store frequency component in array
for $n = 0$ to $frames$ **do**
 Convert frequency component to speed
 Plot speed versus time

Algorithm 4.2: Signal to Noise Ratio

input Recording, Sampling Rate, Frame Size
for $n = 0$ to $frames$ **do**
 Calculate FFT of Sample
for $i = 0$ to $SampleSize$ **do**
 Summation of Frequency Components
 Store SNR per frame
SNR = Summation of SNR per frame divided by total frames
output Signal-to-Noise Ratio

Algorithm 4.3: Tracking

input Recording, Sampling Rate, Frame Size, Frequency Bin Size, Speed Limit

for $n = 0$ to $frames$ **do**

- Calculate FFT of Sample
- for** $i = 0$ to $SampleSize$ **do**

 - Calculate Maximum Component
 - Calculate SNR
 - Convert Frequency to Speed
 - if** Speed > Speed Limit **then**

 - if** Maximum Component \geq SNR **then**
 - if** Frequency Difference \leq Bin Range **then**

 - Store Speed
 - Update bin range

Store Object Frequency

Plot Tracked Vehicle Speed vs Time

output Tracked Vehicle Speed

Algorithm 4.4: Spectrogram

input Signal, Sampling Rate, Frame Size, Filter Type, Overlap

Generate Spectrogram

output Spectrogram

Algorithm 4.5: Cosine Angle Correction

input Measured Speed, Maximum Measured Distance, d

for $n = 0$ to $frames$ **do**

- Calculate change in Distance
- if** $d \geq 5$ **then**

 - Calculate Cosine Angle
 - Calculate Corrected Speed

Plot Corrected Speed vs Time

output Corrected Speed

Appendix E

Antennas

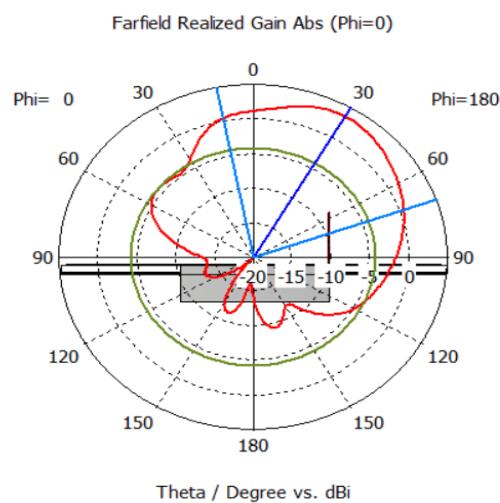


Figure E.1: HB100 Radiation Pattern in CST

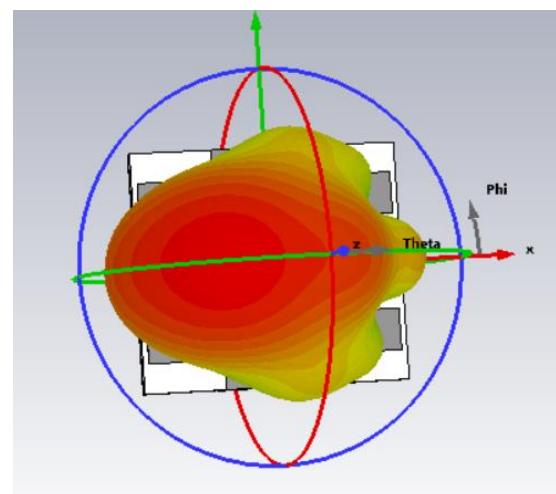


Figure E.2: HB100 3D Radiation Pattern in CST

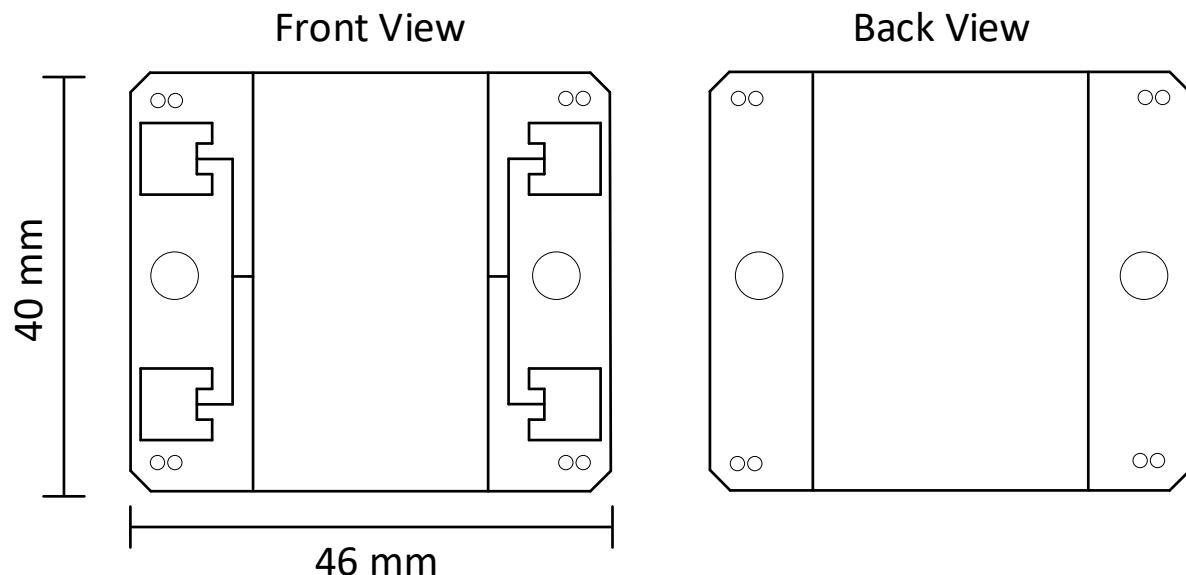


Figure E.3: Schematic Drawing of HB100 Sensor

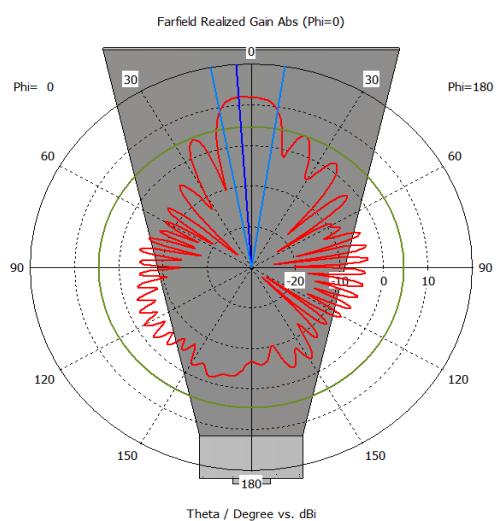


Figure E.4: Horn Antenna 1D Radiation Pattern

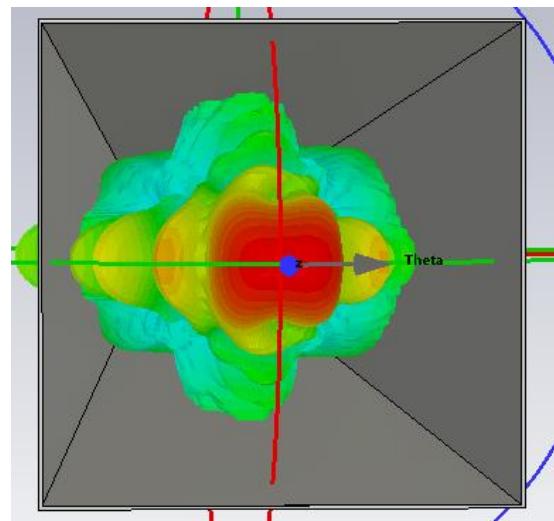


Figure E.5: Horn Antenna 3D Radiation Pattern

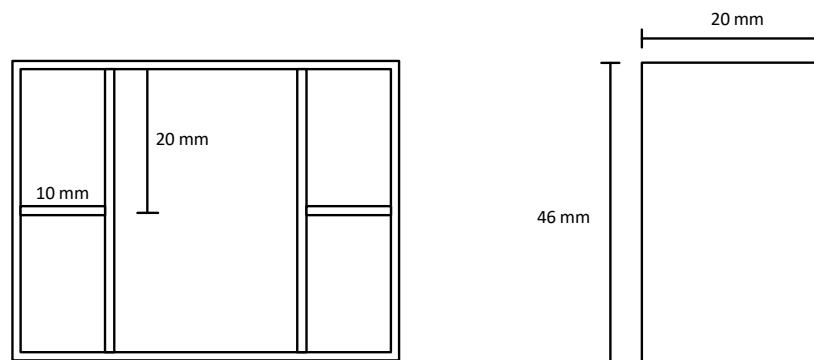


Figure E.6: Schematic Drawing of Waveguide

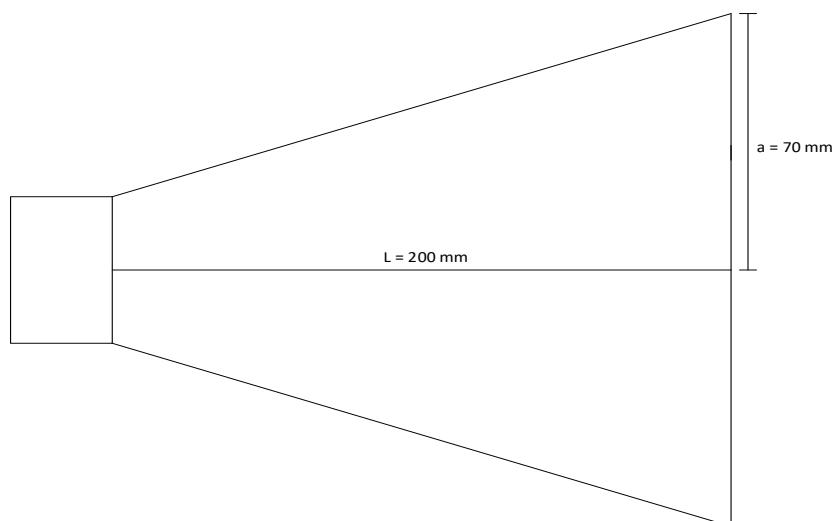


Figure E.7: Schematic Drawing of Horn Antenna

Appendix F

Radar Simulations

The appendix details the simulation of the radars hardware in LTSpice. Figure F.1, demonstrates the workings of the amplifier and lowpass filter. Figure F.2, demonstrates the frequency response of the filter. The whole circuit is illustrated in figure F.3.

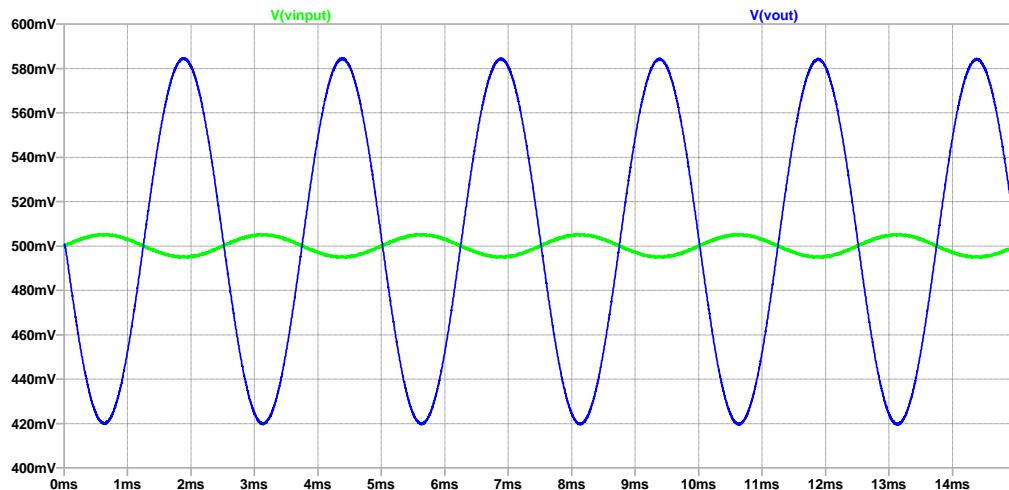


Figure F.1: Input and Amplified Output

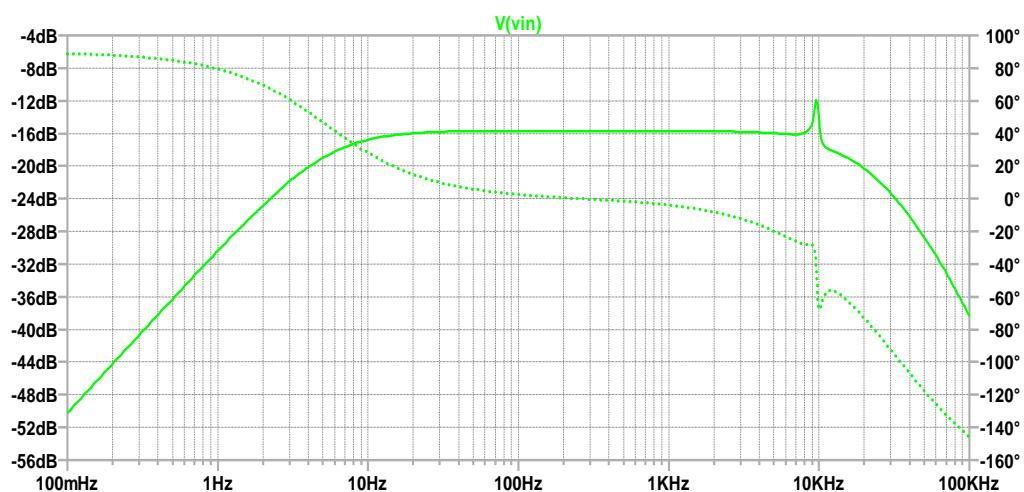


Figure F.2: Frequency Response of Lowpass Filter

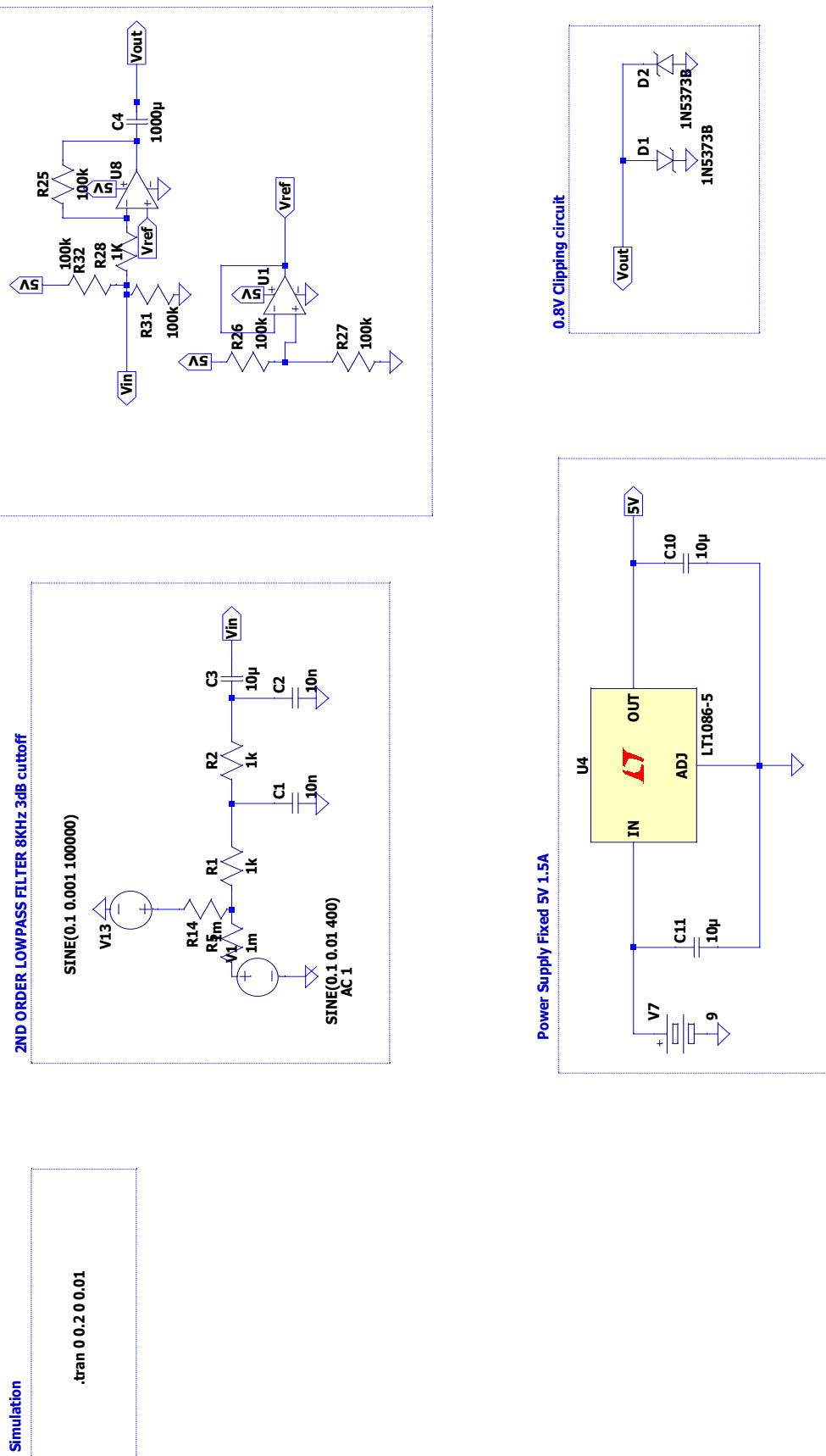


Figure F.3: LTSpice Simulation of Radar Hardware

The radar software was tested by simulating a sine wave in Matlab with a frequency of 1000 Hz, with added Gaussian noise. The signal is simulated to be sampled with a frequency of 44 100 Hz. The signal was imported into the radar software to test its capability to extract the speed. The spectrogram of the signal with the noise is shown in figure F.4 and the measured speed is shown in figure F.5.

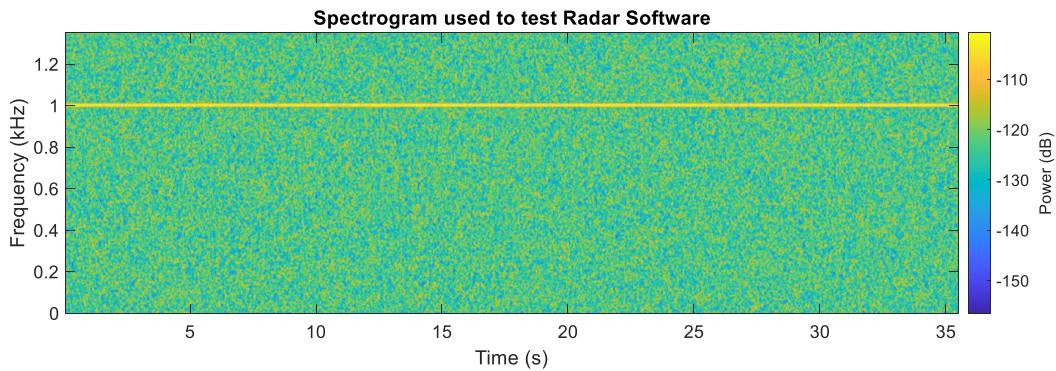


Figure F.4: Spectrogram of Simulated Signal

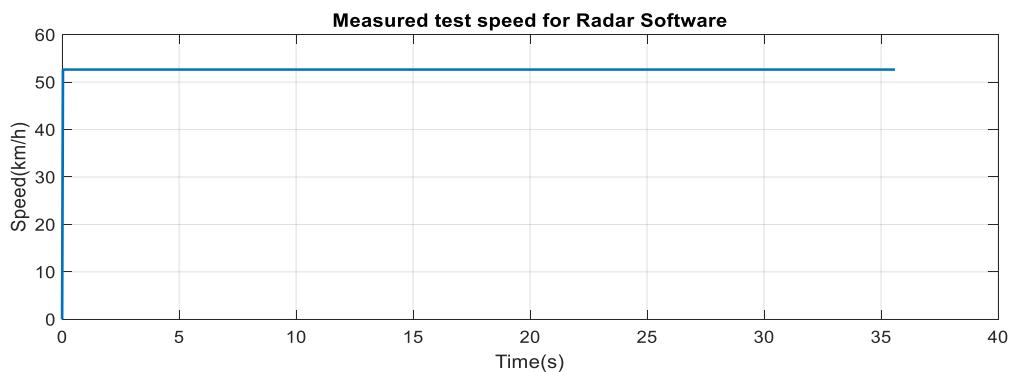


Figure F.5: Measured Speed from Simulated Signal

Appendix G

Spectrogram regarding Accuracy and Acceleration



Figure G.1: Spectrogram with best combination of Time and Frequency Resolution

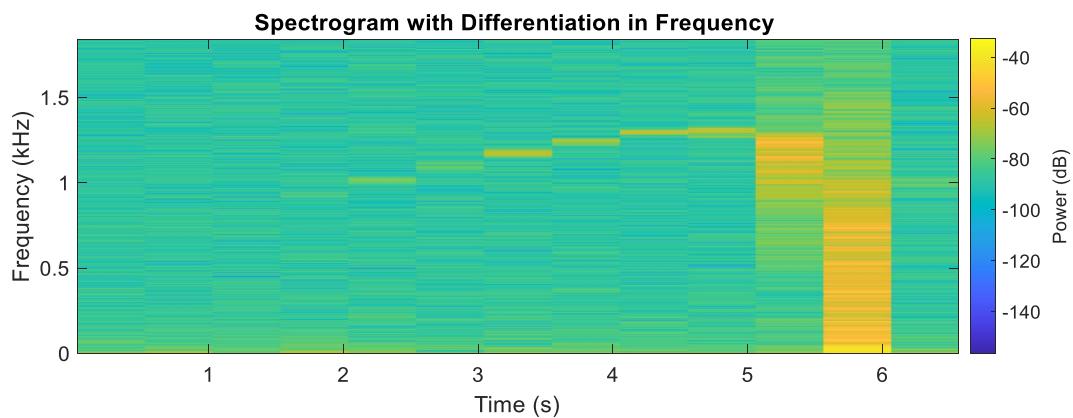


Figure G.2: Spectrogram with Differentiation in Frequency



Figure G.3: Spectrogram with Differentiation in Time

Appendix H

Spectrograms regarding Antenna Sidelobe

The spectrograms below are from measurements with the HB100 sensor before adding the horn antenna. Take note of the radiation pattern of the HB100 antenna, illustrated in figure E.1.

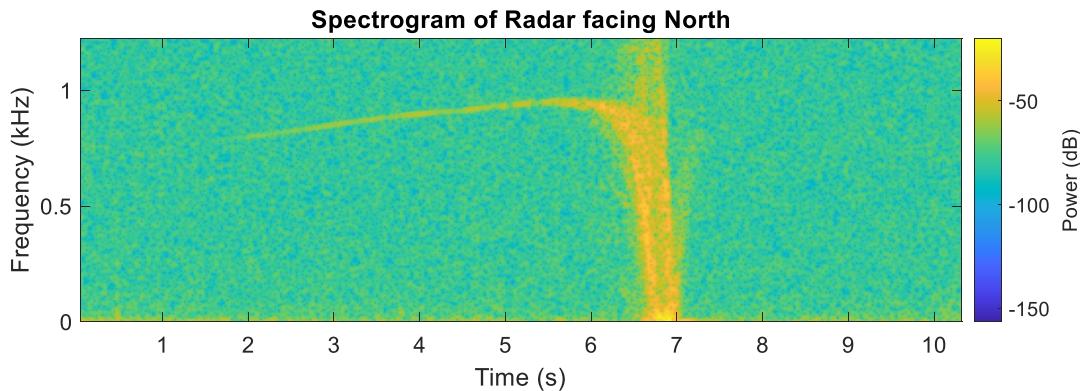


Figure H.1: Spectrogram of Radar facing North

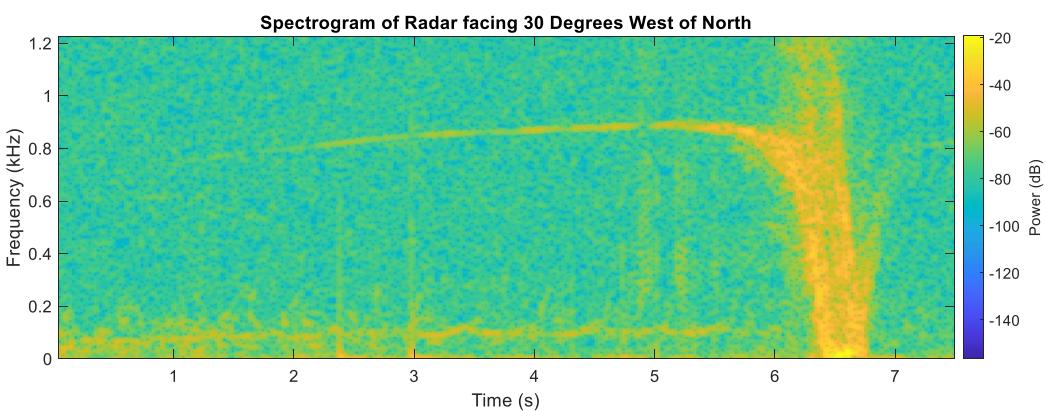


Figure H.2: Spectrogram of Radar facing 30 Degrees West of North

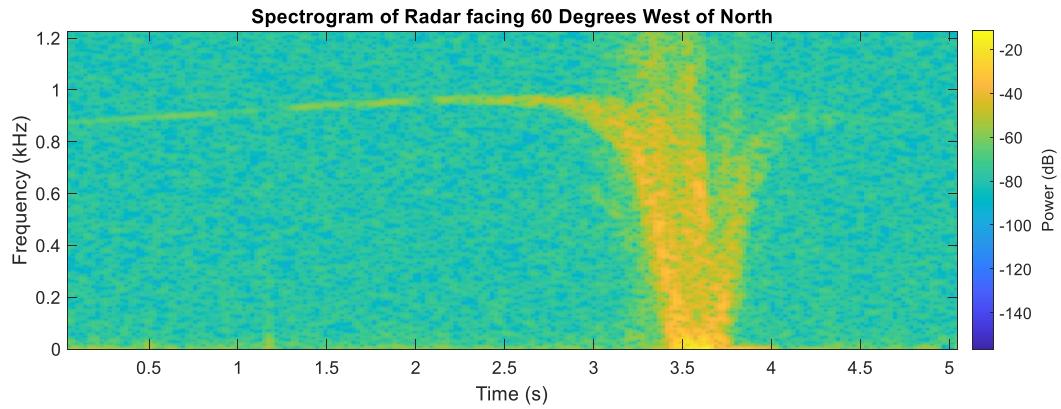


Figure H.3: Spectrogram of Radar facing 60 Degrees West of North

The next set of spectrograms were measured after the adding of the horn antenna. The radiation pattern of the horn antenna added to the radar, is illustrated in figure E.4.

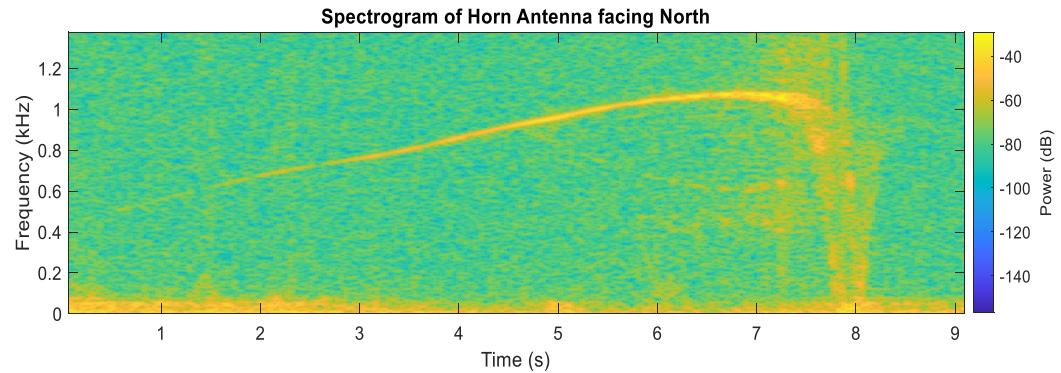


Figure H.4: Spectrogram of Radar facing 0 Degrees West of North

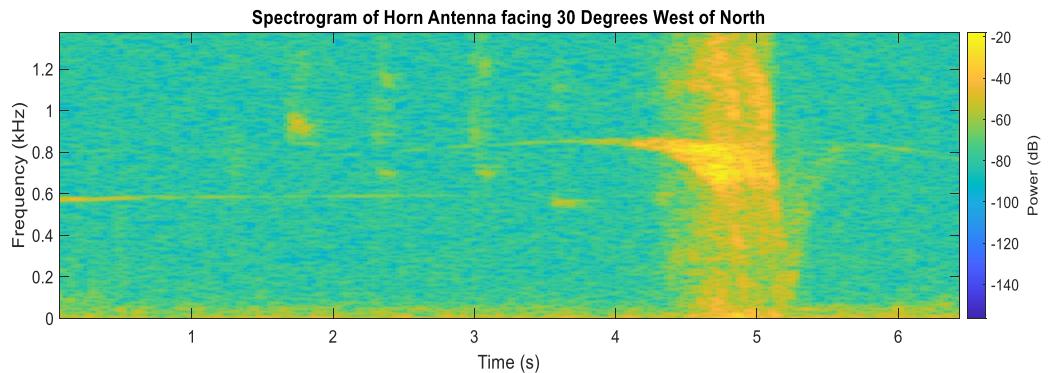


Figure H.5: Spectrogram of Radar facing 30 Degrees West of North

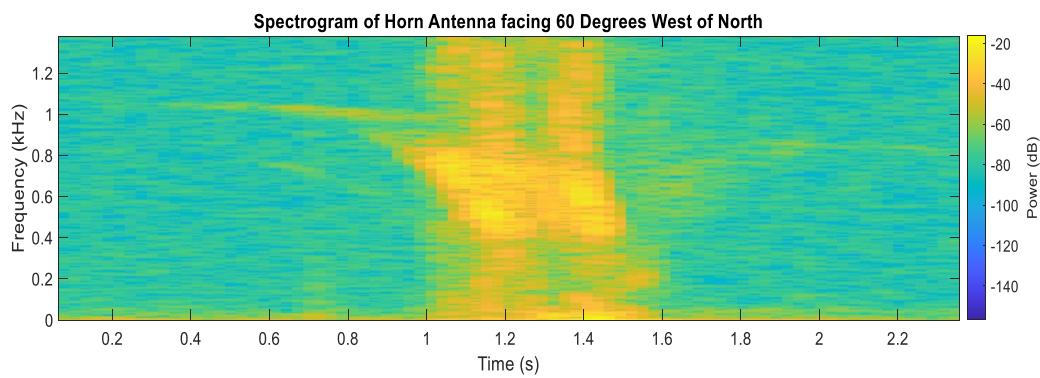


Figure H.6: Spectrogram of Radar facing 60 Degrees West of North

Appendix I

Matlab Code

```
1 % PARAMETERS FILE
2 % Length of STFT in samples
3 Length=300;
4 timeStep=Length/Fs;
5 overlap=0.3;
6 % Frames calculation
7 frames = round(size(y)/Length);
8 frames = frames(1)-1;
9 startFrame=1;
10 endFrame=frames;
11 % Create empty arrays to store frequency and sample array
12 tracked_speed1 = [0 0];
13 tracked_speed2 = [0 0];
14 sample_Array = zeros(Length,1);
15 % Create variables for speed calculation and Speed Limits
16 frequency=0;
17 speed=0;
18 speedLimit=35;
19 % Create bins
20 bins = ((timeStep)^2*(1-overlap))*175.41;
21 % Tracking Flag
22 tracked=0;
23 % Maximum measuring distance and distance from road
24 Rmax=60;
25 d=3;
26 R=Rmax;
27 % Cosine Angle Coeff
28 cosineAngle=0;

1 %SPEED CALCULATIONS FROM SAMPLED DOPPLER RADAR
2 %read data in from WAV file
3 %[y,Fs] = audioread('real_car_testE.wav');
4 y=C;
5 % Define parameters
```

```

6 %length of STFT in samples
7 Length=100;
8 time_step=Length/Fs;
9 %frames calculation
10 frames = round(size(y)/Length);
11 frames = frames(1);
12 %Create empty arrays to store frequency and sample array
13 speed = zeros(frames,1);
14 frequency=0;
15 sample_Array = zeros(Length,1);
16 %STFT calculation
17 for n=1:1:frames
18     max_FFT_index=0;
19     max_FFT=0;
20     for b = 1:1:Length
21         sample_Array(b)=y(b+Length*(n-1));
22     end
23     g=abs(fft(sample_Array));
24     for x = 1:1:Length/2
25         if max_FFT<g(x)
26             max_FFT=g(x);
27             max_FFT_index=x;
28         end
29     end
30     frequency = max_FFT_index*Fs/(Length);
31     speed_kmh = frequency/19.49;
32     speed(n)=speed_kmh;
33 end
34 %Shift array to start at 0
35 c = zeros(frames,1);
36 for n=1:1:size(speed)
37     c(n+1)=speed(n);
38 end
39 c(1)=0;
40 %Draw plot of speed
41 x_axis = 0:time_step:((1/Fs)*size(y));
42 plot(x_axis,c);
43 xlabel("Time(s)");
44 ylabel("Speed(km/h)");
45 title("Measured Speed from Doppler sensor");
46 grid on

```

```

1 %TRACKING OF A SINGLE VEHCILE
2 num=1;
3 %Tracking calculation
4 for n=startFrame:1:(endFrame/(1-overlap))

```

```

5      z=[0 0];
6      p=0;
7      s=[0 0];
8      s_index=[0 0];
9      num=1;
10     SNR_Average=0;
11     max_FFT_index=0;
12     max_FFT=0;
13     sample_Array = [0 0];
14     for b = 1:1:Length
15         sample_Array(b)=y(b+Length*(n-1)-(overlap*Length)*(n-1));
16     end
17     g=abs(fft(sample_Array));
18     if n==5
19     end
20     for x =(round(speedLimit*19.49*Length/Fs)):1:Length/2
21         if max_FFT<g(x)
22             max_FFT=g(x);
23             max_FFT_index=x;
24         end
25     end
26     %Dynamic SNR
27     for x = 1:1:Length
28         SNR_Average = SNR_Average + g(x);
29     end
30     SNR_Average = SNR_Average/Length;
31     for x = 1:1:Length
32         if g(x)>(SNR_Average)
33             s(num)=g(x);
34             s_index(num)=x;
35             num=num+1;
36         end
37     end
38     SNR_Average=0;
39     for x = 1:1:length(s)
40         SNR_Average = SNR_Average + s(x);
41     end
42     SNR_Average = SNR_Average/length(s);
43     SNR_Average = SNR_Average*2;
44     SNR=SNR_Average;
45     if n==5
46         SNR;
47     end
48     if max_FFT>SNR
49         if abs(frequency-max_FFT_index)≤round(bins)
50             speed=(frequency*Fs/Length)/19.49;
51             if speed≥speedLimit

```

```

52             tracked_speed1(n)=speed;
53         end
54     else
55         speed=0;
56     end
57 end
58 frequency=max_FFT_index;
59 end
60 %Improve Accuracy
61 for x=1:1:length(speed)
62     if speed(x)==0 && x>2
63         if (speed(x-1)>speedLimit && speed(x+1)>speedLimit)
64             speed(x) = (speed(x-1)+speed(x+1))/2;
65         end
66     end
67 end
68 time = zeros(1,length(tracked_speed1));
69 for x=1:1:length(tracked_speed1)
70     time(x) = (x-1)*(Length/Fs)*(1-overlap);
71 end
72 plot(time,tracked_speed1);
73 title('Measured Speed');
74 xlabel('Time(s)');
75 ylabel('Speed(km/h)');
76 grid on;

```

```

1 %GENERATE SPECTROGRAM
2 signal=y;
3 filter = hann(428);
4 overlap=350;
5 windowSize = 8192;
6 spectrogram(signal,filter,overlap,windowSize,Fs,'power','yaxis');

```

```

1 %COSINE ANGLE CORRECTION FOR A SINGLE TRACKED VEHICLE
2 R=distance;
3 d=6;
4 cosineCorrectedSpeed=tracked_speed1;
5 for x=7:1:118
6     R = R - (timeStep*(1-overlap))*(cosineCorrectedSpeed(x-1)/3.6);
7     if (R-6)>d
8         cosineAngle=atan(d/R);
9     end
10    cosineCorrectedSpeed(x) = cosineCorrectedSpeed(x)/cosd(cosineAngle);
11 end
12 plot(time,cosineCorrectedSpeed);

```