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

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Abstract

English

Afrikaans

Contents

List of Figures

List of Tables

Nomenclature

Variables and functions

E	Electric
H	Magnetic
R	Range
G	Gain
V	Voltage
I	Current
P	Power
P_t	Transmitter Power
P_d	Power Density
σ	Radar Cross section
λ	Wavelength
A	Receive Aperture
τ	Dwell Time
c	Speed of light
τ_p	Pulse width
t_i	Measurement Time

Acronyms and abbreviations

RADAR	Radio Detection and Ranging
CSIR	Council for Scientific and Industrial Research
EV	Electrical Vehicle
PBY	Patrol Bomber Y
LiDAR	Light Detection and Ranging
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
LCD	Liquid-Crystal Display
SNR	Signal-To-Noise Ratio

Chapter 1

Introduction

1.1. Background

The traditional way of measuring vehicle speeds are 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 own independent case study [3] on the validity of Doppler radars for vehicle speed measurements. The case study reported that a there a number off 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 on 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,

- 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 metres from the radar in the direction of operation

1.2. Problem Statement

The problem I am tasked with is to investigate to possible limitations in vehicle speed measurements and enforcements, when using a CW Doppler radar. The objective of the report is to determine the limitations of a CW Doppler radar and if the prescribed operating laws are sufficient in mitigating the limitations in vehicle speed measurement.

1.3. Objectives

- Identify the possible limitations of CW Doppler radars in vehicle speed measurements
- Develop hardware for a CW Doppler radar that can perform up to 80 m
- Develop software capable of calculating the speed of targets
- Develop software capable of tracking a vehicle
- The radar should clearly be able to distinguish between a vehicle and clutter
- Test the system under the specified laws and regulations standards for speed measuring
- Test the theorized limitations of CW Doppler limitations in vehicle speed measurements
- Conclude on whether the laws and regulations are satisfactory in limiting possible errors and limitations

1.4. Summary of Work

1.5. Scope

1.6. Format of Report

- **Chapter 1** introduces important information that is used to contextually formulate the problem. The objectives for the report is mentioned followed by a reflection on what objectives were successfully executed. The chapter then moves on to discuss 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 into radar physics and what concepts allow for radars to work. I then go on to explain important fundamentals of radars that a reader of this report should know.
- **Chapter 4** formulates the limitations of Doppler radars in vehicle speed measurement.
- **Chapter 5** is where I discuss how I built a Doppler radar that I used to practically test the formulated limitations. This includes hardware and software design and development.
- **Chapter 6** starts off with a formulation of how I tested the CW Doppler radar. I then discuss how the tests where constructed to test the limitations formulated in Chapter 4. I end the chapter off by comparing the results from different tests and designs.
- **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 [4] 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 then be able to determine which vehicle is traveling 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.

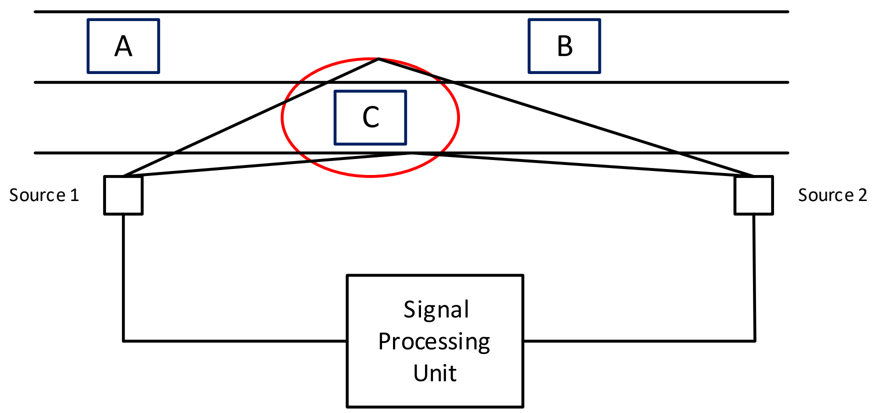

Figure 2.1: Proposed Doppler speed Measurement Configuration

Other noteworthy work was done by Nguyen Giang Lam [5]. Nguyen focussed on developing a Doppler radar with a HB100 X-band sensor [6]. To quite some success Nguyen develop the sensor with a 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. Nguyen's work focussed on building a functional Doppler radar and he did not focus on 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 there is very little information on how big an influence certain limitations of a Doppler radar has on vehicle speed measurements. In my project I will aim to adapt the system design by Nguyen and instead of real time processing I will instead focus on recording data and then applying different processing methods to clearly indicate the formulated limitations, 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 Ampére'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 Ampére'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.

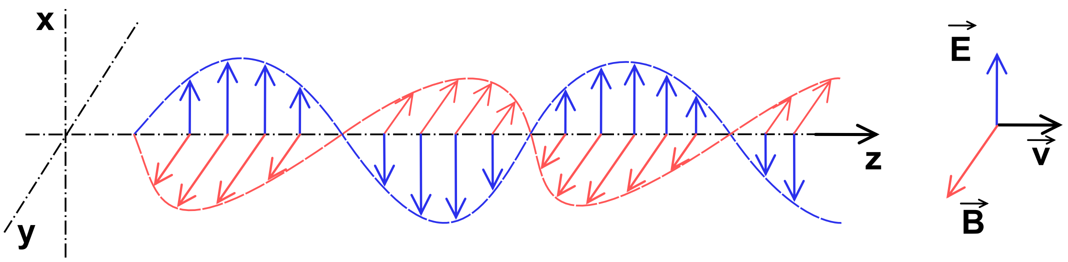

Figure 3.1: Electromagnetic Waveform

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.

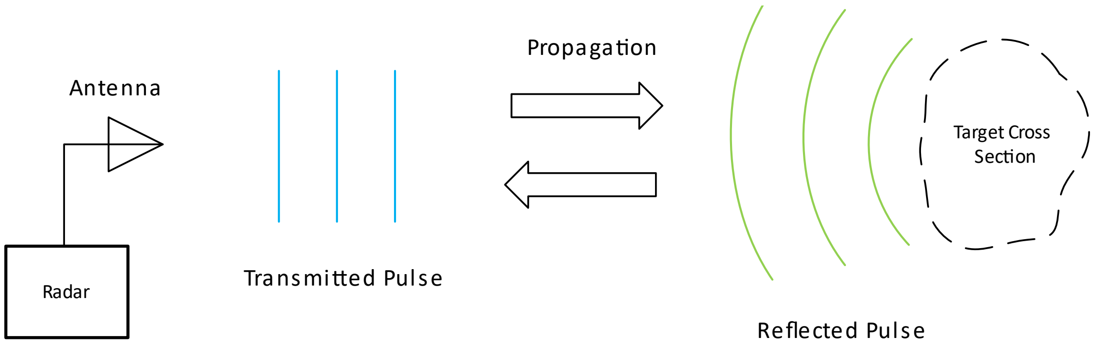

Figure 3.2: A Basic Radar

3.2. Radar Equation

The radar equation relates the range of a radar to the characteristics of the transmitter, receiver, antenna, target and environment [7]. Understanding the radar equation not only gives you means for determining the maximum distance from the radar to the target, but can also serves 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 [8], 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

$$P_d = \frac{P_t}{4\pi R^2} \tag{3.7}$$

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

$$P_d = \frac{P_t G}{4\pi R^2} \tag{3.8}$$

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

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

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 effective are is denoted by A_e, the power P_r, received by the radar is

$$P_r = \frac{PtGA_e\sigma}{(4\pi)^2R^4} \tag{3.10}$$

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

$$R_{max} = \left(\frac{PtGA_e\sigma}{(4\pi)^2S_{min}}\right)^{\frac{1}{4}} \tag{3.11}$$

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

$$G = \frac{4\pi A_e}{\lambda^2} \tag{3.12}$$

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

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

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 [9]. 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 safe guard military secrecy, 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)
UHF	0.3-1
L	1-2
S	2-4
C	4-8
X	8-12
K_u	12-18
K	18-27

Doppler radars are operated in the X-band region, this is mainly due to law enforcement from the mid 1950s [10]. The reason behind using X-band opposed to K-band or K_u-band is due to X-band being less affected by poor weather conditions. There is 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 reason for this is due to the wavelength

$$\lambda = \frac{c}{f} \tag{3.14}$$

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

3.4. Radar Cross Section

The radar cross section (RCS) [11], is a measure of an objects reflectivity and is formulated as

$$\sigma = \lim_{R\to\infty} 4\pi R^2 \frac{I_r}{I_i} \tag{3.15}$$

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

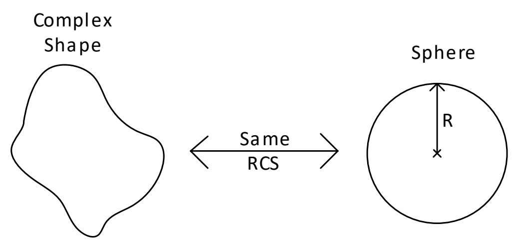

Figure 3.3: Equivalent Sphere shape

Most of the incident energy is scattered and only a small fraction is reflected back to 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 [12]. Flat surfaces reflect energy better than contoured shapes. Edges with diameters on the order of 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, fiberglass 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 shift in frequency will result. This is known as the Doppler Effect and is the basis of CW Doppler Radar [7]. 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

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

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

$$f_d = \frac{2v}{\lambda} = \frac{2v f_o}{c} \tag{3.17}$$

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_d, 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.

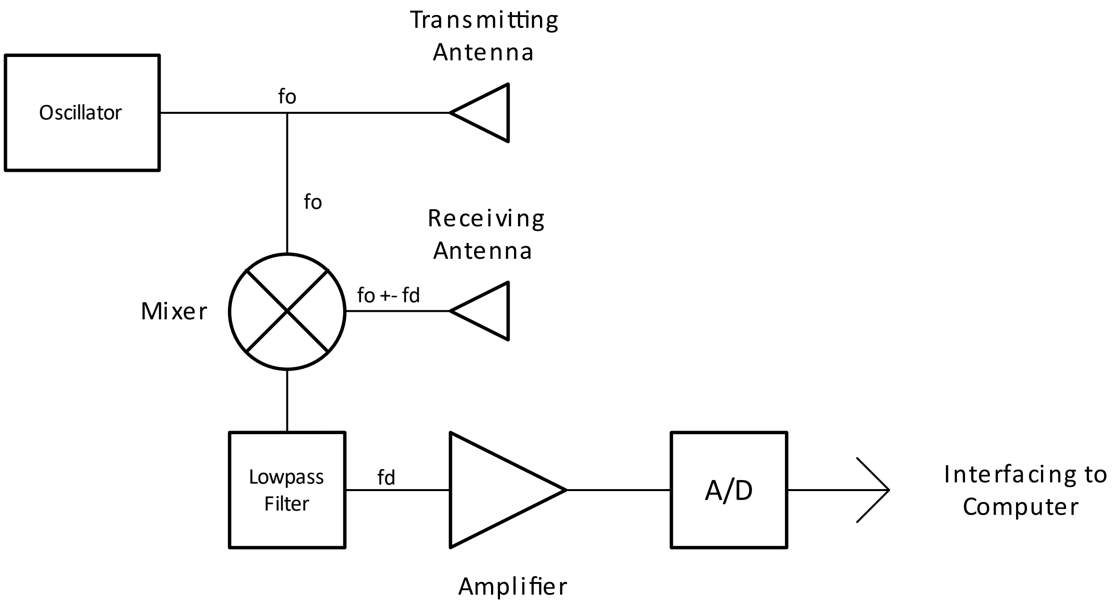

Figure 3.4: CW Doppler Radar

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 analog-to-digital converter and then passed on to the computer interface for signal processing and analyzing.

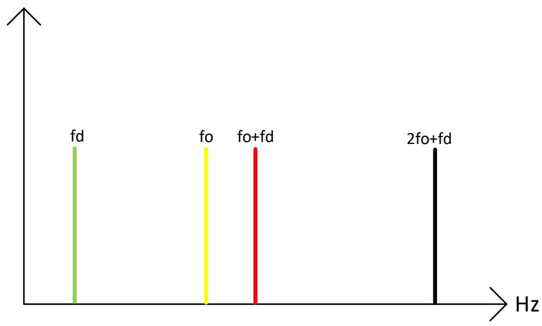

Figure 3.5: Result of Frequency Mix

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

$$\triangle f_D = \frac{1}{\tau} \tag{3.18}$$

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

$$\delta f_D = \frac{\triangle f_D}{t\sqrt{2SNR}} \tag{3.19}$$

In order to plot the spectrum of the sampled signal individual narrow band filters(NBF) must be as narrow as possible in bandwidth in order 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.

A 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 $\triangle f_D$, then the effective radar Doppler bandwidth is

$$B = N_f \triangle f_D \tag{3.20}$$

The table 3.2 below indicates the Doppler shift as a function of velocity and frequency [13].

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

f		Doppler Shift f_D (Hz)	
Band	Frequency (GHz)	1 m/s	1km/h
L	1	6.67	4.8
S	3	20	14.39
C	5	33.3	23.99
X	10	66.7	47.98
K_u	16	107	76.797
K_a	35	233	167.44

3.7. Range Resolution

Range resolution of a radar is its ability to distinguish between two or more targets on the same bearing, angle measured relative to a hypothetical north, but at different ranges [14]. 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 of a radar can be calculated from

$$S_r = \frac{c\tau_p}{2} \tag{3.21}$$

A 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 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 the mark, the broader the transmitted spectrum will be. This follows from the properties of the Fourier transform,

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

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 section, like motorcycles. Birds flying past a radar also seen as a type of clutter.

3.9. Antenna Parameters

The purpose of the radar 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 is very complex. To understand the application of antenna's in radars there is 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_0:

$$S = \frac{P_0}{4\pi R^2} \tag{3.23}$$

As isotropic antenna radiates equally in all directions and the power density S 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.

$$S = \frac{P_0 G}{4\pi R^2} \tag{3.24}$$

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

$$Directivity = \frac{U_{max}}{U_{avg}} \tag{3.25}$$

Directivity and gain differ only by the efficiency, but 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.

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

Chapter 4

Limitations of a Doppler radar in Vehicle Speed Measurement

4.1. Cosine Effect

The incorrect Doppler frequency is read from the radar when the vehicle is not traveling 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 vehicle direction of travel. The cosine angle is calculated by the equation below,

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

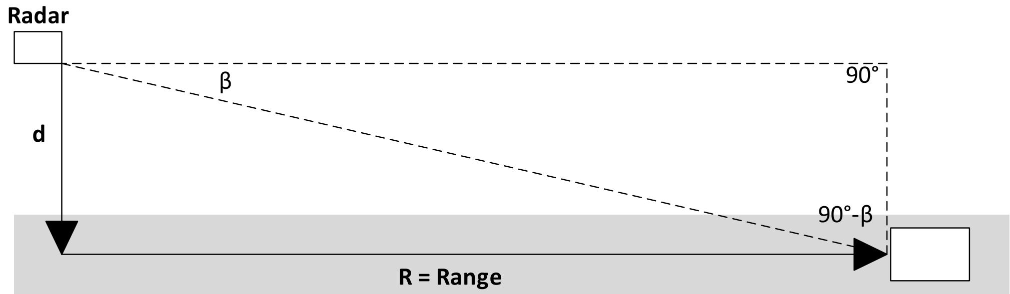

Figure 4.1: Cosine Angle β

The error in speed measurement is calculated in equation 4.2, were β is the angle of incident, R target range to radar and d is the antenna distance to middle of target lane. For this example I only considered a straight lane in which the target travels and the radar is placed on the ground. 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 and accurate result.

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

As highlighted in section 3.7 the CW Doppler radar does not have the ability to determine how far away a target is from the radar. There is some software techniques you can apply, but whose accuracy is questionable. The measured speed will always be less than the actual speed and thus care should be taken when enforcing of minimum speed limits.

4.2. Accuracy and Acceleration Limits

Under ideal conditions most speed measurement radars should have an accurate reading to about ±1 km/h. A very important part of a radar is to discriminate between different frequency components in a signal, in a short time period. A radar is 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. In order to differentiate between frequency components a short period of the signal is used to calculated the frequency spectrum, hence the name Short Time Fourier Transform(STFT). The sample taken in the time domain has a trade of 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.

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

The DFT takes a finite amount of samples, N, to calculate the frequency spectrum of discrete signal h. In order to increase the resolution of the frequency spectrum one can increase either the sampling frequency or the sampling period. Both methods has trade offs, increasing the sampling frequency increases the processing power required to calculate the DFT in real time and by increasing the size of the sample you are decreasing the resolution in the time domain. The results of a DFT is represented in a spectrogram, which has time displayed on the horizontal axis, frequency on the vertical axis and the spectral magnitude displayed as third axis by colour. Figure 4.2 illustrates the trade off between time and frequency, the first graph highlights how to clearly 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.

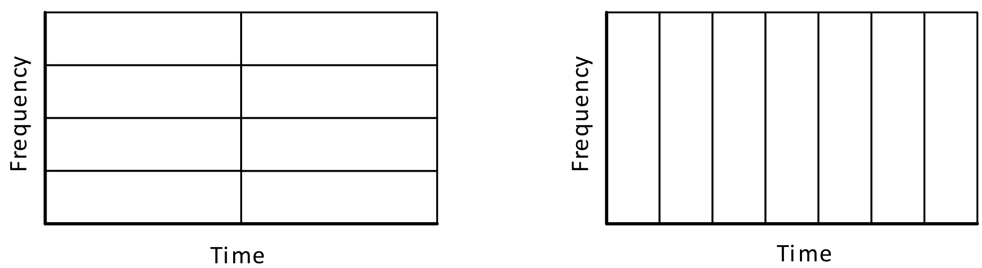

Figure 4.2: Frequency Versus Time Resolution

4.3. Object Identification

A 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 a object is moving. This is a very sound method and is capable of very accurate measurements. There is a problem however, how does the radar identify which object is travel at what speed. For the case of a CW Doppler radar which does not have range resolution, discussed in section 3.7. A Doppler radar cannot distinguish between multiple vehicle/objects travelling at different speeds, both in the range of the radar. Due to AGC being applied to different 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 motorist their RCS is relatively small, the motorcycle RCS normalised to a full size pickup is $0.05\,\mathrm{m}^2$. 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	200m^2
Large Car	120m^2
Medium Size Car	60m^2
Small Car	30m^2
Motorcycle	10m^2
Bicycle	5m^2

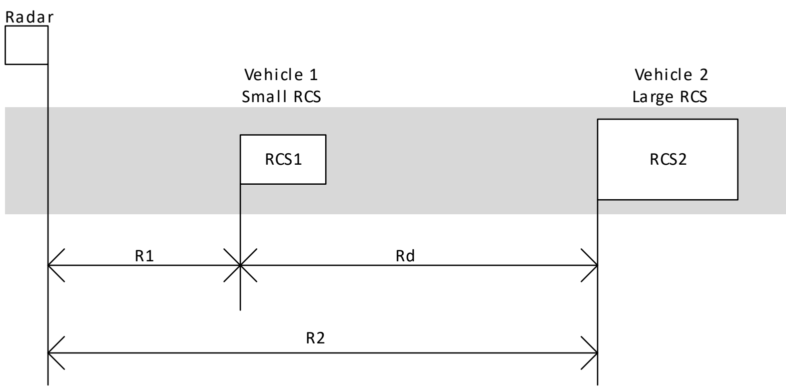

Figure 4.3: Vehicle Ranges for Equal Echo Power

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

$$R2 = R1\left(\frac{\sigma 2}{\sigma 1}\right)^{\frac{1}{4}} \tag{4.4}$$

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

$$Rd = R1\left[\left(\frac{\sigma 2}{\sigma 1}\right)^{\frac{1}{4}} - 1\right] \tag{4.5}$$

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 birds RCS usually around $0.1\,\mathrm{m}^2$. But when a swarm of birds fly past a radar it will cause the radar to have a false reading.

4.4. Antenna Sidelobes

Antenna radiation pattern is a visual representation of the radiation emission from an antenna. Figure 4.4 shows how this can be plotted in polar coordinates. The main lobe is directed in the direction of 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. 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.

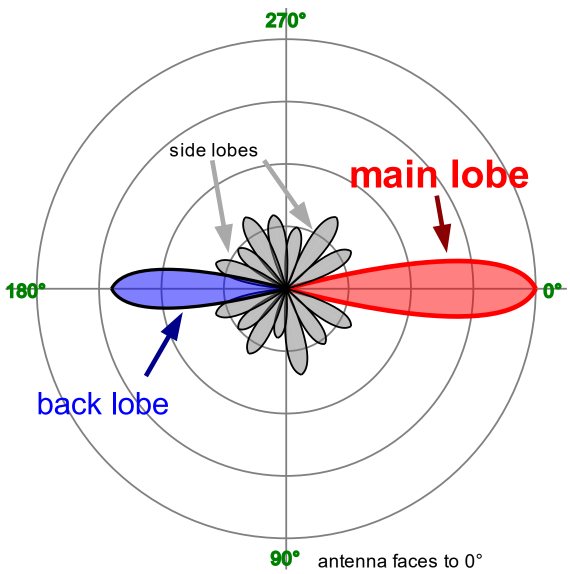

Figure 4.4: Antenna Radiation Pattern

Looking at the antenna radiation pattern of the HB100 sensor shown in figure C.1, the antenna is not very directional. When applying AGC, which is later explained in detail in section 5.1.3, to the received signals, it further complicates the process. This adds to the confusion of not knowing what object is reflecting what signal. Combining antenna radiation, side lobes, and AGC. It compromises the credibility of a radar. Is important to know the radiation pattern of your radar for both the transmitting and receiving antenna, otherwise you will not be able to 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, who are good reflectors, my 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. For instance a common object like an overhead or off road highway sign can cause signals to reflection in multiple ways. Figure 4.5 shows two reflection paths the radar will measure when an overhead sign is placed on a highway.

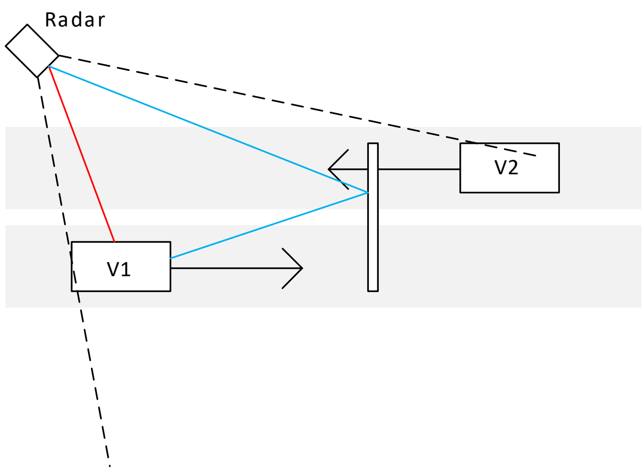

Figure 4.5: Multiple Reflections

The above illustration is just one example. There is 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 radar range. Strong signals that saturate the radar receiver 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 at 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.

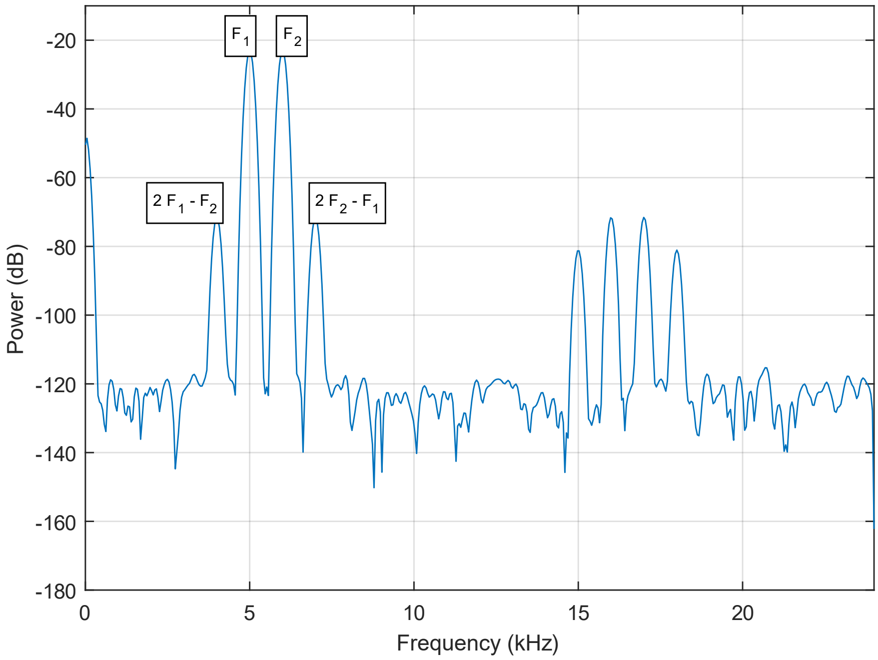

Figure 4.6: Intermodulation Distortion

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

Chapter 5

Doppler Radar

5.1. System Design

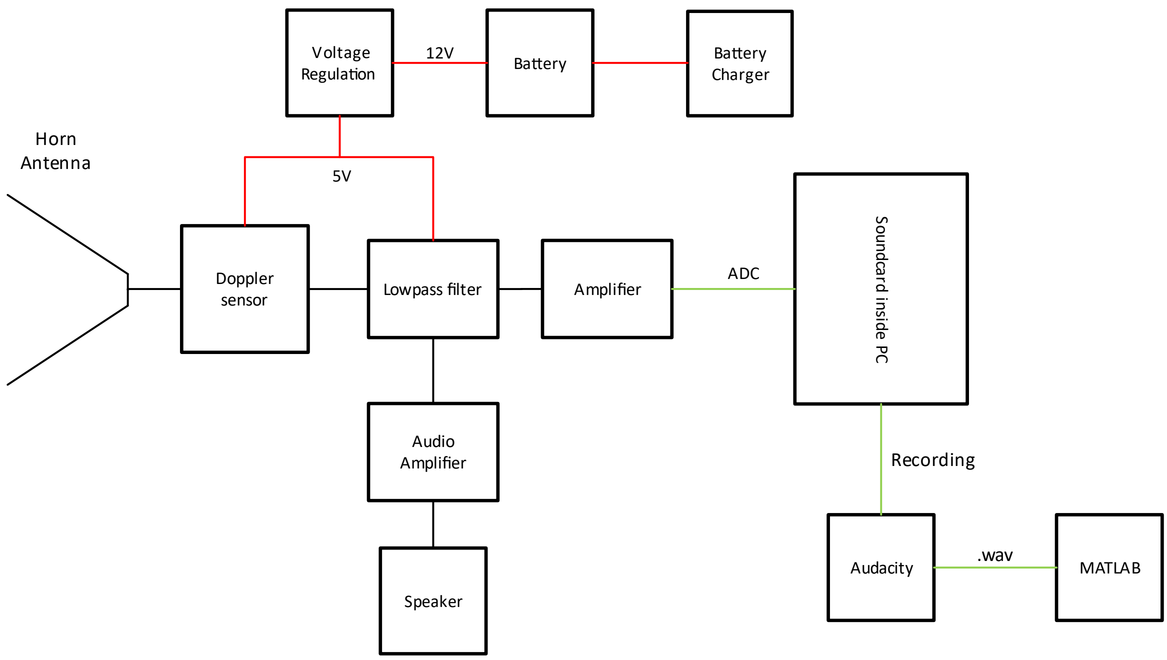

Figure 5.1: System Diagram of Project

5.1.1. Doppler Sensor

The Doppler sensor I will make use of for sensing the Doppler frequency are the HB100 [6]. The sensor operates at 10.25 GHz, and is designed for velocity measuring. The sensor includes a 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 C.1, and the half power beamwidth is illustrated in Figure C.2. The sensor requires a lowpass filter and pre-amplifier before it is able to be sampled for analysis, this is discussed in Section 5.1.3. Another option I considered was to build a sensor from individual components, but this proved to be too expensive and not inside the scope of this projects.

5.1.2. Antenna

The patch antenna's on the HB100 sensor is shown in Figure 5.2. After looking at the radiation pattern I decided to design a horn antenna to increase directivity of the antenna. A horn antenna, illustrated in Figure 5.3, was designed in CST software to act as a directional antenna for the patch antenna. I decided to add a wave guide part to separate the transmit and receive antennas from each other to increase directivity.

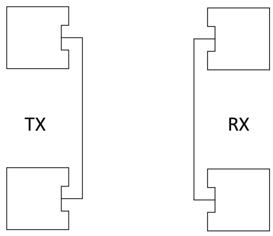

Figure 5.2: Patch Antenna on HB100

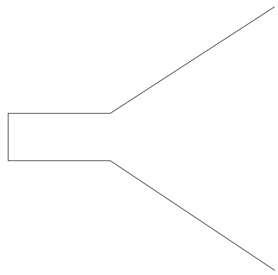

Figure 5.3: Horn Antenna

5.1.3. Lowpass Filter and Amplifier

The lowpass filter will be a second order RC circuit, due to its simplicity and further filtering that will be done in software. Active filters where considered but did not provide any advantage over a passive filter. The amplification of the sensor output proved to be a bit more ambitious. Due to little information available on HB100 sensor and the uncertainty of the output voltage. The only information about output levels, where that it is in the range of a few mV [15].The amplification will be tested and adapted as needed to sufficiently amplify the signal. In order to protect the soundcard of a 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. The functional block diagram is illustrated below.

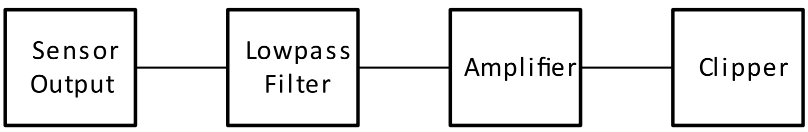

Figure 5.4: Functional Block diagram

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 a 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. Battery Charger

For the battery and charger, I thought to have something that is both portable and rechargeable. I decided to go with a 112 V Lead-Acid battery [16] and charger [17]. The charger module can charge batteries from 6 to 60V, with a LCD interface to indicate charge levels of battery. I also considered a alkaline 9 V battery, but due to a its small capacity I decided to go with a Lead Acid battery.

5.1.6. Audio Amplifier

I decided to make use of a audio amplifier module [18], instead of building an audio amplifier. Building an amplifier is outside the scope of this project and the speaker will only feature as a debug tool for in field test. I connected a 8 Ω speaker to the output of the audio amplifier.

5.1.7. 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 6 KHz. The input limits is around $1\,V_{rms}$ and thus the amplification is designed with this limitation taken into account.

5.1.8. Software

The sampled signal from the soundcard will be recorded in Audacity [19], it is a open source audio software. The recorded file will then be exported as a .wav file and further analyzed in MATLAB. In MATLAB I will apply software techniques to determine vehicle speed, noise levels and apply tracking of the vehicle. A GPS unit will be placed inside the car used for testing the system that will help with calibrating the system and used for comparison in non-ideal conditions. The GPS unit is a Ublox, GNSS smart board [20], with an external antenna to improve accuracy. 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 operating frequency expected from the Doppler sensor, I decided to use a second order RC filter to get a better attenuation at higher frequencies. The filter circuit is illustrated in Figure 5.5, the cut-off frequency is calculated by equation 5.1. The cut-off frequency is selected as 15 kH. This is quite a high cut-off frequency considered the expected output not to exceed 6 kH. The choice for cut-off frequency is chosen due to the fact that the filter circuit has a gain that equals 0.707^n, where n equals the number of stages. The gain will therefore be 0.5 and thus I don't want to attenuate the necessary signals that I intend to measure any further. The values of the resistors and capacitors are chosen to be equal, R1=R2 and C1=C2. The capacitor value is chosen to be 10 nF, the calculated resistor value is 1.06 kΩ.

$$f_c = \frac{1}{2\pi\sqrt{R_1C_1R_2C_2}} \tag{5.1}$$

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

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

The newly calculated cut-off frequency $f_c = 9.653\,\text{kHz}$. The new cut-off frequency still satisfy the 6 kHz requirement.

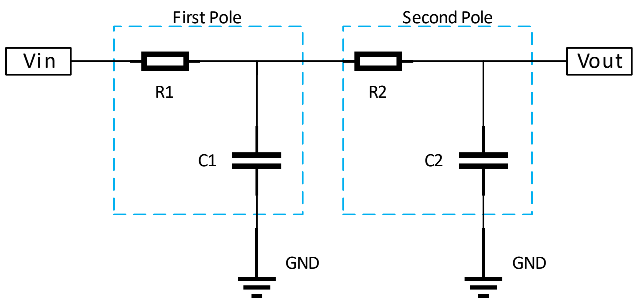

Figure 5.5: Filter Circuit

5.2.2. Amplifier

To amplify the output from the Doppler sensor to be sampled adequately by the PC soundcard the circuit should be designed to be adjusted in the field. That is why I decided to amplify the signal through a differential amplifier op-amp. The op-amp gain equation is shown below

$$V_{OUT} = \frac{R3}{R2} \times (V_b - V_a) \tag{5.3}$$

The amplifier is illustrated in figure 5.2.2, resistor R3 will be variable resistor, known as a rheostat, R2's size is 1 kΩ. Thus a variable resistor that ranges up to around 1 MΩ is used, that will allow for a gain of up to 1000. From the datasheet of the op-amp I used, MCP602 [21], the gain versus frequency plot is illustrated in figure C.3. 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 6000 Hz, so the gain specifications can be met with one op-amp.

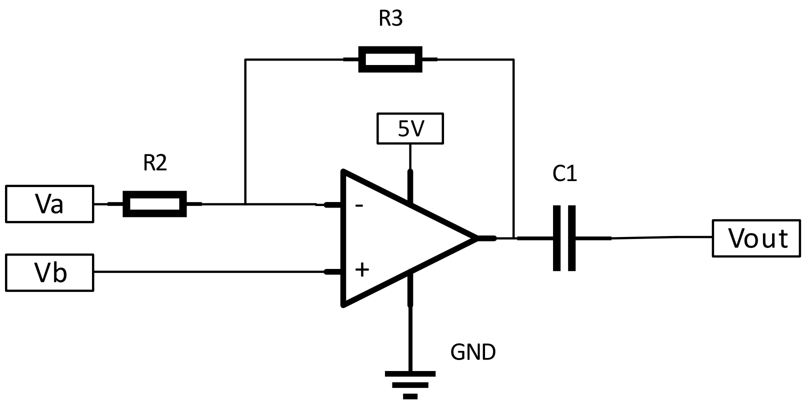

Figure 5.6: Amplifier Circuit

The voltage labels Va and Vb, will both be centered around 2.5 V. This was chosen 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. Therefor 2.5 V safely lies between the common mode voltage limits. The circuit required to produce voltage V_a is illustrated in 5.7, a decoupling capacitor is place 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 are calculated by the equation below

$$V_{ref} = 5 \times \frac{R1}{2 \times R1} = \frac{5}{2} \tag{5.4}$$

it is clear that 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 kΩ. 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 5.8. Voltages V_a and V_b are attached to the same labels in the circuit illustrated in figure 5.6.

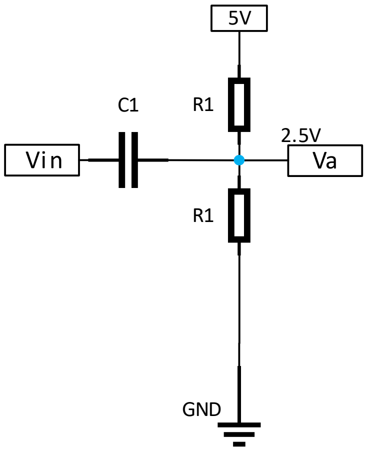

Figure 5.7: Voltage Swing Circuit

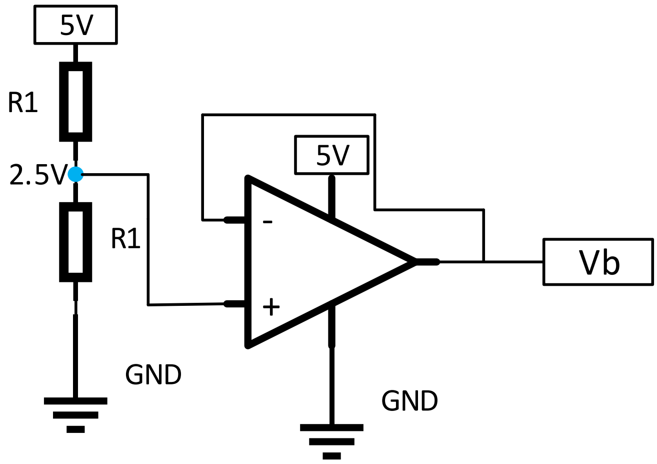

Figure 5.8: Voltage Reference Circuit

5.2.3. Voltage Regulator

The regulator circuit for generating 5 V is illustrated in figure 5.9. 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. The input voltage will be 9 V coming from an alkaline battery [22]. The expected output current will not exceed 50 mA. The power dissipated by the voltage regulator is 0.2 W and therefore there is no need for a heat sink or to do thermal calculations, because the heat dissipated is so little.

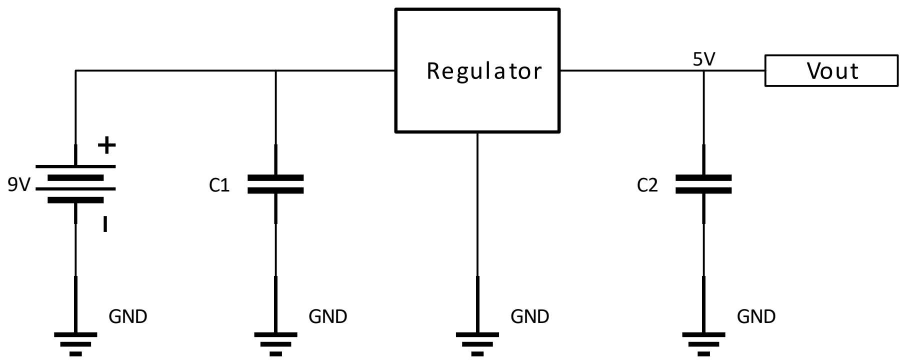

Figure 5.9: Voltage Regulator Circuit

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 5.10. Two diodes 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 was around 0.5 V. It decided to place four diodes in the circuit with two of them having the same polarity. This limits the voltage swings at $\pm 1V$.

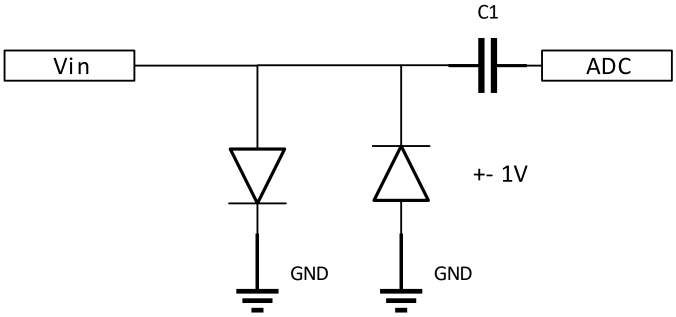

Figure 5.10: Diode Clipper Circuit

5.2.5. Antenna

5.2.6. Software

The common signal processing technique used in radars is to determine the strongest frequency component in a short period of time, through a STFT. This frequency component is then converted to speed and if it is above the limit the camera will be triggered to take a photo. With this knowledge I designed a speed calculation to imitate that of a real radars processing. The algorithm takes as inputs the recorded file, sampling rate, frame size and signal-to-noise ratio. The algorithm is illustrated in algorithm 5.1. The output of the file will be an array with the speeds measured from the strongest frequency component of the signal in that short time period.

Algorithm 5.1: 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

For the noise-to-signal ratio, I decided on taking real measurements of roads where I intend to place my radar for measurements. Thus my SNR will therefore take into consideration antenna transmitter and receiver, system and environment noise. Due to many different noise levels from my inside the radar and noise from the environment it would be difficult to mathematical estimate the noise level. Every time I change measurement locations I can first start with calculated the SNR level before starting with measurements to improve the accuracy of algorithm 5.1. This will also be the standard calibration that will be done when a permanent radar is installed in the field. The SNR algorithm is illustrated in algorithm 5.2. An example of a SNR is illustrated in figure C.4, where the red line is the SNR. All the components above this line is measured as targets.

Algorithm 5.2: 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

The last processing I will do is tracking of an object. This entails establishing an object and the tracking its speed for as long as it is in range of the radar. Radar usually require a time period of tracking an object before it can legally record a speed reading or issue a speed fine. The algorithm can be quite difficult if it takes into account more than one object might be in range of the radar. For my case I will assume only one object will be in range of the radar or in other words only try to track one vehicle. The radar tracks an object by identifying a target that rises above the SNR. The STFT time period is then used to determine the assumed maximum change in speed a vehicle can exercise. This speed variation is then used to setup 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 bins range, meaning the target is out of range or possibly not a vehicle in the first place. After a certain amount of successfull tracks the target will be labelled as a vehicle. The measurable change in speed of a vehicle is directly proportional to how long period is used to calculate the STFT. Equation 5.5 shows how this speed change can be calculated if the radar will have 100 % accuracy in speed changes.

$$Speed = \frac{1}{t_i} \tag{5.5}$$

The tracking algorithm is illustrated in algorithm 5.3.

Algorithm 5.3: Tracking

---

input Recording, Sampling Rate, Frame Size, Signal-to-Noise Ratio, Frequency Bin Size

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

    Calculate FFT of Sample

    for $i = 0$ to $SampleSize$ **do**

      Calculate Maximum Component

      if Maximum Component $\geq$ SNR **then**

        if Frequency Difference $\leq$ Bin Range **then**

          Label Object

          Update bin range

    Store Object Frequency

  Plot Tracked Object Speed vs Time

output Tracked Object Speed

Chapter 6

Results

Chapter 7

Conclusion

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Appendix A

Project Planning Schedule

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Appendix B

Outcomes Compliance

This is another appendix.

Appendix C

Figures

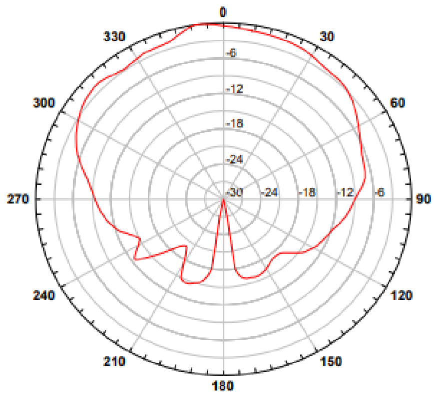

Figure C.1: HB100 Radiation Pattern

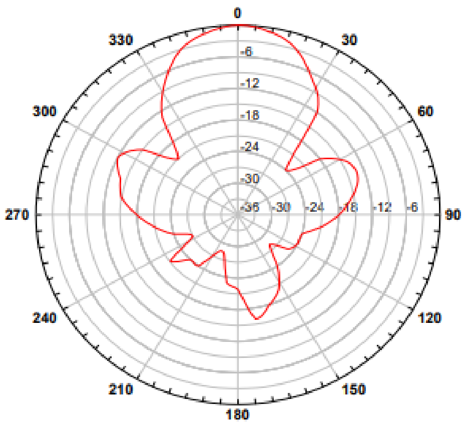

Figure C.2: HB100 half power beam width

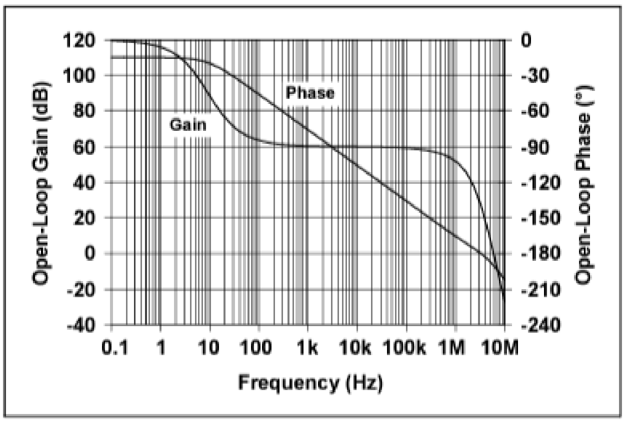

Figure C.3: Gain versus Frequency plot of MCP602 op-amp

Table C.1: Requirements for prosecution using RADAR

RADAR Class	Prosecution requirements
Class A1 and A2	no metal road signs or vertical flat surfaces larger than 1 meter in height within 15 (fifteen) degrees on either side of the aiming direction, within a distance of 200m of the antenna no signals received and processed from vehicles more than 500 metres away no other moving vehicle other than the measured vehicle within 600 metres from the SME in the direction of operation
Class B1 and B2	no metal road signs or vertical flat surfaces larger than 1 meter in vertical height within 15 (fifteen) degrees on either side of the aiming direction, within a distance of 100 metres of the antenna no high voltage overhead power cables in the radar's field of detection for at least 100m

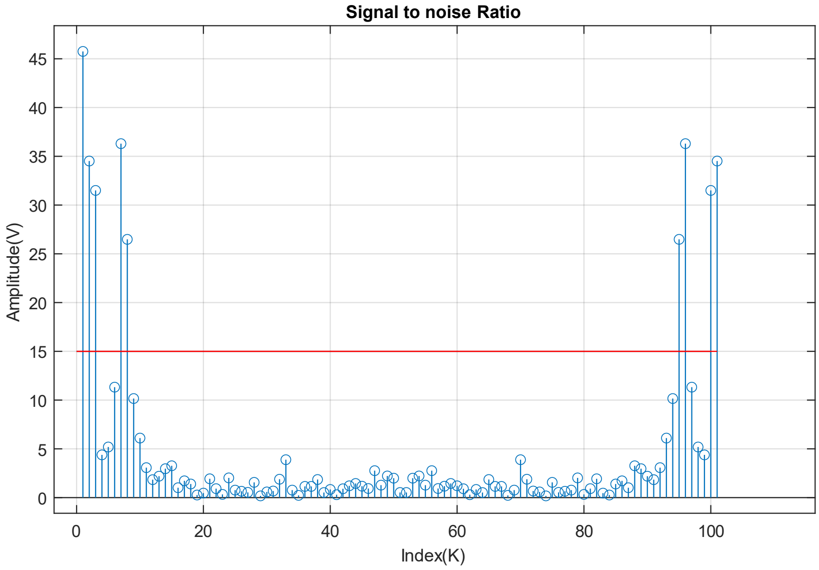

Figure C.4: Signal-to-Noise Ratio