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

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Abstract

English

To whom has yet to receive a speeding ticket, I envy you. The rest of us can wholeheartedly agree that it is rather unpleasant. When looking at the blurry photo exposing you behind the steering wheel and noticing another vehicle in the photo, the question lingers, was it me? Is it not possible that the other vehicle was speeding? A question that might have some merit.

Afrikaans

Aan diegene wat nog nooit ’n spoed boete ontvang het nie, ek is jaloers. Die van ons wat al een gekry het, weet dit is ’n onaangename ervaring. Wanneer jy kyk na die dowwe foto met jouself agter die stuurwiel en jy sien ’n ander motor in die prentjie,bly die vraag drentel, was dit ek? Is dit nie moontlik die ander motor wat te vinnig gery het nie? ’n Vraag wat moontlik meriete het.

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

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
RC	Resistor and Capacitor
ADC	Analog to Digital Converter
RMS	Root Mean Squared
GNSS	Global Navigation Satellite System
NMEA	National Marine Electronic Association

Chapter 1

Introduction

1.1. Background

The traditional way of measuring vehicle speed 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 have come under some scrutiny, because of the limitations in their usage [3]. Knowing these limitations can limit the error on vehicle speed measurements and improve results.

With newer technology developed over the years, their might be call for leaving Doppler radars to be retired as historic momentoes or to museums. The newest technology, LiDAR [4], offer a substitute to traditional Doppler radars. A typical LiDAR sensors emits pulsed light waves into the environment. The pulses bounce of surrounding objects and return to the sensor. The sensor uses the elapsed time to calculate the distance the object travelled and therefore can calculate its speed.

The old saying goes, " If it ain't broke, don't fix it." If Doppler radars still prove to be accurate there is no need to change something that works.

1.2. Problem Statement

The project aim is to identify and formulate the limitations of Doppler radars in the measurement of vehicle speed. This will be done by determining non-ideal conditions in which Doppler radars can be operated and whether or not that can be eliminated through proper operation or adaption to the system. Then determining how much the limitations affect the accuracy of Doppler radars and do they warrant a change in how we measure and enforcement vehicle speed.

1.3. Objectives

- Identify the possible limitations of CW Doppler radars
- Develop hardware for a Doppler radar that can perform up to 100 m
- Develop software capable of calculating the speed of targets in the radar target range, but also is able to suppress noise
- Test the accuracy of the designed system by comparing it to GPS speed measurements
- Test the system under the specified laws and regulations standards for speed measuring
- 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. Roadmap

Chapter 2

Literature Review

2.1. Proposed Doppler Radar Solutions

Ever since Doppler techniques were developed for vehicle speed measurements, it has come under scrutiny due to inaccuracies in the readings. In 1987 a case study done by the CSIR [5], reported that a major problem with Doppler technique is that it cannot accurately identify which vehicle is supplying the measurement. This is later discussed in more detail in section 2.2.3.

A proposed solution to this problem was developed by Neil Cameron Martin [6] 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 which 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 report of the CSIR still at the heart of the problem. This might be due to the complex real-time processing required to successfully implement the system.

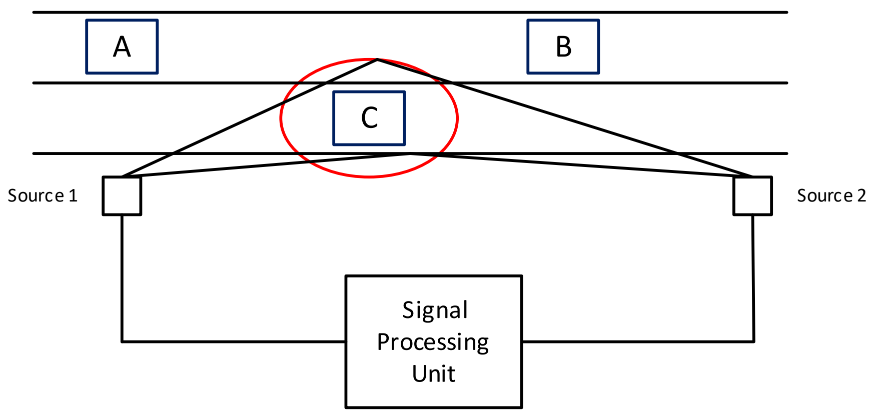

Figure 2.1: Proposed Doppler speed Measurement Configuration

Other noteworthy work was done by Nguyen Giang Lam [7]. Nguyen focussed on developing a Doppler radar with a HB100 X-band sensor [8]. 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. A shortcoming of Nguyen's work was that he never considered measuring under non-ideal conditions and only measured vehicles at 7 m from the sensor.

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

In my project I will aim to amplify the system designed by Nguyen to measure vehicles close to 100 m from the sensor and then test it under non-ideal conditions to see how these conditions limit the capabilities of the Doppler Radar. The conditions under which the radar will be tested is discussed in Chapter 5.

2.2. Radar Physics

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 2.1 and 2.2. Faraday's law of induction is shown in equation 2.3 and 2.4.

$$\nabla \cdot E = 0 \qquad (2.1)$$

$$\nabla \times E = -\frac{\partial B}{\partial t} \qquad (2.2)$$

$$\nabla \cdot B = 0 \qquad (2.3)$$

$$\nabla \times B = \mu\epsilon \frac{\partial E}{\partial t} \qquad (2.4)$$

Maxwell derivation is today replaced by combining Ampére's and Faraday's to obtain the electromagnetic wave equation in a vacuum shown in equation 2.5 and 2.6, known as the wave equation.

$$\frac{1}{\sqrt{\mu\epsilon}} \frac{\partial^2 E}{\partial t^2} - \nabla^2 E = 0 \qquad (2.5)$$

$$\frac{1}{\sqrt{\mu\epsilon}} \frac{\partial^2 B}{\partial t^2} - \nabla^2 B = 0 \qquad (2.6)$$

The electromagnetic waveform is generated by a periodic change in the current inside an antenna. The antenna can take many forms and shapes [9], for example a horn, loop or strip antenna. The waveform that is generated from the antenna is indicated in Figure 2.2, 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.

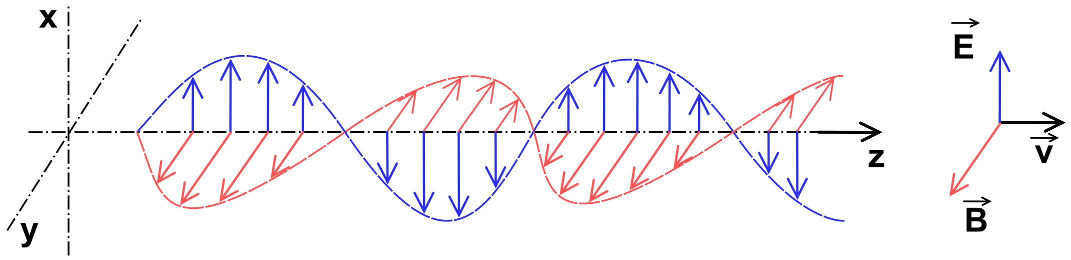

Figure 2.2: Electromagnetic Waveform

Consider the basic radar illustrated in Figure 2.3, 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.

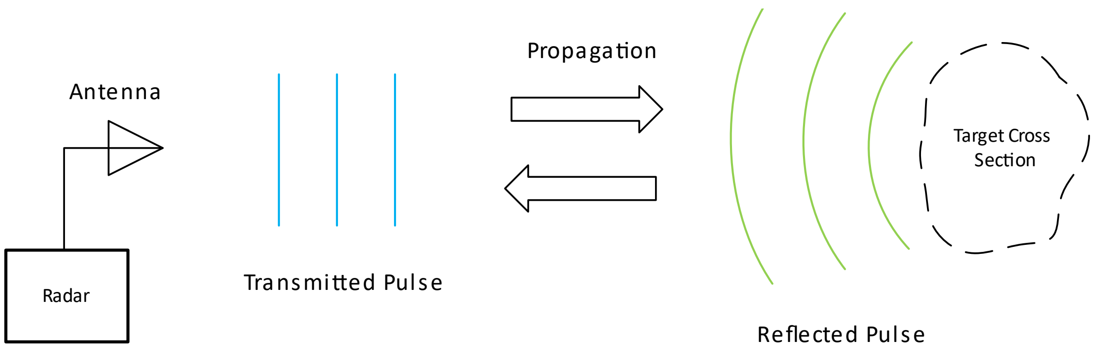

Figure 2.3: A Basic Radar

2.2.1. Radar Equation

The radar equation relates the range of a radar to the characteristics of the transmitter, receiver, antenna, target and environment [10]. 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 [11], 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

$$P_d = \frac{P_t}{4\pi R^2} \tag{2.7}$$

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

$$P_d = \frac{P_t G}{4\pi R^2} \tag{2.8}$$

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

$$P_d = \frac{P_t G}{4\pi R^2}\frac{\sigma}{4\pi R^2} \tag{2.9}$$

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

$$P_r = \frac{PtGA_e\sigma}{(4\pi)^2 R^4} \tag{2.10}$$

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

$$R_{max} = \left(\frac{PtGA_e\sigma}{(4\pi)^2 S_{min}}\right)^{\frac{1}{4}} \tag{2.11}$$

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

$$G = \frac{4\pi A_e}{\lambda^2} \tag{2.12}$$

Generally radars use the same antenna for transmit and receive by substituting equation 2.12 into equation 2.11, resulting in

$$R_{max} = \left(\frac{Pt(A_e)^2\sigma}{4\pi(\lambda)^2 S_{min}}\right)^{\frac{1}{4}} \tag{2.13}$$

2.2.2. 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 [12] for radar. 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 2.2 shows the designated bands inside the Microwave region.

Table 2.2: 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 [13]. 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

$$\lambda = \frac{c}{f} \tag{2.14}$$

the wavelength will determine the finer detail the radar is capable of measuring.

2.2.3. Radar Cross Section

The radar cross section [14], is a measure of an objects reflectivity and is formulated as

$$\sigma = \lim_{R \to \infty} 4\pi R^2 \frac{I_r}{I_i} \tag{2.15}$$

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

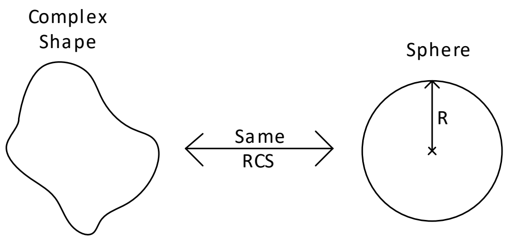

Figure 2.4: Equivalent Sphere shape

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 [15]. 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.

The incident angle of the apparent microwave determines the RCS of a object. In Table 2.3 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 2.5, illustrates this phenomenon.

Table 2.3: 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	$5m^2$

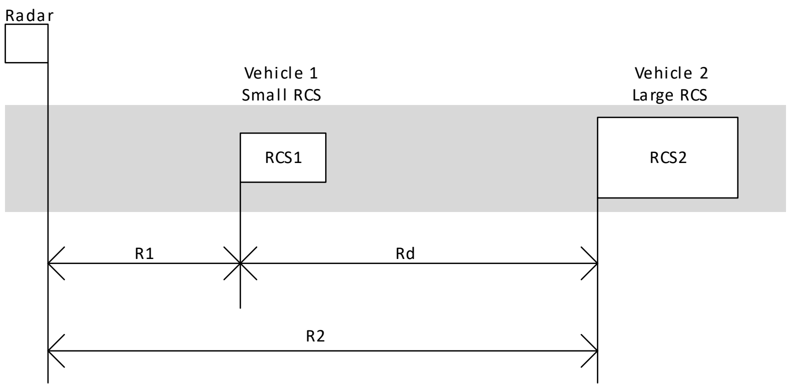

Figure 2.5: Vehicle Ranges for Equal Echo Power

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

$$R2 = R1 \left(\frac{\sigma 2}{\sigma 1}\right)^{\frac{1}{4}} \tag{2.16}$$

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

$$Rd = R1 \left[\left(\frac{\sigma 2}{\sigma 1}\right)^{\frac{1}{4}} - 1\right] \tag{2.17}$$

2.2.4. 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 Radar [10]. 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 2.18

$$2\pi f_d = \omega = \frac{4\pi \partial R}{\partial t} = \frac{4\pi v}{\lambda} \tag{2.18}$$

where f_d = Doppler frequency shift and v = relative velocity of target with respect to radar. The Doppler frequency shift is given by equation 2.19

$$f_d = \frac{2v}{\lambda} = \frac{2v f_o}{c} \tag{2.19}$$

where c is the speed of light in a vacuum. Consider the CW radar as illustrated in

Figure 2.7. 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 form the transmitted frequency f_o, by an amount $+-f_d$, given by equation 2.19. 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 $f_o + -f_d$, 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 2.6, note that the sign of f_d is lost in the process.

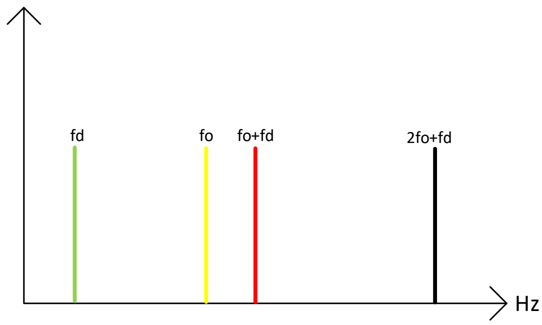

Figure 2.6: Result of Frequency Mix

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 it is sampled by an analog-to-digital converter and then passed on to the computer interface for signal processing and analyzing.

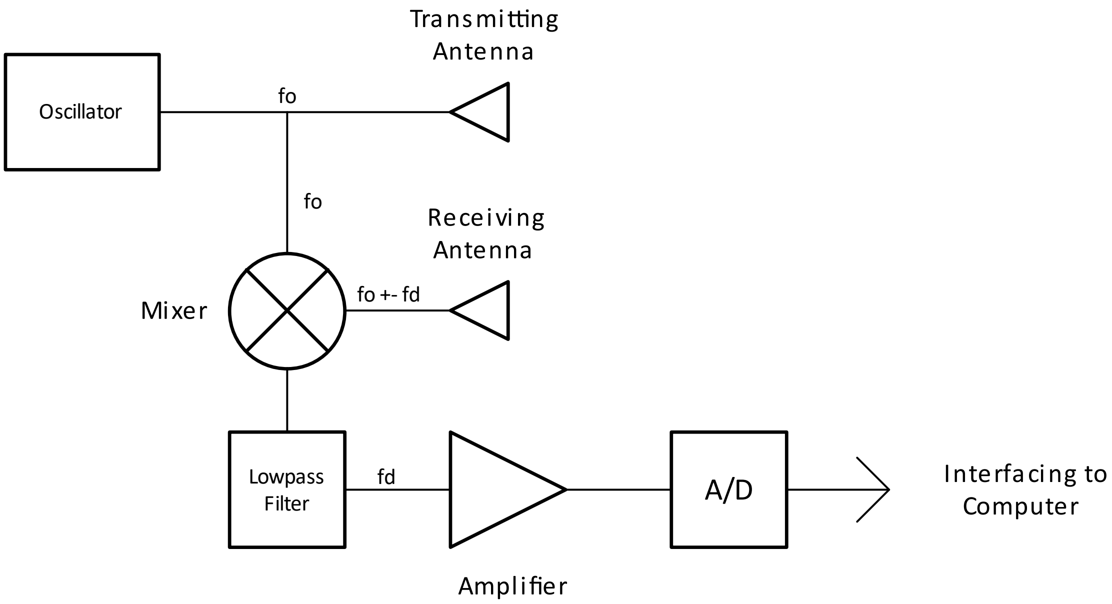

Figure 2.7: CW Doppler Radar

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 greater the dwell time the finer the frequency resolution

$$\triangle f_D = \frac{1}{\tau} \tag{2.20}$$

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

$$\delta f_D = \frac{\triangle f_D}{t\sqrt{2SNR}} \tag{2.21}$$

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 radar is infinitesimal. However systems with infinitesimal bandwidths cannot physically exist and thus, the bandwidth of CW 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 $\triangle f_D$, which springs from equation 2.20, then the effective radar Doppler bandwidth is

$$B = N_f \triangle f_D \tag{2.22}$$

The table 2.4 below indicates the Doppler shift as a function of velocity and frequency [16].

Table 2.4: 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

2.2.5. Range Resolution

Range resolution of a radar is its ability to distinguish between two or more targets on the same bearing but at different ranges [17]. 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

$$S_r = \frac{c\tau_p}{2} \tag{2.23}$$

A unmodulated CW 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,

$$\mathfrak{F}(h(t)) = \int_{-\infty}^{\infty} h(t)\dot{e}^{-j2\pi f_t}\, d_t \tag{2.24}$$

therefore a finite spectrum must be transmitted if transit 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, FMCW, the carrier.

2.2.6. 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 may cause false readings to occur.

2.2.7. 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.

The directive gain, used in equation 2.12, is the ability of an antenna to concentrate energy in a particular direction. The directive gain of a transmitting antenna may be defined as

$$G_D = \frac{P_{max}}{P_{ave}} \tag{2.25}$$

where P_{max} is the maximum radiation intensity, and P_{ave} is the average radiation intensity

The definition of directive gain is based primarily on the shape of the radiation pattern. It does not take account of dissipative losses. The power gain, which will be denoted by G_P, and can be similarly defined to the definition of directive gain in equation 2.25, except that the denominator is the net power accepted by the antenna from the connected transmitter. The radiation pattern of a helix antenna is illustrated in Figure 2.8, the radiation pattern is a function of gain versus angle. When designing a radar it is important to look at the radiation pattern to calculate the directive gain. The radiation pattern is determined by the source frequency, antenna structure and polarization.

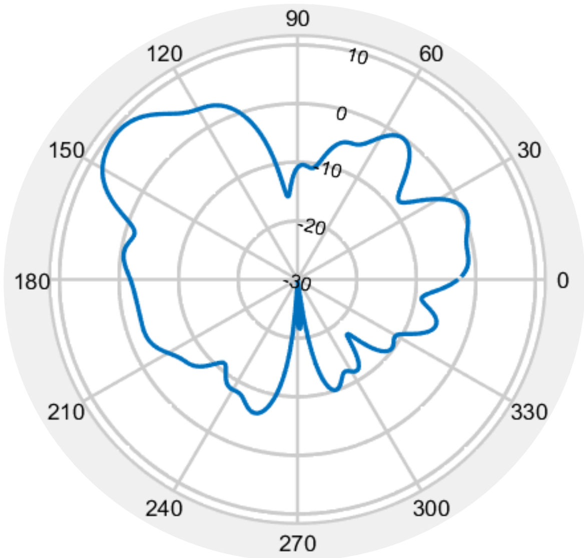

Figure 2.8: Radiation Pattern for Helix Antenna at X-band

Chapter 3

System Design

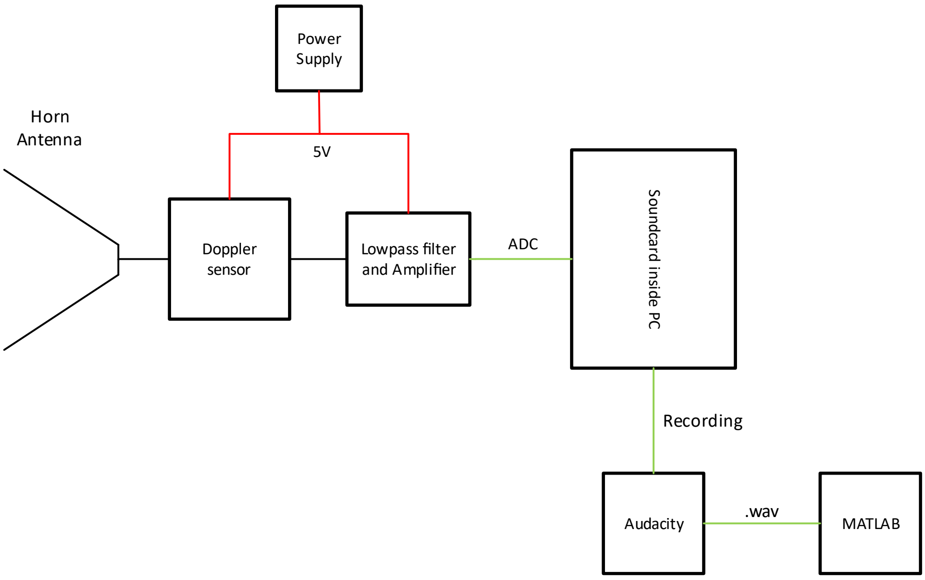

Figure 3.1: System Diagram of Project

3.1. Doppler Sensor

The Doppler sensor I will make use of for sensing the Doppler frequency are the HB100 [8]. 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 beam width 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 3.3. 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.

3.2. Antenna

The patch antenna's on the HB100 sensor is shown in Figure 3.2. 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 3.3, 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.

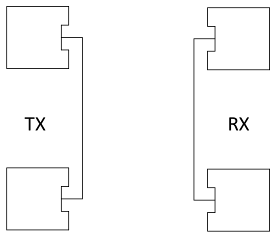

Figure 3.2: Patch Antenna on HB100

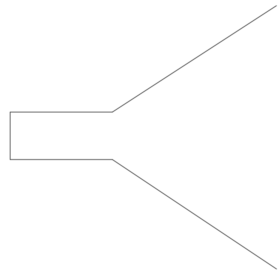

Figure 3.3: Horn Antenna

3.3. 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 [18].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.

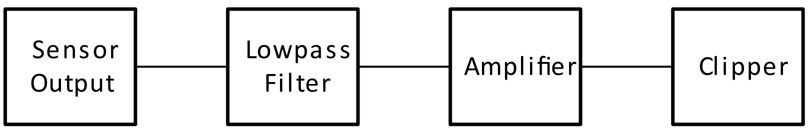

Figure 3.4: Functional Block diagram

3.4. Power Supply

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.

3.5. 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 6 KHz. The input limits is around 1 V_{rms} and thus the amplification is designed with this limitation taken into account.

3.6. 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 the recording will be used to determine the speed of the vehicle and used to plot the Spectrogram. The Spectrogram is the frequency plot versus time, giving you insight on when the speed was recorded. 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.

Chapter 4

Detailed Design

4.1. Filter

4.2. Amplifier

4.3. Voltage Regulator

4.4. Clipper

4.5. Antenna

4.6. Software

Chapter 5

Results

Chapter 6

Conclusion

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Appendix A

Project Planning Schedule

This is an appendix.

Appendix B

Outcomes Compliance

This is another appendix.

Appendix C

Figures

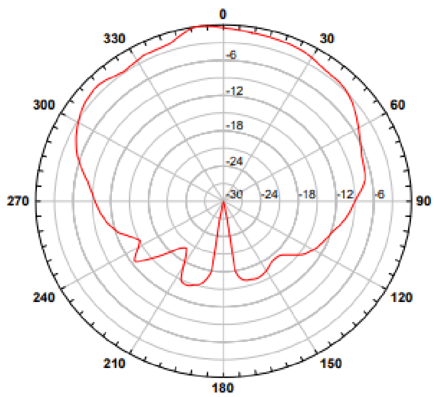

Figure C.1: HB100 Radiation Pattern

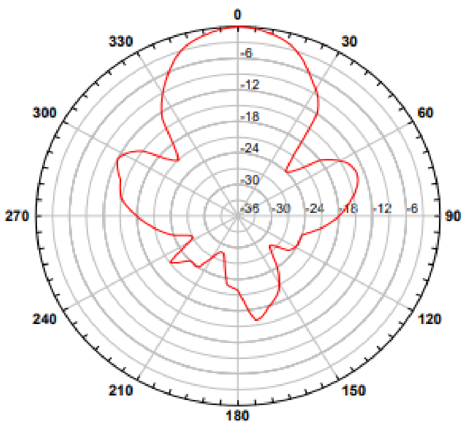

Figure C.2: HB100 half power beam width