POLITECNICO DI TORINO

MASTER’s Degree in ELECTRONIC ENGINEERING

MASTER’s Degree Thesis

IN-CAR MULTI-FUNCTION MICROWAVE DEVICE SPEED MEASUREMENTS RESPECT TO THE ROAD SURFACE

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Abstract

Speed measurement is useful for vehicle safety, high speed car performance improvements for better traction control, autonomous vehicles collision avoidance, and autonomous navigation. Therefore, it should be precise to have better results for these applications. This paper explores the implementation of a vehicle-mounted Doppler radar for true speed-over-ground (SOG) estimation. Mainly we will use this application for limited series sport vehicles, to make those vehicles better in track performance. This approach provides a good way to handle speed measurements because it avoids the wheel slip and is independent of satellite reception. The core of this study focuses on Doppler signal spectrum estimation. One approach is by calculating the Doppler power density spectrum and then extracting the dominant frequency component, that is, the peak of the spectrum. Another technique, based on a modern analysis, compares the measured Doppler spectrum with a set of pre-estimated theoretical spectral models in order to find the best fit. This research validates the efficacy of Doppler radar as a good alternative for speed measurement compare to classical methods, ensuring the accurate data required for robust traction control for high-speed vehicles.

Abbreviations

BT – Bluetooth

FFT – Fast Fourier Transform

IF – Intermediate Frequency

PSD – Power Spectrum density

RF – Radio Frequency

MW – Microwave

SNR – Signal to noise ratio

SOG – Speed-Over-Ground

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1. Introduction

1.1 Motivation

Vehicle speed is often detected as a simple variable for the vehicle. However, it is a critical variable for modern automotive control systems. Accurate and reliable velocity measurement is fundamental for ensuring the vehicle state estimation within the Electronic Control Unit (ECU). Vital safety mechanisms, including Anti-lock Braking Systems (ABS), Electronic Stability Control (ESC), and autonomous navigation, rely on the accuracy of this data. Therefore, the precision of speed measurement directly connects to the effectiveness of these applications.

Currently, normal cars use wheel speed sensors. However, this method has significant errors when the wheels lock up or when there is a loss of traction. GPS is another option for ground speed, but it has reliability problems in places without good signal, like tunnels or between tall buildings. Also, Lidar sensors or ultrasonic sensors can be used but they are not reliable in practice [1], [2]. To fix these problems, this research investigates using a vehicle-mounted Doppler radar to estimate the true Speed-Over-Ground (SOG). This application is mainly for limited-series sport vehicles, because track performance needs data that does not have errors from wheel slip. When the car needs to do good cornering in the track, vehicle itself should understand if the car is losing control or not, or to have better down force to use the spoiler efficiently, vehicle itself should know the speed precisely. Also, for high-speed cars, seconds are important so it should be fast measuring.

The main part of this study focuses on the signal processing of the reflected radar waves. We focus on estimating the Doppler signal spectrum by calculating the Power Spectral Density (PSD) to find the main frequency peak and using a modern analysis that compares the measured spectrum with theoretical models. In the end, this work aims to show that Doppler radar is a good alternative for traction control in high-speed vehicles.

1.2 Description Of The Problem

Vehicle speed is an important variable for modern safety systems like ABS and traction control, but the current ways we measure it have big limitations. Standard cars use wheel speed sensors, which give wrong data if the wheels lock up or lose traction, like when drifting or driving on ice. GPS is another option, but it is not reliable in tunnels or areas where the satellite signal gets blocked. To fix these issues, this project looks at using a Doppler radar mounted on the car to measure the true SOG by bouncing waves off the road. However, the signal that comes back from the road is very noisy, so the main problem is figuring out which mathematical algorithm or strategy is best to examine the incoming signal with noise and find the speed of the high-speed vehicle since the company MAT works with high-speed vehicles.

1.3 Overview

The thesis outline is here proposed.

- Chapter 1 Introduction of the thesis states the motivation for the usage of the Doppler radar to find the speed of high-speed vehicles following with the introduction theory about Doppler, and description of the problem.

- Chapter 2 After introducing the general background about Doppler effect general usage of the Doppler effect explained. Doppler speed measurement procedure introduced. In the final part Doppler radar IF signal reported.

- Chapter 3 Placement idea of the Doppler radar on the vehicle and the structure of the device explained.

- Chapter 4 Analysis of power spectral density methods and understanding their behavior to find vehicle speed with explaining the benefits.

- Chapter 5 Results been shown initially used by OPS243 measurements. Since it is ready-to-use product, also some simulations have been done to show how this system works.

- Chapter 6 Conclusion and future work have been done.

2. Theoretical Background

2.1 Doppler Effect

First identified in 1842 by Austrian physicist Christian Doppler, the Doppler effect is the apparent change in the frequency of a wave caused by the relative motion between the source and the observer. While this phenomenon occurs in all waves, based physical systems its application in electromagnetics is particularly valuable for instrumentation.This principle is a fundamental characteristic of wave propagation, applicable across the spectrum from acoustic waves to electromagnetic radiation. While the effect is most intuitively understood through sound-such as the sound increase (frequency compression) of an approaching object and the sound decrease (frequency expansion) as the object going away from the source. The same mechanics apply to microwaves. In engineering applications, measuring this shift in the microwave domain requires precise instrumentation to detect the subtle frequency changes caused by relative velocity. Today, this technology is common, underpinning systems in various fields. For the purpose of this research, we will harness the Doppler effect within a microwave radar framework to achieve precise vehicle speed estimation [3].

In the context of modern technology, the Doppler shift is the operating principle behind diverse systems ranging from blood flow monitoring in medical ultrasound to celestial velocity measurements in astronomy. In automotive engineering, this effect allows for the direct measurement of velocity independent of wheel rotation. By transmitting a continuous microwave signal and analyzing the frequency shift of reflection, this study utilizes Doppler radar to accurately determine vehicle SOG.

In the car technologies nowadays, they use the radar technologies a lot frequently. However, with the development of the radar systems, in cars they were using 24 GHz radar, because it was low-cost with sufficient performance. Now the industry prefers the 77 GHz more than 24 GHz because it offers better performance of resolution, range, and accuracy. In our system we will use 24 GHz because that is the radar available for us [4].

f_0 is the observed frequency
f_s is the source frequency
v is the speed of wave (speed of sound or light)
v_0 is the speed of the observer
v_S is the speed of the source [5]

If the object is approaching the top sign and if the object is departing the bottom sign will give us the information.

Table 1 The Doppler Effect [6]

Doppler shift $f_o = f_s\left(\frac{v \pm v_o}{v \mp v_s}\right)$	Stationary observer	Observer moving towards source	Observer moving away from source
Stationary source	$f_o = f_s$	$f_o = f_s\left(\frac{v+v_o}{v}\right)$	$f_o = f_s\left(\frac{v-v_o}{v}\right)$
Source moving towards observer	$f_o = f_s\left(\frac{v}{v-v_s}\right)$	$f_o = f_s\left(\frac{v+v_o}{v-v_s}\right)$	$f_o = f_s\left(\frac{v-v_o}{v-v_s}\right)$
Source moving away from observer	$f_o = f_s\left(\frac{v}{v+v_s}\right)$	$f_o = f_s\left(\frac{v+v_o}{v+v_s}\right)$	$f_o = f_s\left(\frac{v-v_o}{v+v_s}\right)$

Based on the information our Doppler frequency shift is here:

$$f_d = \Delta f = f - f_0 \quad (2.1)$$

f_0 is the frequency value before the speed changes.
f is the frequency after the speed change [7]

2.2 Doppler radar used areas

Doppler radar is a versatile technology used in any application that requires measuring the speed and direction of a moving object at a distance [8].

Many fields using Doppler effect to find the speed of the objects.
There are some applications, broken down by field:

Weather Forecasting
This is one of the most common uses. Doppler radar allows meteorologists to see *inside* storms, not just where they are.

- Storm Tracking: Measures the speed and direction of precipitation (rain, snow, hail) [9].
- Wind Speed & Direction: Measures wind velocity at different altitudes, helping to detect dangerous wind shear for aircraft [10].

Automotive and Transportation
It's crucial for modern vehicle safety.

- Adaptive Cruise Control (ACC): A forward-facing radar measures the speed of the car in front to automatically adjust your car's speed and maintain a safe following distance [11].
- Collision Avoidance Systems: Detects how fast the vehicle is approaching an obstacle (another car, a pedestrian) to provide a warning or trigger Automatic Emergency Braking (AEB).
- Ground Speed Measurement: radar pointed at the ground measures the car's *true* speed. This is more accurate than wheel sensors, especially if the tires are slipping on ice, water, or mud [12].
- Police Radar (Speed Guns): Used by law enforcement to measure the speed of individual vehicles [13].

2.3 Doppler Speed Measurement Procedure

To do proper measurements we need to place the radar where it can see the road surface clearly with and angle α. While the car is moving the radar emits waves constantly and it will give us doppler shift to find the frequency.

Figure 1 Doppler radar placement

Using Table 1 we can derive the equations:

$$f_1 = \frac{v}{v - V\cos\alpha} \times f_s \tag{2.2}$$

The frequency in Eq (2.2) is for when the wave is going to surface.

$$f_2 = \frac{v + V\cos\alpha'}{v - V\cos\alpha} \times f_s \tag{2.3}$$

This frequency in Eq (2.3) is for when the wave is reflected from the surface.

Doppler frequency equation simplified version will be [14],[15].

$$f_d = f_2 - f_0 = \frac{2V\cos\alpha}{v} \times f_s \tag{2.4}$$

v is speed of light [15]

Eq (2.4) serves as the fundamental basis for our subsequent velocity estimation.

The radiated power is Pt. The power density at a range R the release power and it is divided by the surface area is [16]

$$P_d = \frac{P_t}{4\pi R^2} \tag{2.5}$$

Power density with gain is

$$P_d = \frac{P_t G}{4\pi R^2} \tag{2.6}$$

The gain G is comparison of increase in power directed radiation and power of isotropic antenna [16].

Target surface stops some of the waves incident power which is the power directed to the surface, and it will reflect back. To measure the incident power in this situation, we have variable called radar cross section σ with units of area [16].

$$\frac{Pt}{4\pi R^2}\frac{\sigma}{4\pi R^2} \tag{2.7}$$

When the radar sends waves, it has effective area, and this area is denoted A_e. Received power of radar is [16]

$$P_r = \frac{P_t G A_e \sigma}{(4\pi)^2 R^4} \tag{2.8}$$

Using antenna theory, we can find the relationship between transmitting gain and effective area of an antenna [16]

$$G = \frac{4\pi A_e}{\lambda^2} \tag{2.9}$$

2.4 Doppler Spectrum Estimation

- The Fast Fourier Transform (FFT)

The sampling required for the digitalization of a signal determines the representation of the signal in the time domain. The time domain representation shows the amplitudes of the signal during the time it was being sampled. For many applications detailed information on the frequency components of the signal is important for a deeper understanding of the signal and the system which generates the signal. The display of the frequency components of a signal is called frequency domain representation [17].

Discrete Fourier Transform (DFT)

The Discrete Fourier transform (DFT) algorithm transforms samples of signals from the time domain into the frequency domain. The DFT is widely used in the fields of spectral analysis, applied mechanics, acoustics, medical imaging, numerical analysis, instrumentation, and telecommunications.

The DFT of a time-based signal with N samples produces a frequency range representation with also N values. If the signal is sampled with a sampling rate of f_s, the time interval between the samples is Δt [17]:

$$\Delta t = \frac{1}{f_s}$$

If the N samples are x_i with $0 \leq i \leq N-1$, the DFT is calculated with the following formula [17]:

$$x_k = \sum_{i=0}^{N-1} x_i e^{\frac{-j(2\pi ik)}{N}} \qquad k = 0,1,2,\dots,N-1 \tag{2.10}$$

The result (X_k, $0 \leq k \leq N-1$) is the frequency range representation of x_i. Analogous to the time interval Δt between the samples of x in the time domain, a frequency interval of Δf is produced between the components of X in the frequency domain [17].

$$\Delta f = \frac{f_s}{N} = \frac{1}{N\Delta t}$$

Δf is also known as the frequency resolution. To increase the frequency resolution and to thus decrease Δf, increase the number of sampling rates N with a constant value f_s or decrease the sampling rate f_s with a constant value N [17].
N samples of the input signal in the time domain equal N values in the frequency domain representation. The DFT equation illustrates that regardless of whether the input signal x_i is real or complex, X_k is complex even if the imaginary part is zero. The values amplitude and phase can also define the frequency domain representation.

Fast Fourier Transform (FFT)

The DFT calculation for N samples requires approximately N·N complex calculation operations and is a time intensive and a memory intensive calculation. If the length of the sequence is a power of 2,

$$N = 2^m, m = 1,2,3,\dots$$

the DFT can be calculated with approximately $N \cdot \log_2(N)$ operations. The algorithms for this special case are called Fast Fourier transform (FFT).
The advantages of the FFT include speed and memory efficiency. The DFT can process sequences of any size efficiently but is slower than the FFT and requires more memory, because it saves intermediate results while processing [17].

- The periodogram method

The periodogram is a common and straightforward method used in signal processing to estimate a signal's power spectral density.
In simple terms, it's a way to take a time-domain signal and see which frequencies are present and how much power each of those frequencies contains.

This method is to estimate the spectrum.

$$P_{xx}(f) = \frac{1}{N}\left|\sum_{n=0}^{N-1} x\,(n)e^{-j2\pi fn}\right|^2 = \frac{1}{n}|X(f)|^2 \tag{2.11}$$

Hence the periodogram is not a consistent estimate of the true power density spectrum that is it does not converge to the true power density spectrum. Basically, the frequency spectrum resolution is not high enough because variance does not converge to zero. Several other methods have been shown in the following parts [18].

- The Bartlett Method

Bartlett's method is another technique for estimating a signal's power spectral density, just like the periodogram. Its main purpose is to improve upon the basic periodogram by reducing its variance (noise) [19].

So Barlett's method reduces the variance in the periodogram. It consists of three steps: First, the N-point sequence is subdivided into K nonoverlapping segments, where each segment has length M.

$$x_i = x(n + iM) \qquad i = 0,1,\dots,K-1$$
$$n = 0,1,\dots,M-1$$

Then compute the periodogram

$$P_{xx}^{(i)}(f) = \frac{1}{M}\left|\sum_{n=0}^{M-1} x_i\,(n)e^{-j2\pi fn}\right|^2 \qquad i = 0,1,\dots,K-1 \tag{2.12}$$

Last, we average the periodogram for the K segments to obtain the Barlett estimate

$$P_{xx}^{B}(f) = \frac{1}{K}\sum_{i=0}^{K-1} P_{xx}^{(i)}(f) \tag{2.13}$$

In this method with respect to the periodogram, Bartlett’s method reduces the variance of the Bartlett power spectrum estimate by factor K [18].

- The Welch Method

Let's assume we have a long source signal that we want to analyze.
Segment with Overlap: The total signal is divided into multiple segments. Unlike Bartlett's method, Welch's method overlaps these segments. A 50% overlap is very common [18]
Window: A window function is applied to each segment. A window function tapers the signal down to zero at its edges. This step is crucial for reducing spectral leakage, which is where a strong signal "leaks" its power into neighboring frequency bins, hiding weaker signals.
Periodogram: The periodogram is calculated for each windowed segment. (This is done by taking the FFT of the segment and then finding the squared magnitude of the result).
Average: All these individual periodograms are averaged together.

This final average spectrum is the Welch estimate [20].

The Welch method made two basic modifications to the Bartlett method. For the first, it allowed the segments to overlap and for the second modification is to window the data segments prior to computing the periodogram.

$$\bar{P}_{xx}^{(i)}(f) = \frac{1}{MU}\left|\sum_{n=0}^{M-1} x_i(n)\omega(n)e^{-j2\pi fn}\right|^2 \qquad i = 0,1,\dots,L-1 \tag{2.14}$$

U is normalization factor for the power in the window function [18], [21].

$$U = \frac{1}{M}\sum_{n=0}^{M-1} \omega^2(n) \tag{2.15}$$

The Welch power spectrum estimate is the average of these modified periodograms,

$$P_{xx}^{W}(f) = \frac{1}{L}\sum_{i=0}^{L-1} \tilde{P}_{xx}^{i}(f) \tag{2.16}$$

The Welch method is an improvement on the Bartlett method for figuring out the power of different frequencies in a signal. The main difference is how it uses a window to smooth the data. The Welch method applies this window to each small piece of the signal first, before doing the main calculation. This, combined with overlapping the pieces of data, makes much better use of the entire signal. Because all the data is used more fully, you can get a good result even with a smaller amount of data. This process is much better at reducing noise, giving you a final graph that is smoother and more reliable [18].

These methods are simple and easy to use the FFT. However, these methods require the availability of long data records in order to obtain the necessary frequency resolution required in many applications. Furthermore, these methods suffer from spectral leakage effects, due to windowing, that are inherent in finite-length data records. Often, the spectral leakage masks weak signals that are present in the data.
In effect, the modeling approach eliminates the need for window functions and the assumption that the autocorrelation sequence is zero. As a result, model-based power spectrum estimation methods avoid the problem of the leakage and provide better frequency resolution than do the FFT-based. This is especially true in applications where short data records are available due to time-variant or transient phenomena [18].

- AR model

An AR (Autoregressive) model is a parametric method for spectral estimation. Unlike methods that analyze the signal directly (like the Periodogram or Welch's method), the AR model takes a different approach. It assumes that your signal can be "modeled" or "predicted" as a linear combination of its own past values, plus a white noise input. The core idea is to find a set of model parameters (coefficients) that best describe this relationship [22].

- MA model

As a general rule, required many more coefficients to represent a narrow spectrum. Consequently, it is rarely used by itself as a model for spectrum estimation. By combining poles and zeros, the ARMA model provides a more efficient representation, from the viewpoint of the number of model parameters, of the spectrum of a random process [22]. Equation 2.17 and 2.18 shown [18].

$$H(z) = \frac{B(z)}{A(z)} = \frac{\sum_{k=0}^{q} b_k z^{-k}}{1 + \sum_{k=1}^{p} a_k z^{-k}} \tag{2.17}$$

$$x(n) = -\sum_{k=1}^{p} a_k x(n-k) + \sum_{k=0}^{q} b_k w(n-k) \tag{2.18}$$

In the model-based approach, the spectrum estimation procedure consists of two steps. Given the data sequence x(n), we estimate the parameters $[a_k]$ and $[b_k]$ of the model. Then from these estimates, we compute the power spectrum estimate according to this in equation 2.19 [18].

$$\Gamma_{xx}(f) = \sigma_\omega^2 |H(f)|^2 = \sigma_\omega^2 \frac{|B(f)|^2}{|A(f)|^2} \tag{2.19}$$

The random process x(n) generated by the pole-zero model is called an autoregressive-moving average (ARMA) process of order (p, q) and it is usually denoted as ARMA (p, q). If q=0 and $b_0 = 1$, the resulting system model has a system function H(z) = 1/A(z) and its output x(n) is called an autoregressive (AR) process of order p. This is denoted as AR(p). The third possible model is obtained by setting A(z) = 1, so that H(z) = B(z). Its output x(n) is called a moving average (MA) process of order q and denoted as MA(q) [18].

2.5 Doppler Radar IF signal

Doppler radar transmits an unmodulated and continuous signal of frequency f. That signal transmits and reflects from the surface, this signal is compared to the signal that we normally transmit. When the surface seems to be moving from the radar view, the signal will be shifted as we explained in figure 1. Therefore, the incoming signal is divided into two pieces. One of them is the one we transmit, and the other one is reference signal. In the system mixer and compare the signals, and it gives us IF signal. The signal will contain $f_0 \pm f_d$. f_0 is transmitting frequency and the shift is $\pm f_d$. The sign meaning explained in figure 1 as well [16].

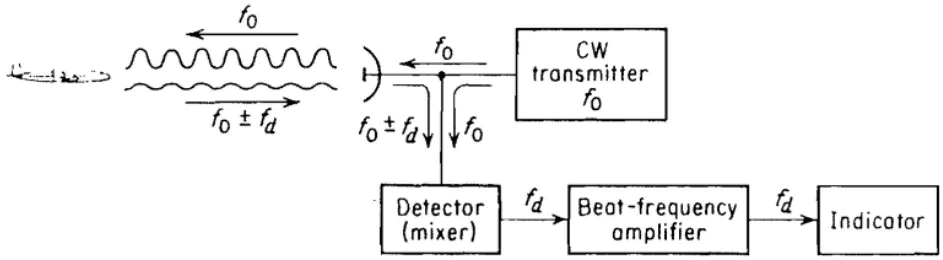

Figure 2 Simple Radar Block Diagram [16]

3. Placement and Structure of Doppler Radar on the Vehicle

This chapter investigates the Power Spectral Density estimation techniques most applicable to our system, incorporating the Doppler frequency formulation derived in the preceding section.

3.1 Our radar example

According to the data sheet of the doppler radar OPS243, the detection range of the OPS243 covers a narrow 20° azimuth (horizontal) and 24° altitude (vertical) beam width (measured at -3dB point).

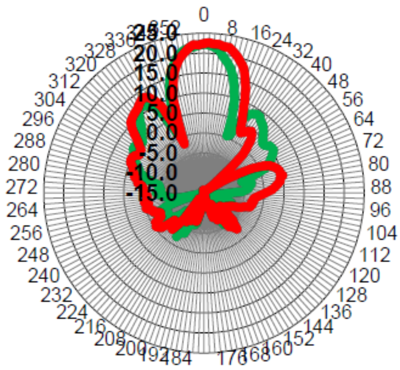

Figure 3 Antenna Pattern

We will put our radar module to a vehicle 45 degree because this angle is the optimum [15].

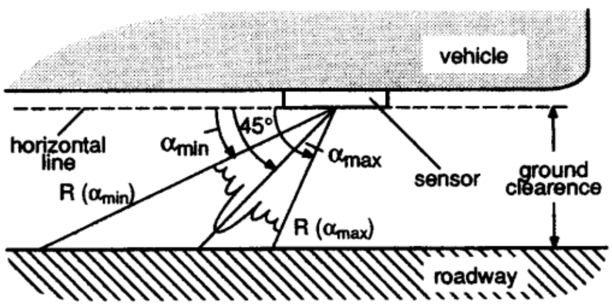

Figure 4 Vehicle and road [4]

The idea is that we will receive our signal respect to the road surface. Then we apply our algorithm to AR and the others to see the difference. Our OPS243 doppler radar already has FFT algorithms inside. Mainly we are calculating the doppler frequency which is proportional to the speed.

Our radar will be positioned on the vehicle. It will be fixed and tilted to 45 degrees. The radar radiation area is the area from the reflected waves. Outside of this area there are more waves, however those waves are relatively weak compared with the main signal area. The shape of the area is not important because the actual idea is to measure the reflected power from the road surface. In the geometrical illustration we can see the placement of the radar in coordinate system.

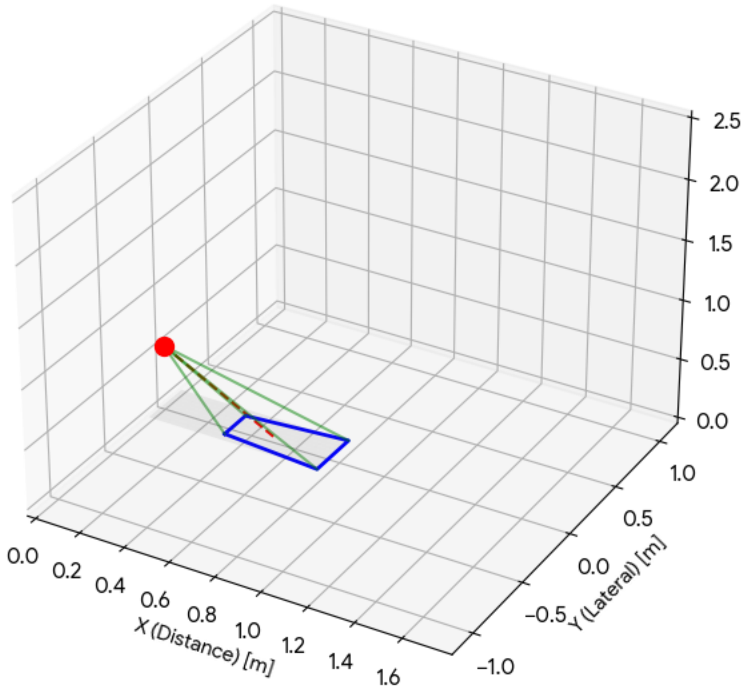

Figure 5 Illustration of radar

To accurately quantify the radiation area, we employ a discretization method based on integral calculus. The surface shape where our radar is emitting waves, allowing us to calculate the specific reflected power and Doppler frequency shift for each individual cell. By summing these contributions, we derive the total reflected power spectrum with respect to frequency. For the simulation parameters, the radar is positioned at a height of 0.5 meters [23].

3.2 Doppler Frequency and Reflected Power

Our radar specifications are

- Narrow 20 degree (horizontal) or 24 degree (vertical) beam width (-3 dB)
- 24 GHz millimeter wave
- Transmit Power 11 dBm (12.59 mW)

Here after the simulation, we can see the doppler frequency and the reflected power.

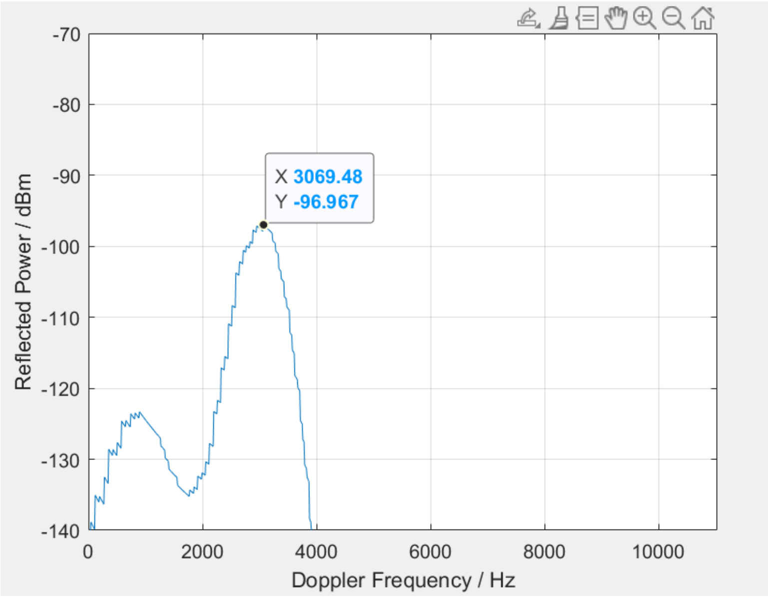

Figure 6 The Doppler frequency and the reflected power. Test speed is 100 km/h

As we see in the calculation a. as well, the peak point is around Doppler frequency.

As illustrated in Figure 10, maximum value is 3069 Hz for Doppler Frequency. Using Doppler Frequency formula we can observe the similar values. This is similar because the antenna beam has width. The power is not distributed evenly, center of gravity of the return power is slightly shifted from the geometric center (45 degree) due to the $1\ /\ R^4$ loss (the bottom of the beam is closer to the ground than the top) [16].

a. $((2 * (100/3.6) * \cos(\alpha))/c) * f = 3144$ Hz.

$f = 24\ GHz\ (device\ frequency)$
$\alpha = 45\ degree$
$c =\ 3 \times 10^8\ m/s$ (speed of light)
100/3.6 to convert km/h to m/s

As demonstrated in the following plots, the Doppler frequency scales positively with velocity; higher speeds result in a visibly larger frequency shift within the spectrum.

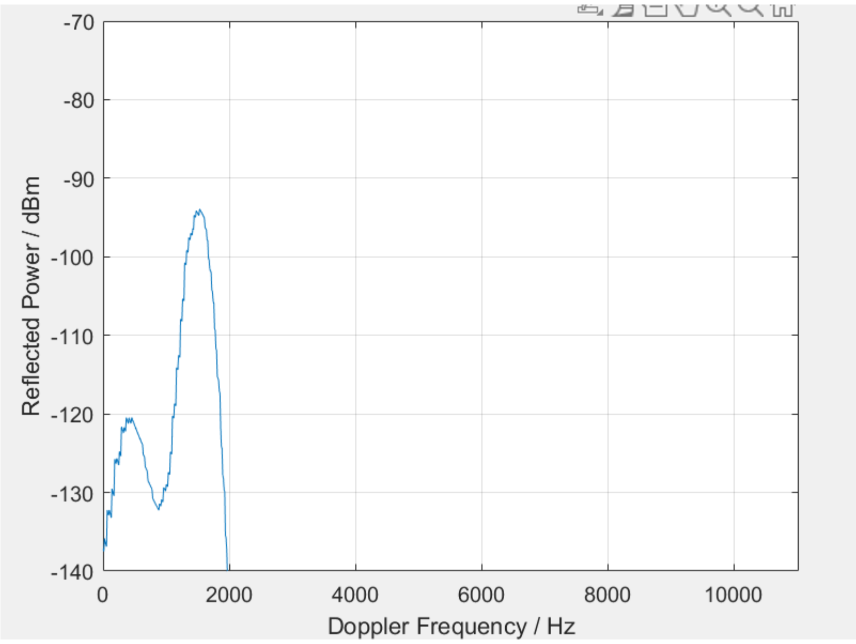

Figure 7 Speed 50 km/h

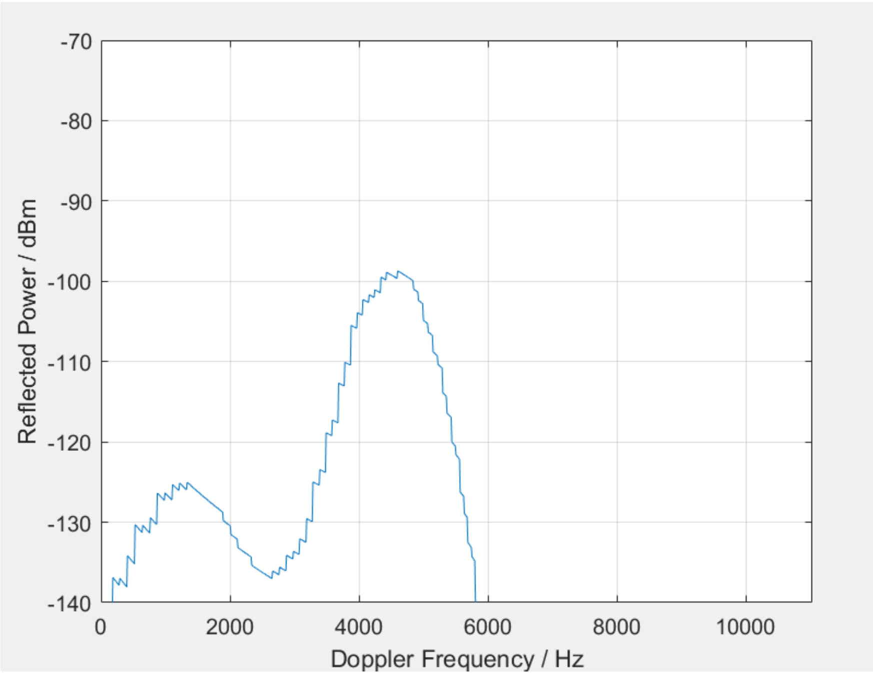

Figure 8 Speed 150 km/h

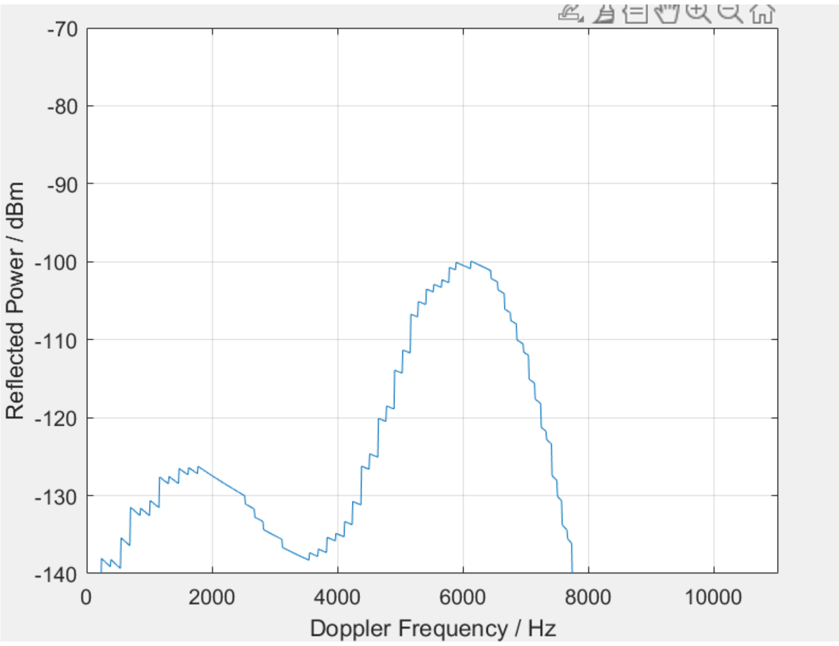

Figure 9 Speed 200 km/h

4. Analysis

4.1 Simulations without noise

Our radar signal is ideal so there is no noise signal. We will do tests without noise initially in equation 3.1 [24].

$$x_{IF}(t) = A.\sin(2\pi f_d t + \varphi) \qquad (3.1)$$

A: amplitude

Amplitude of the signal is square root of reflected power. A is $\sqrt{P_r}$ ($P \propto V^2$).

First simulation will show us the comparison between FFT, Periodogram, Barlett Method, and Welch Method.

Doppler frequency equation

$$f_d = \frac{2V\cos\alpha}{v} \times f_s$$

To validate the calculation model, we assume a reference velocity of 10 m/s. Applying the derived Doppler equation, this velocity yields a theoretical frequency shift of 1132 Hz. To ensure signal fidelity and prevent aliasing, the system's sampling rate is configured to strictly adhere to the Nyquist-Shannon sampling theorem ($f_s \geq 2f_{max}$). As we can see in the resulting spectrum, the magnitude peak matching with the calculated value.

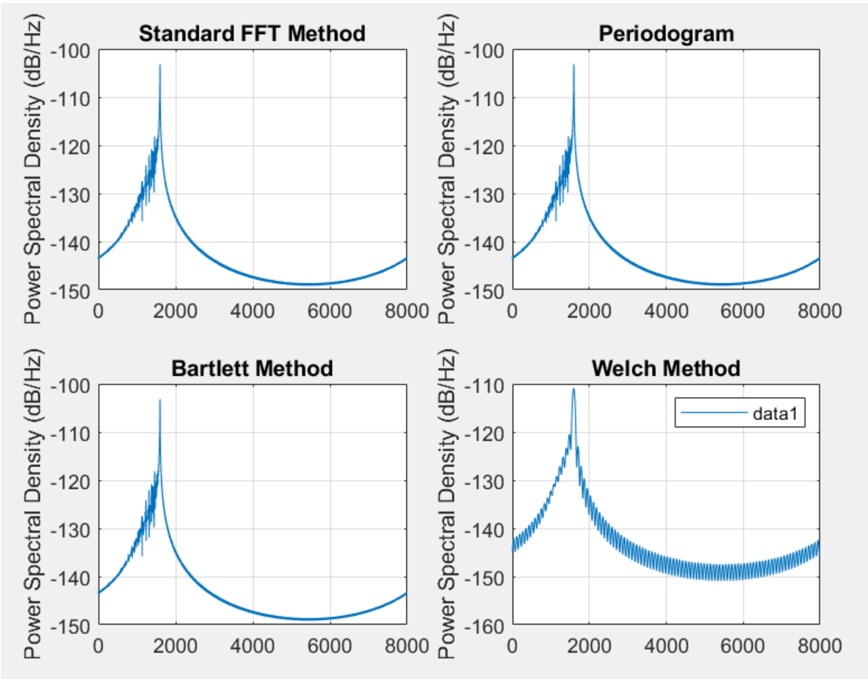

Figure 10 PSD Estimation comparison

As we talk in the literature part the core problem the Welch method solves is the high variance and unreliable nature of the basic Periodogram (a simple Fourier transform of the entire signal to estimate power spectral density).

The Welch method uses averaging by splitting the signal into multiple with overlapping and segmenting them and average their periodograms. Also, it does window function to smooth the signal.

The most critical reason for using a window is to control spectral leakage. Spectral leakage is when you take a finite-length segment of a signal (which is what each Welch segment is), you are effectively multiplying the infinite signal with a rectangular window [25].

- In the frequency domain, this multiplication becomes a convolution.
- The Fourier Transform of a rectangular window is the sinc function (a central lobe with side lobes).
- Convolving the true signal's spectrum with this sinc function leaks power from one frequency bin into all the others.

A rectangular window is like a sharp, clean keyhole. It gives a precise view but creates strong diffraction patterns (leakage) around the edges, distorting the waves [26].

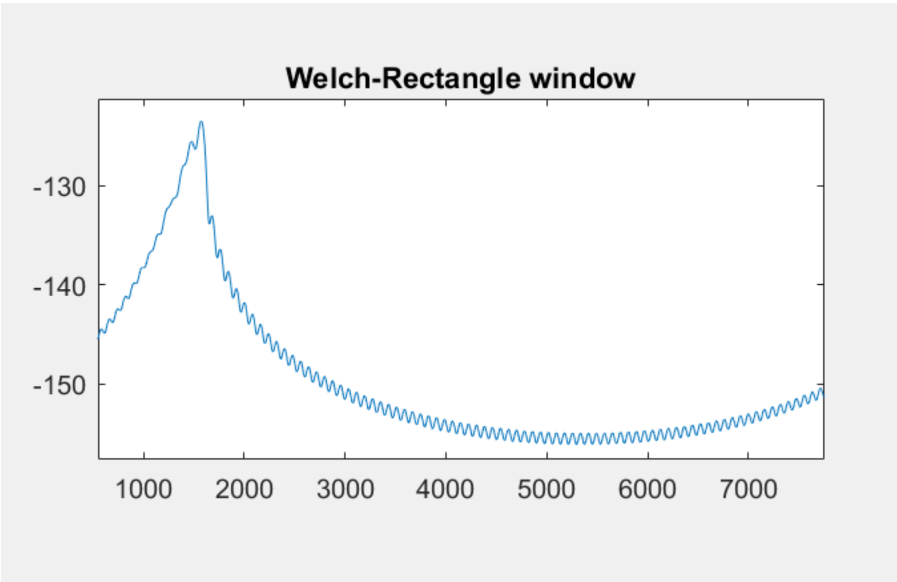

Figure 11 Welch Rectangle window

AR model

As we set the velocity is 10 m/s and Doppler frequency is 1132 Hz.

In AR model our p value is the order. When we increase the order, we gain some advantages but if we apply too many orders there will be disadvantages as well.

Advantages: It is increasing flexibility and details. A higher-order model has more parameters. This allows it to capture more complex patterns, more details, and longer-lasting oscillations in the data. It is better fit to the training data with more parameters, so the model can reshape itself to fit the observed data points more closely. Also, the errors will generally decrease. In the frequency domain, a higher p allows the AR-model-based Power Spectral Density to have more and sharper peaks, potentially resolving closely spaced frequencies [18], [27].

Disadvantages: There can be overfitting. This is the biggest risk. The model starts fitting not only the underlying signal but also the random noise in the training data. Another point can be Spurious Peaks can appear in the spectrum. In the PSD estimate, overfitting often displays many small, sharp peaks that do not correspond to any real periodic component in the signal. They are remaining parts of modeling noise. Computational costs will increase. Estimating more parameters requires more computation [18], [27].

We use Yule-Walker equations because they provide a direct mathematical link between the model parameters and the functions [22].

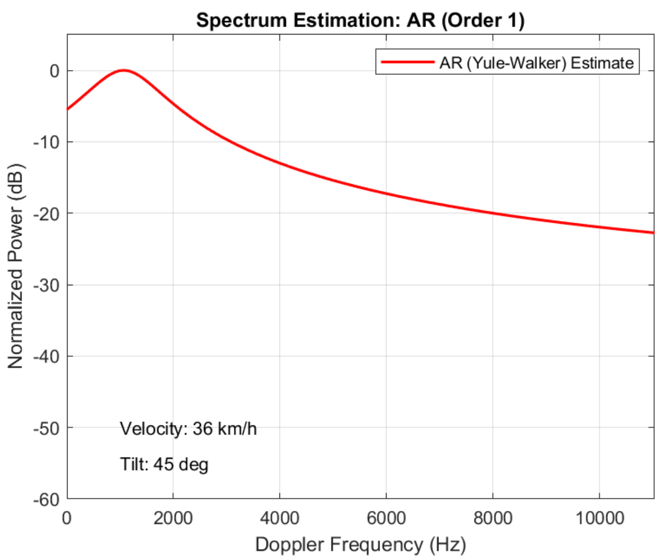

Figure 12 AR Power Spectral Density - speed 10m/s - AR p order 1

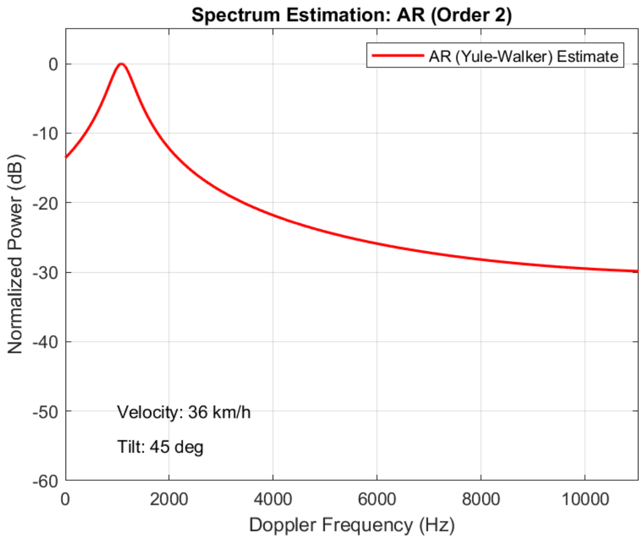

Figure 13 AR Power Spectral Density - speed 10m/s - AR p order 2

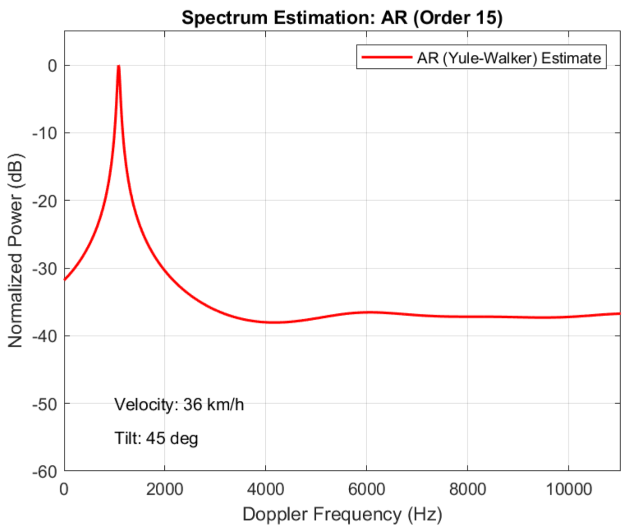

Figure 14 AR Power Spectral Density - speed 10m/s - AR p order 15

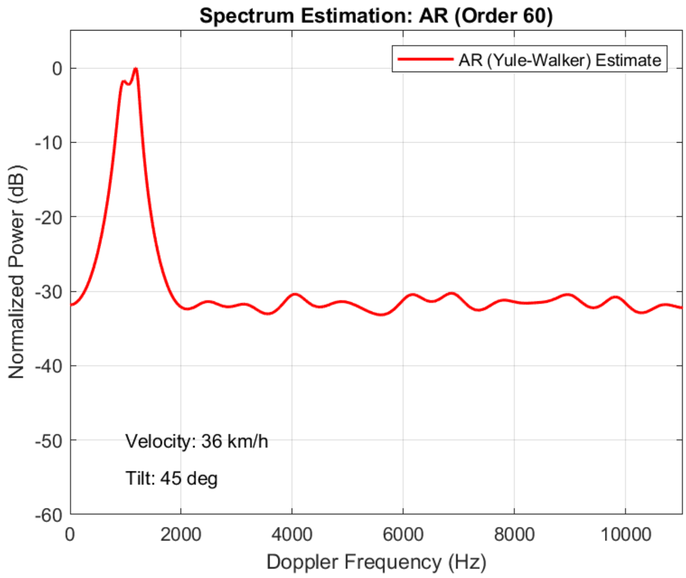

Figure 15 AR Power Spectral Density - speed 10m/s - AR p order 60

As we can see, when we increase the order too much, we start to create noise in our signal. If we increase the order enough, we can have precise results however, if we increase too much, we can have high variance.

4.2 Simulation with noise

To make our experiment more realistic, we can add gaussian white noise and SNR.

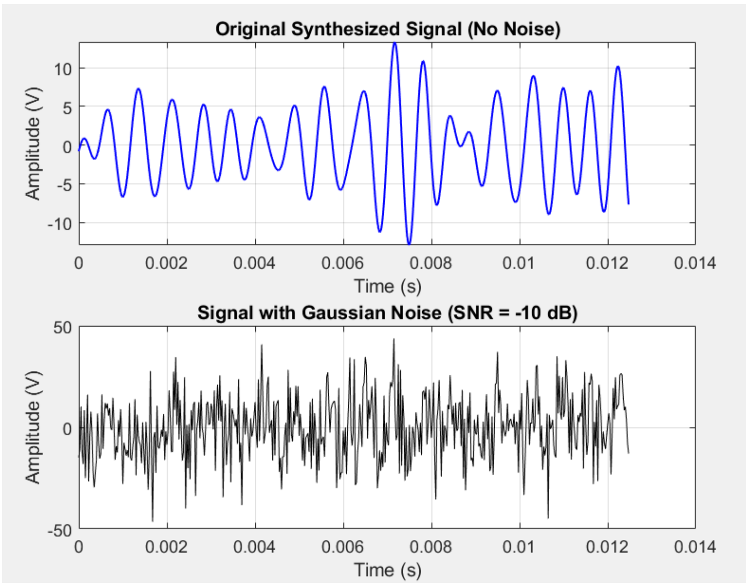

Figure 16 Original signal vs Signal with noise

As an example, we choose our SNR value -10 dB.

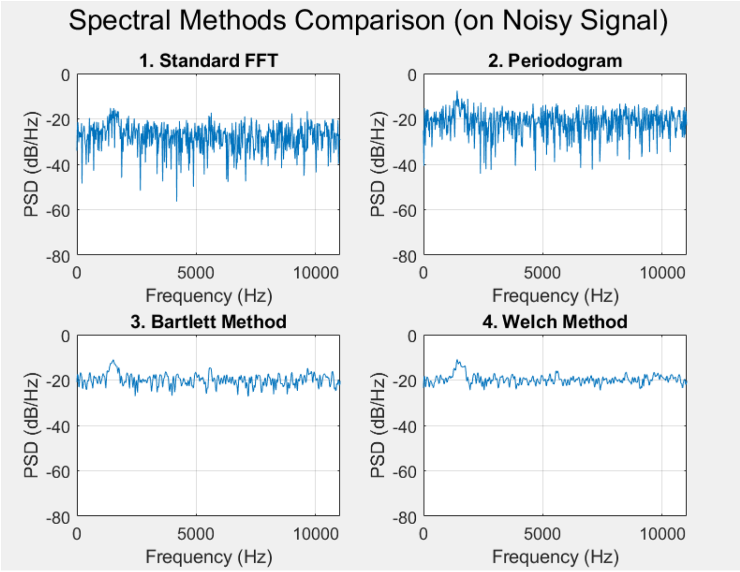

Figure 17 PSD comparison with noise SNR -10 dB

SNR -20db

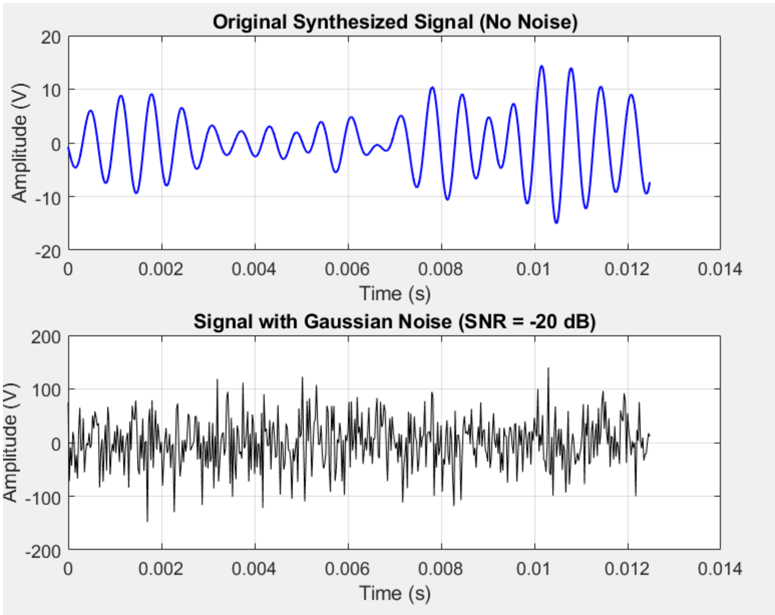

Figure 18 Original signal vs Signal with noise

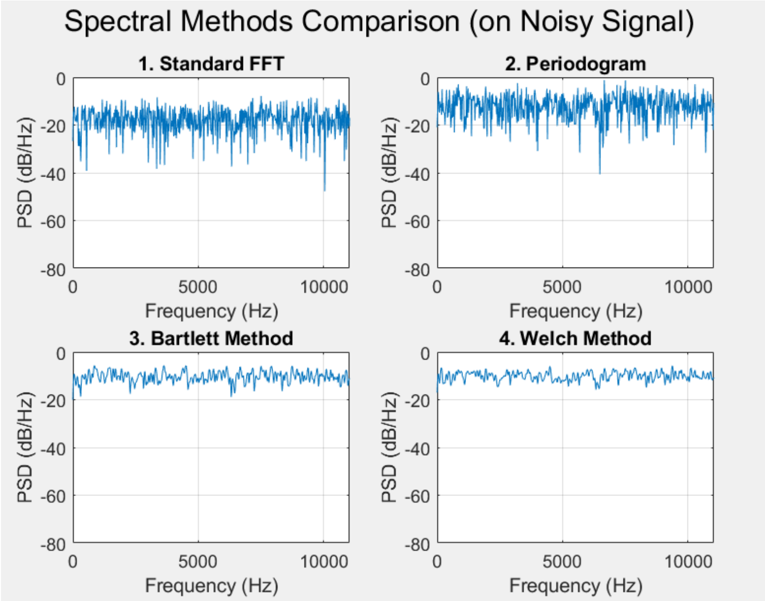

Figure 19 PSD comparison with noise SNR -20 dB

When we use those methods, we can clearly see that increasing SNR has bad impact on our results. As we know from the theory part, Welch method is still handling well compared to other methods.

AR model with noise

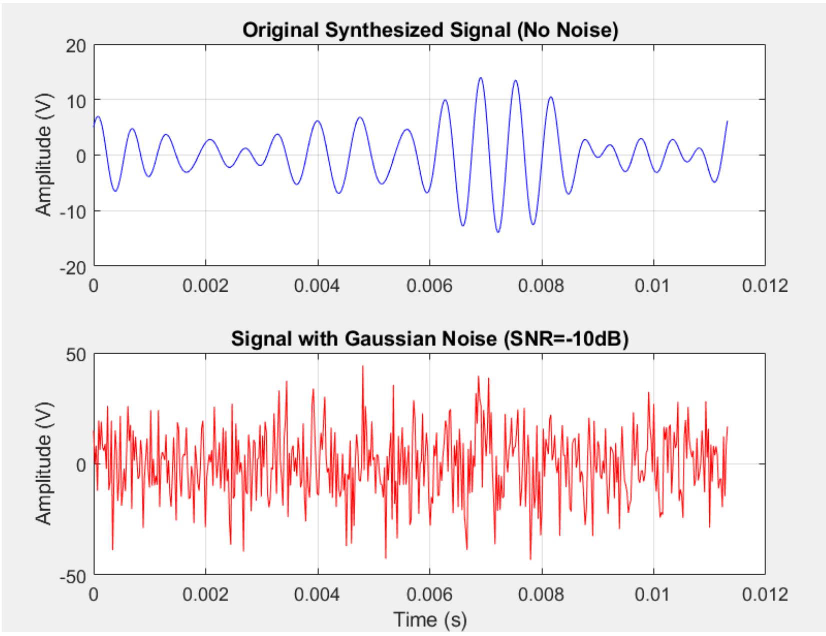

Figure 20 Original signal vs Signal with noise for AR model SNR= -10dB

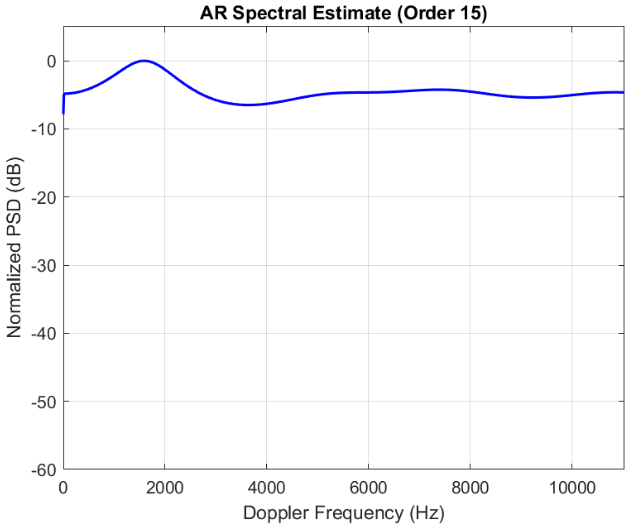

Figure 21 AR Power Spectral Density - speed 10m/s - AR p order 10 with noise

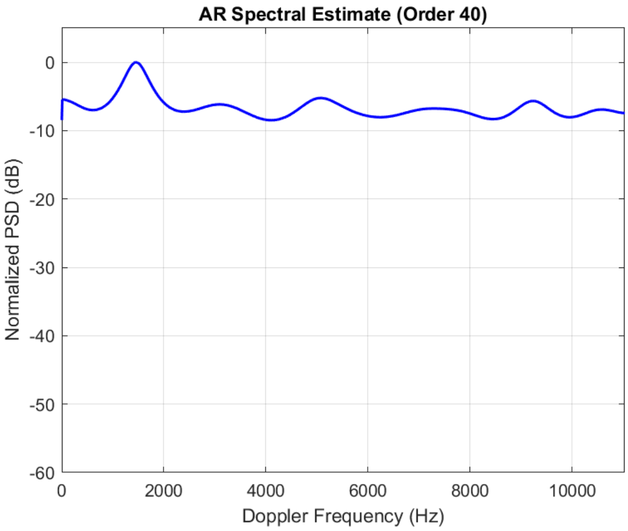

Figure 22 AR Power Spectral Density - speed 10m/s - AR p order 40 with noise

AR model can result in good shape for power spectrum estimation. The Welch methods with rectangular window function is better than the other classical methods. The other methods direct FFT, the periodogram, and the Bartlett do not perform as well as the modern PSD estimation methods, they are simple to understand and implement, and so they are widely used.

5. Results

In the end to see some real results we can test our device. Our device is OPS243 Doppler Radar Sensor. All the radar signal processing is done on board, and a simple API reports the processed data [28].

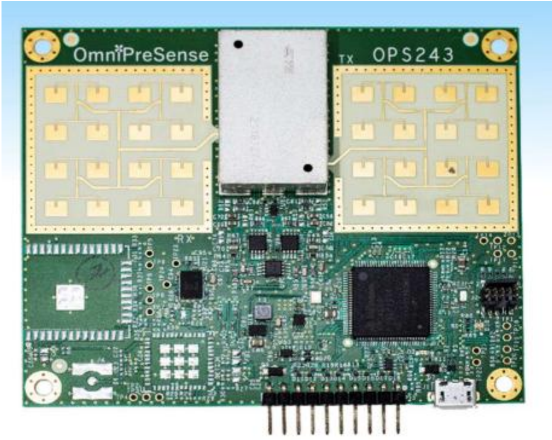

Figure 23 OPS 243 Doppler Radar Sensor

The block diagram of the OPS 243 is shown in Figure 1. The key components shown are the antenna, 24GHz RF, processor, and interfaces (USB, RS-232, WiFi/Bluetooth).

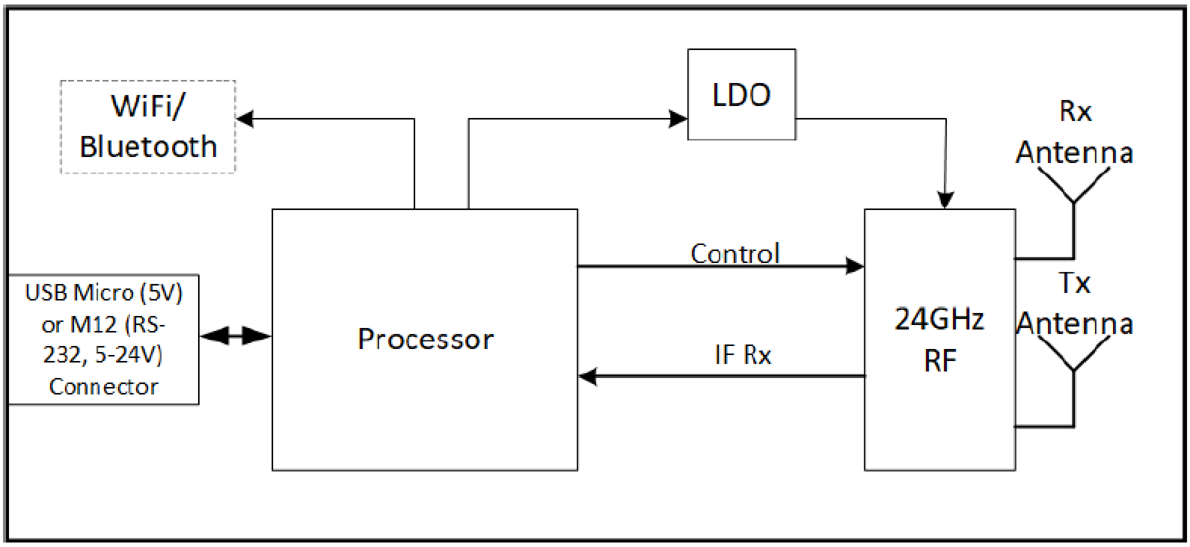

Figure 24 OPS 243 Block Diagram [28]

```
RAW: {"unit":"kmph", "magnitude":"20", "speed":"-9"}
Parsing JSON data...
 RADAR DETECTION
──────────────────

Speed: 9.00 kmph
Status: MOVING

RAW: {"unit":"kmph", "magnitude":"25", "speed":"7"}
Parsing JSON data...
 RADAR DETECTION
──────────────────

Speed: 7.00 kmph
Status: MOVING

RAW: {"unit":"kmph", "magnitude":"67", "speed":"14"}
Parsing JSON data...
 RADAR DETECTION
```

Figure 25 OPS 243 live measurements

As the results show, the device is capable of detecting both the speed and the direction of travel, which indicates simply using a positive or negative sign. One of the main advantages of this unit is that it is self-contained; all the necessary calculations happen directly inside the device.

Basically, the idea is behind that the sensor mixes the signal it transmits with the reflected signal it receives. This comparison creates a frequency value which is Doppler frequency that is directly related to how fast the object is moving. It follows the standard Doppler rule: if an object is approaching, it is increasing the frequency, and if it is retreating, it is decreasing the frequency. An onboard ARM processor handles the process by running FFT algorithms to analyze these shifts and determine if the target is inbound or outbound.

To see this process in simulation environment we can use example audio file containing raw data from a Doppler radar sensor. We use audio file because it contain the sound waves suitable for our purpose. After applying filter, we can analyze the frequency content to find the Doppler values and convert to speed. The test has been done in Matlab [29], [30].

Loading and filtering

```
[x,fs]=audioread(fname);

fc = 200;

B= fir1(100,fc*2/fs,'high');

xfilt = filter(B,A,x);
```

FIR filter applied to the input. We cut the frequencies below 200 Hz because Doppler radar signals often have a lot of low-frequency or noise that doesn't represent the moving car. This filter isolates the higher frequencies caused by the car's movement [31].

Spectral Analysis part

Here first we applied Welch method.

pwelch function estimates the Power Spectral Density using Welch's method. It converts the time-domain signal into the frequency domain. It tells us which frequencies are strongest at that moment [32].

```
Pxx = pwelch(xfilt(i:i+N),hamming(M),D,M,fs);

[m, index] = max(Pxx);

fspeed = (index / M) * fs;
```

Converting the frequency to speed

```
v(j) = (fspeed*3e8)/(2*24e9*cos(pi/4)) * 3.6;
```

This equation is already explained in chapter 2. This is derived from doppler frequency equation.

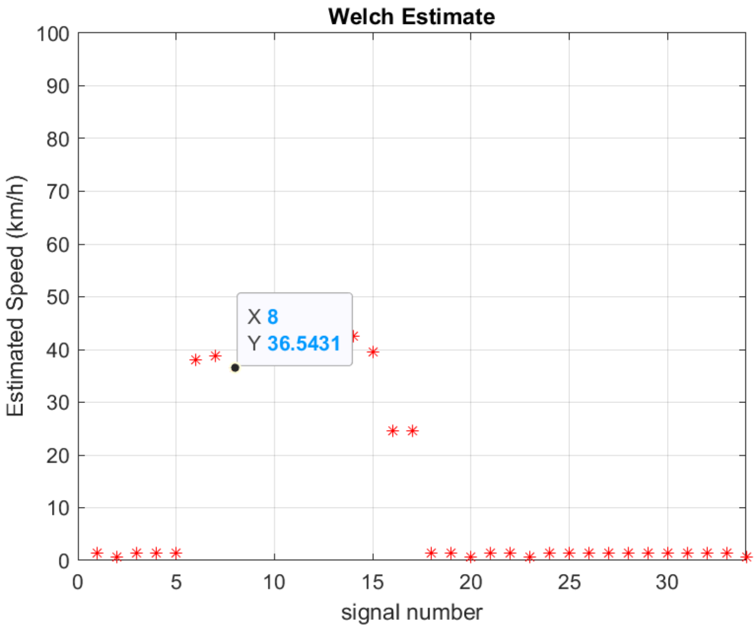

Figure 26 Incoming Doppler audio file converted to speed with Welch method

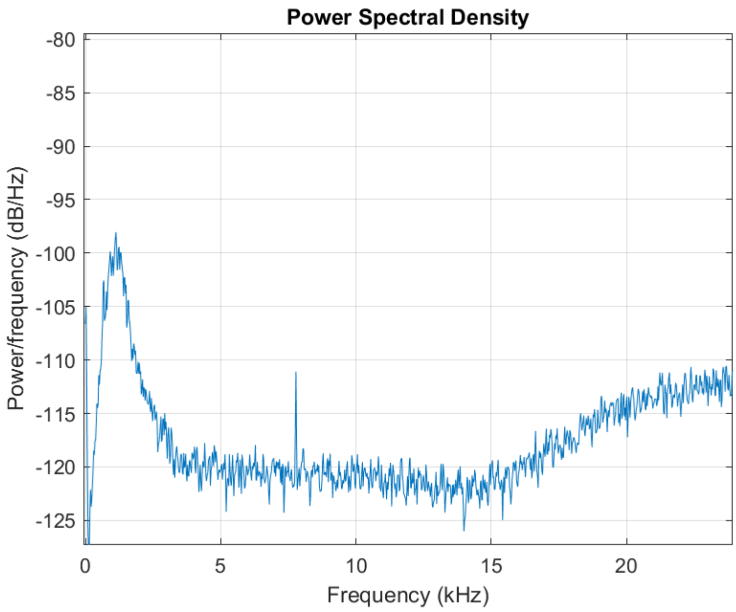

Figure 27 Power Spectral Density from Welch method

To make some comparison we will try another method which is FFT-based Periodogram method.

FFT and PSD application [33]

```
xdft = fft(x_seg);

xdft = xdft(1:L/2+1);

psdx = (1/(fs*L)) * abs(xdft).^2;

psdx(2:end-1) = 2*psdx(2:end-1);
```

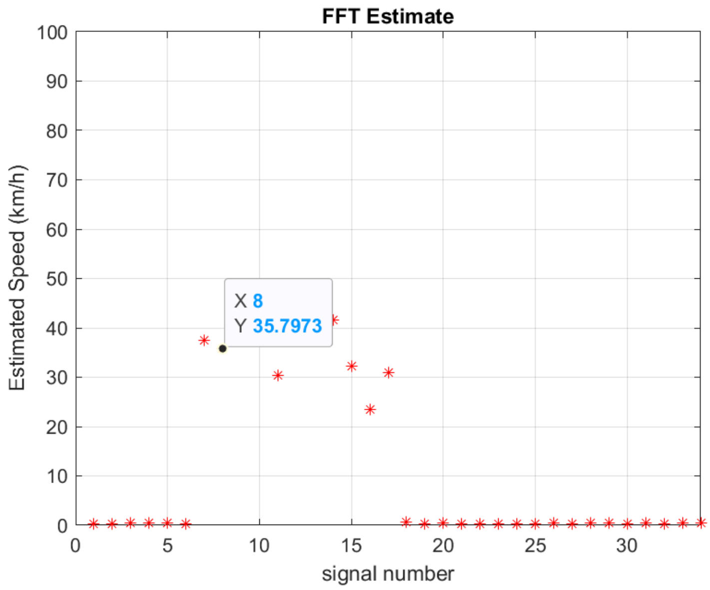

Figure 28 Incoming Doppler audio file converted to speed with FFT periodogram method

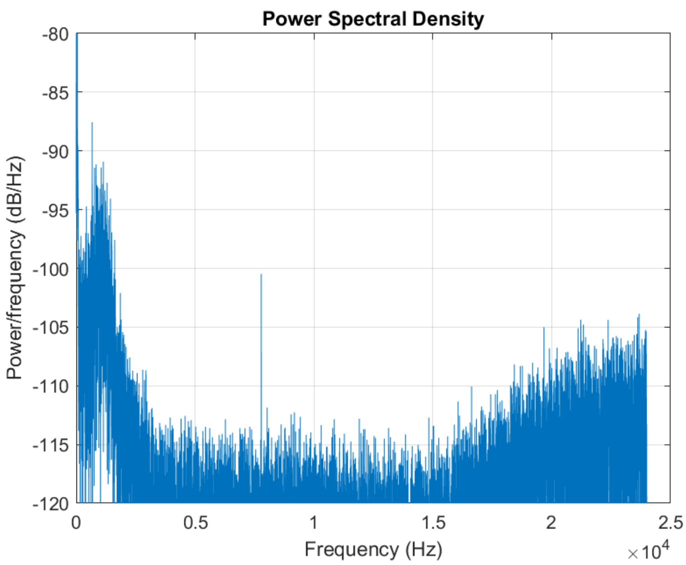

Figure 29 Power Spectral Density from FFT Periodogram method

Speed comparison table

	Welch	FFT Periodogram
Speed (km/h)	36.54	35.79

FFT Periodogram method calculates the Periodogram on the full segment. The resulting speed plot is highly noisy. Because the raw Periodogram is not a consistent estimator, the variance does not decrease even with more data points. The peak detection jumps too much between adjacent frequency bins due to noise spikes, and this creates a scattered plot of speed over time. However, it offers very fine frequency resolution, potentially capturing subtle speed shifts if the signal-to-noise ratio were perfect.

Welch method takes the average of multiple periodograms. Therefore, the speed plot is much cleaner. Doing averaging in Welch's method, it reduces the noise variance and makes it stronger against random signal fluctuations. The trade-off is lower frequency resolution, which means the speed estimate might look like a step rather than continuous, but it tracks better the Doppler effect.

6. Conclusion and future work

6.1 Conclusion

The goal of this project was to study how Doppler radar can be used for precise speed estimation. To do this, we first established the physical principles of the Doppler effect and derived the frequency equation that acts as the foundation for measuring speed.

The research is mainly signal processing. We evaluated several PSD estimation techniques to optimize how we handle the signal and how the common PSD techniques are working well in our speed measurement case. They are explained with literature background. We placed the sensor for our simulation environment 45-degree angle looking to the surface from a certain height. Through simulations, we compare these algorithms to see their working principle and compare them with our case to see compatibility. Finally, in the result section OPS243 radar sensor has been shown. This sensor is provided by the company MAT. This hardware contains all the components for our speed measurements. The components are Doppler radar, ARM M4 chip and building Wi-Fi/BT. In that section we used this hardware to see real simulations to understand how the system should be working fast to adapt our car speed. After that we did simulations using raw Doppler radar audio file to run simulations. Basically, with these simulations we understand the device.

6.2 Future works

To improve the algorithms and the speed range, better antenna can be used. Antenna specs are important because they can give better range to analyze and more strong waves. All the used algorithms are important for speed calculation, but it takes time to calculate since they are estimation based. To improve the speed algorithms can be written in more efficient way. By running some real tests, we can understand which algorithm is useful and easy to adapt for the purpose of finding speed of vehicle.

To achieve real-time work, the selected algorithms must be optimized for automotive-grade microcontrollers. To have more efficient way of algorithms it is important that adapting the algorithms to more compact and efficient programming language compatible with car ECU. In this simulation level we used OPS243 module operating at 24 GHz. Moving to the higher frequency for automotive radar band would allow for smaller antennas and higher Doppler frequency shifts for the same velocity, theoretically it can improve velocity resolution.
Additionally, using phased array antenna to change the area of the wave can be improved. This would allow the system to work more efficiently, because the road surfaces and the car will not be stabilized. Road surfaces can be in different shape, and car can bounce at high speed, so adapting the antenna for the environment will give us better results.

Using this research converting the Doppler radar-based simulation approach to reliable device can be compatible with high-speed cars to increase their performance and their safety.

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