OPERATIONAL CONDITIONS OF CONTINUOUS WAVE DOPPLER RADAR DEVICES FOR ACCURATE VEHICLE SPEED MEASUREMENT IN TRAFFIC MANAGEMENT

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ABSTRACT

Doppler radar technology plays a crucial role in vehicle speed measurement and enforcement, making it an integral part of transportation and traffic management systems. This study investigates the limitations of continuous wave (CW) Doppler radar technology, with a specific focus on practical implications within the transport industry. While CW Doppler radar is a valuable tool, its optimal performance is contingent on specific conditions. This research demonstrates real-world limitations which can influence the accuracy of speed measurements. The findings underscore the necessity for stricter operational guidelines to address these limitations in less-than-ideal conditions. A comprehensive understanding of Doppler radar behaviour, coupled with improved operating protocols, can enhance its effectiveness in real-world traffic scenarios. The findings aid in advocating for the establishment of enhanced operational standards for Doppler radars in vehicle speed measurement and enforcement. By addressing the limitations and proposing practical solutions, the transport industry can optimise the use of Doppler radar technology for more accurate and reliable traffic management. This paper aims to provide a comprehensive perspective that benefits both industry professionals and government officials, bridging the gap between engineering aspects and practical implications in the transportation and traffic management sectors.

1. INTRODUCTION

1.1 Background

Doppler radars were invented in the second world war, by John L. Barker Sr. and Ben Midlock (Stacy, no date). The Doppler effect is defined as the change in frequency of a wave to an observer who is moving at a relative speed compared to the source of the wave. The Doppler frequency shift is the fundamental concept used in a Continuous-Wave (CW) Doppler Radar. A CW radar transmits a non-changing finite frequency. If a target is R distance away from the radar, the total distance the wave will travel to the target and back is $2R$. A Doppler radar is a common method used for vehicle speed measurement. It is capable of measuring a vehicle’s speed through the Doppler effect (Jakus & Coe, 1975). In 1979, the CSIR conducted an independent case study on the validity of Doppler radar for vehicle speed measurement (van der Riet, 1979). The case study reported several limitations in vehicle speed measurement, but most importantly the limitation that posed the greatest drawback was identifying which vehicle was supplying the speed measurement. A 2013 study on the various methods for vehicle speed measurements (Adnan et al., 2013) found that Doppler radars are subject to disturbance from other vehicles in different lanes. The radar is unable to determine if more than one vehicle is being measured. These limitations give rise to the question, *how does a Doppler radar know which vehicle is measured*? This responsibility used to be on traffic officers who operated the radar guns. But with the evolution of speed measurement systems to include the use of a camera for automatic capturing of the number plate of speeding vehicles (Sato, 1994), the identification of vehicles is now entirely reliant on the radar.

Doppler radars, for speed measurement, can be categorised into two main types: CW Doppler radars with horn antennas, which use continuous wave signals for Doppler measurements, and Frequency-Modulated Continuous Wave (FMCW) Doppler radars with antenna arrays (MIMO Antenna), employing frequency-modulated continuous wave signals for enhanced range resolution and target discrimination capabilities.

Accurate speed readings from Doppler radars are vital for the reliability of speed enforcement. The goal of speed enforcement is to increase safety on roads and limit accidents while punishing the transgressor for speeding. Below are the operational parameters prescribed by law when using CW Doppler radars to measure vehicle speed in South Africa (Arrive Alive, 2012):

- “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 200m of the antenna”,
- “No signals received and processed from vehicles more than 500 meters away”,
- “No other moving vehicle other than the measured vehicle within 600 meters from the radar in the direction of operation”, and
- “The vehicle’s speed should be tracked for 3 seconds for a valid reading to be possible”.

A proposed solution to the problem of vehicle identification during Doppler radar speed measurement was developed by Neil Cameron Martin (1987) in his master’s dissertation. The proposed, system shown in Figure 1 illustrates the use of two sources to measure and compare their results. Source 1 only measures vehicle speeds of B and C and source 2 only measures vehicle speeds of A and C. The configuration allows the processor to determine which vehicle is travelling at what speed. The study 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 to successfully implement the system.

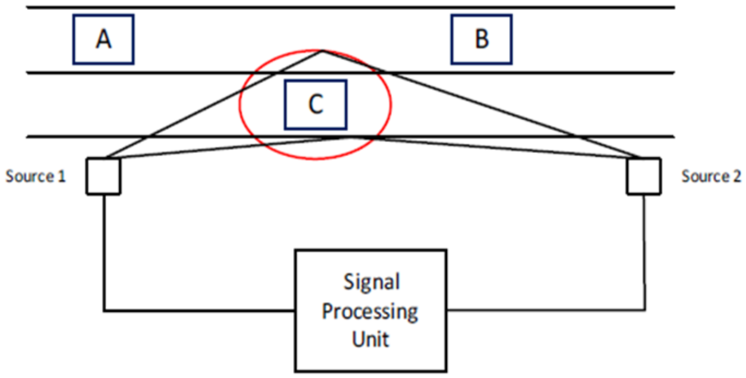

Figure 1: Proposed Doppler radar measurement configuration (Adapted from Martin, 1987)

1.2 Objectives of Study

Apart from the CSIR case study, which is referenced in Neil Cameron Martin's master's dissertation (1987), there is limited published literature on the magnitude of the issues influencing the limitations of a CW Doppler radar on vehicle speed measurements. This paper aims to add to available literature on this important issue, evaluating the magnitude of identified Doppler radar limitations.

CW Doppler radars have several limitations in vehicle speed measurement. These limitations include:

- Cosine effect – The cosine effect occurs when the incorrect Doppler frequency is measured from the radar when the vehicle is not travelling directly toward the radar. It is called the cosine effect due to the direct relationship between the cosine angle between the vehicle and the radar. There are some software techniques that can be applied, but their accuracy is questionable.
- Accuracy and acceleration limits – A radar can either differentiate in frequency or in time. Differentiating in frequency allows the radar to accurately measure a constant speed but the radar is bad a measuring a change in speed. The opposite is true when differentiating in time, the radar can measure a change in speed accurately but won't be very accurate for a constant speed.
- Object identification – A CW radar cannot distinguish between multiple vehicles/objects travelling at different speeds in the range of the radar. The assumption that the closest object will generate the strongest signal is not always true.
- Antenna sidelobes – The main lobe is in the direction of the intended measurement. The size of the side lobes can affect the radars tendency to measure unintended objects that are not in the direction of measurement. It is important to know the radiation pattern of your radar for both the transmitting and receiving antenna to ensure accurate readings.
- Multiple path reflection – Any metal object, which is a good reflector, may lead to another path of reflection for the radar to measure. The radar is not capable of detecting how a signal has travelled from and back to the radar.
- Radar receiver saturation – When a vehicle travels close to a radar, either the amplification circuit or the mixer is prone to saturation.

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

The scope of this paper is to evaluate the limitations of a CW Doppler radar with horn antennas in vehicle speed measurement. This paper does not detail the design of a CW Doppler radar or how design choices might affect the radar. This study focussed on building a suitable radar that would demonstrate the limitations of a CW Doppler radar with horn antennas in vehicle speed measurement. A moving CW Doppler radar is not considered. The full design of hardware and software is available in GitHub (van Tonder, 2021).

2. RADAR AND SETUP

Figure 2 and Figure 3 illustrate the structure and hardware of the radar developed for this study. The radar is built on a wooden structure that imitates the size and height of an industry produced speed radar.

Figure 2: Radar side view

Figure 3: Radar rear view

Figure 4 illustrates the placement of the radar, 3 m from the centreline of the single-lane road pointed toward oncoming vehicles.

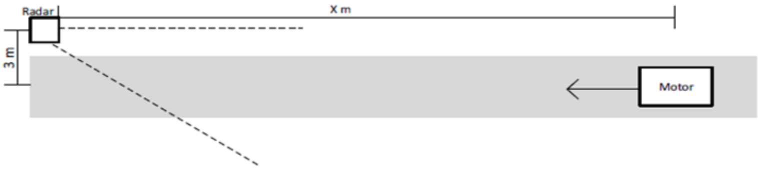

Figure 4: Radar setup

2.1 Accuracy Testing of Designed and Built Radar

The common signal processing technique used in radars is to determine the strongest frequency component in a short period of time, through a Short-Term Fourier Transform (Mahafza, 2013). The radar extracts the frequency from the recorded signal by a Discrete Fourier Transform (DFT) analysis. The transformed signal is then plotted in a spectrogram. A spectrogram is a colour spectrum indicating the strength of different frequency components over time.

The spectrogram, illustrated in Figure 5 clearly indicates the measured vehicle as a yellow line, describing the power (dB) of the return signal to the radar.

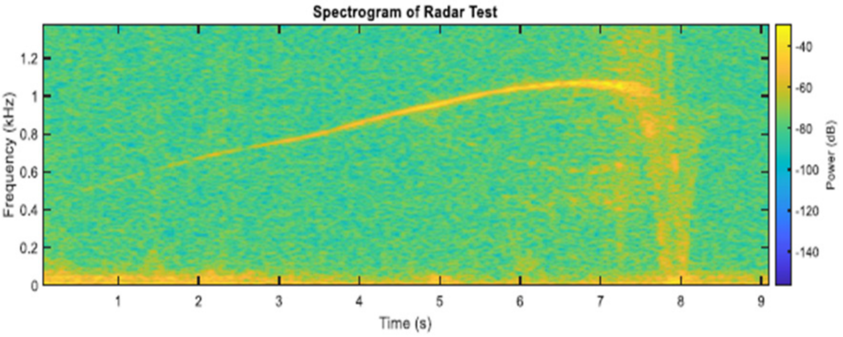

Figure 5: Measured spectrogram of vehicle

The spectrogram frequency recording is imported into Matlab where the vehicle's speed is determined from the frequency (kHz) of the return signal. To test the accuracy of the radar, the measured speed of the radar was then compared with the GPS-measured speed of the same vehicle. The GPS speeds were collected by a Ublox GPS module (*NEO-M8 series,* 2023). The radar speed is compared to the GPS speed in Figure 6.

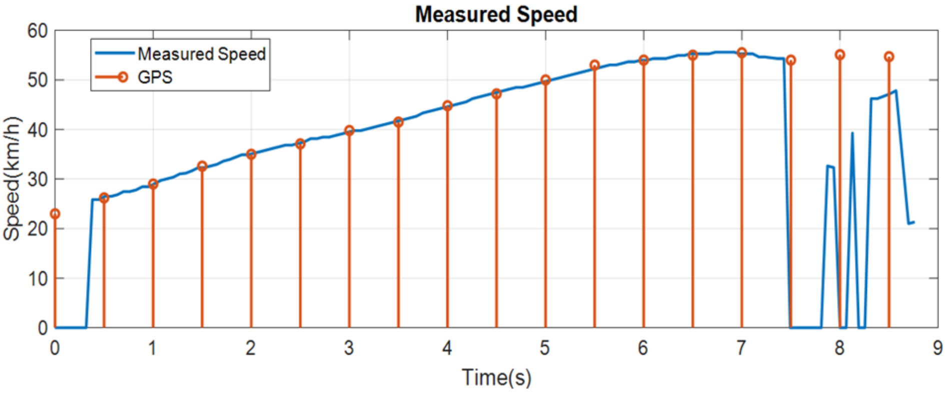

Figure 6: Speed measured from radar and GPS

The radar is capable of accurately measuring the speed of a vehicle and is similar to that of the GPS measurement. From the measurement illustrated in Figure 6 the radars maximum range is calculated as R = 85.7m. The radar stops measuring the speed when the vehicle passes by the radar at around 7.5 seconds.

3. RESULTS OF LIMITATIONS

3.1 Cosine Effect

The measurement used to test the radar is taken as the original measurement. The cosine error is then corrected with offset of d = 3m and d = 6m. By knowing the maximum distance from which a vehicle is visible to the radar, software can be used to estimate and correct the cosine error. The corrected cosine error for both distances are illustrated in the Figure 7. When the vehicle is within 3 to 5 m of the radar, the speed of the vehicle is no longer measurable due to saturation.

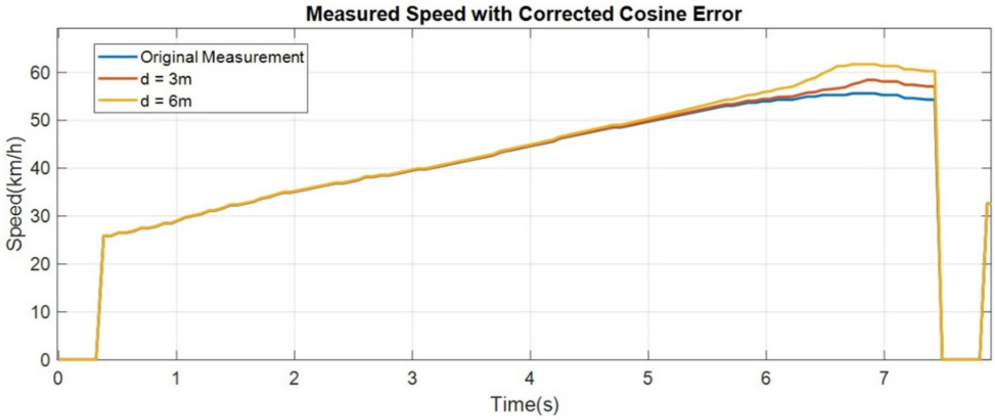

Figure 7: Cosine error on vehicle speed

Despite being able to correct the cosine error, the operation and setup of a radar is very important. The radar is not capable of determining in what lane the vehicle will be travelling. This means that the radar cannot correct the cosine error on more than one lane. The cosine error can only be corrected where the distance will remain the same for all vehicles passing by the radar. When the vehicle is limited to traveling in one lane at a fixed distance, the cosine error is small enough for most of the distance measured, that no correction is needed. For the speed measurement illustrated in Figure 7, the cosine error is only visible once the vehicle is within 10 to 20m of the radar.

3.2 Accuracy and Acceleration Limits

The configuration of the Discrete Fourier Transform (DFT) sample size is important for the accuracy of a radar. To illustrate this phenomenon a vehicle accelerating past the radar is measured. The radar accurately calculates the acceleration of the vehicle without too many calculations. Figure 8 illustrates the measured frequency with the best combination of time and frequency.

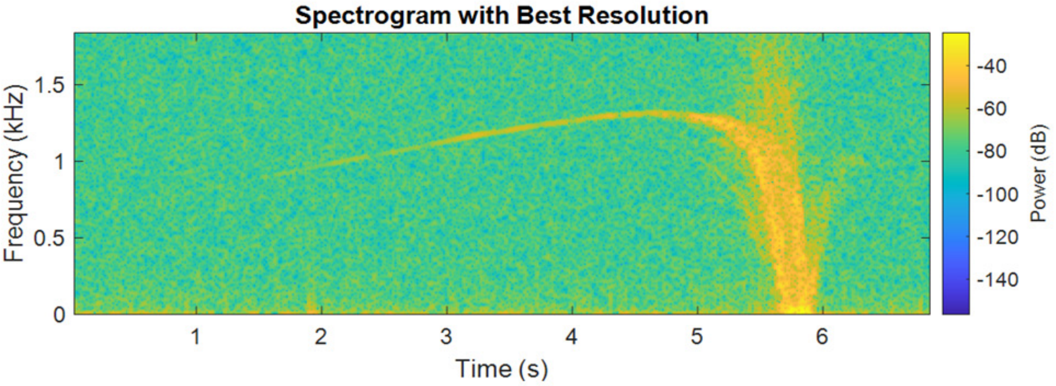

Figure 8: Spectrogram with best resolution

When the DFT sample size is too big, the radar is incapable of calculating a fast change in speed as illustrated in Figure 9. The measured speed is not an accurate estimate of the accelerating vehicle. The change in speed per sample is around 3.5 km/h which does not satisfy the required accuracy for a radar. The radar is capable of differentiating between frequency components, but unable to differentiate in time.

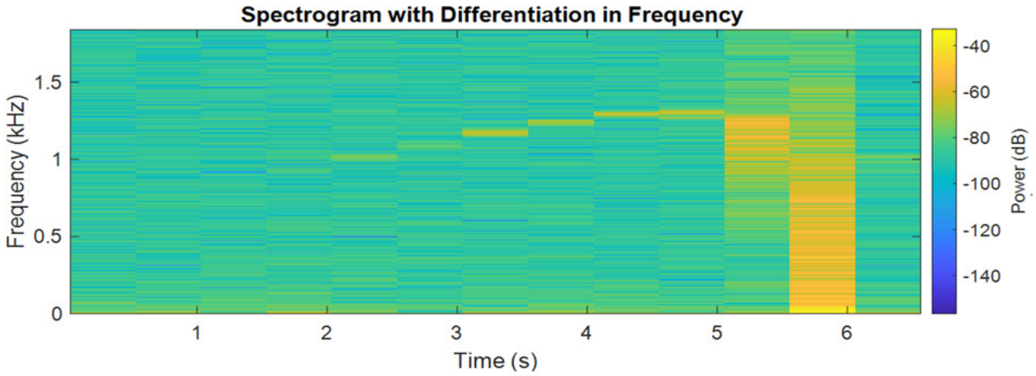

Figure 9: Spectrogram with differentiation in frequency

If the DFT sample size is too small the radar is too sensitive to a change in frequency and cannot accurately calculate determine the Doppler Frequency, as illustrated in Figure 10. This will also require powerful processing which is unnecessary. Frequency differentiation is lost when time differentiation is prioritised.

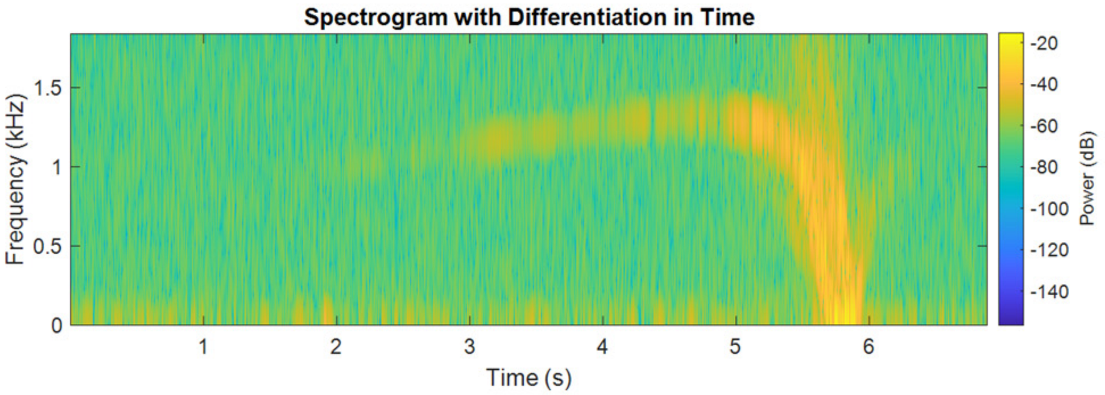

Figure 10: Spectrogram with differentiation in time

Table 1 below concludes the difference between sampling rate, size and speed sensitivity. As the sample size decreases, the speed sensitivity increases and vice versa. The sample size, also noted as speed sensitivity, is decided upon in the design aspect of the radar and the operator should be aware of this.

Table 1: Comparison between sample sizes

	Best Resolution	Time Resolution	Frequency Resolution
Frame Size (s)	0.1224	0.0289	0.5442
Sample Rate (Hz)	8.17	34.6	1.84
Change in speed (km/h)	1.4	0.33	3.5

3.3 Object Identification

The radar is unable to determine how far away the object that is being measured is, this is known as range resolution. It is possible that two vehicles, travelling at the same speed but at different distances from the radar, can be measured as one vehicle. Measuring the speed of two vehicles travelling at the same speed but at different distances from the radar is illustrated in Figure 11. The radar is only measuring one vehicle shown in Figure 12.

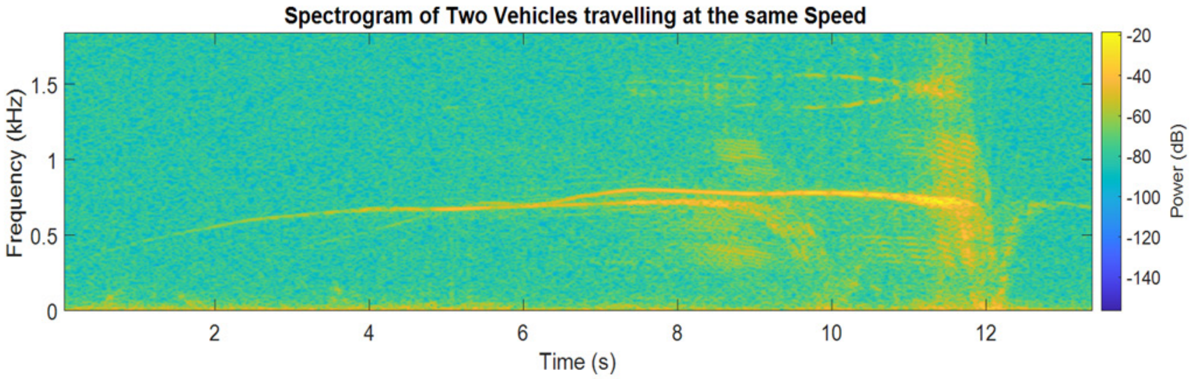

Figure 11: Spectrogram of two vehicles travelling at the same speed

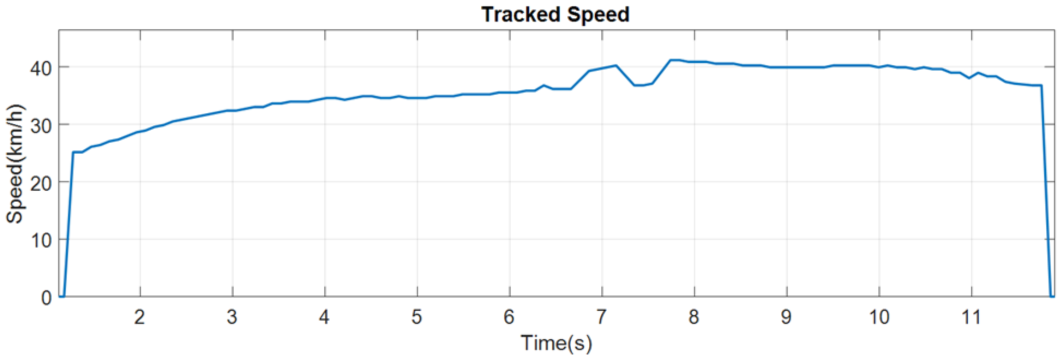

Figure 12: Tracked speed of two vehicles travelling at the same speed

The radar is unable to differentiate between two vehicles travelling close behind one another as well. The radar only measures one vehicle while the second vehicle goes unmeasured. The spectrogram of two vehicles travelling with a short following distance is shown in Figure 13. The radar is also unable to determine a vehicles Radar Cross Section (RCS), and this greatly affects the measured distance of the vehicle.

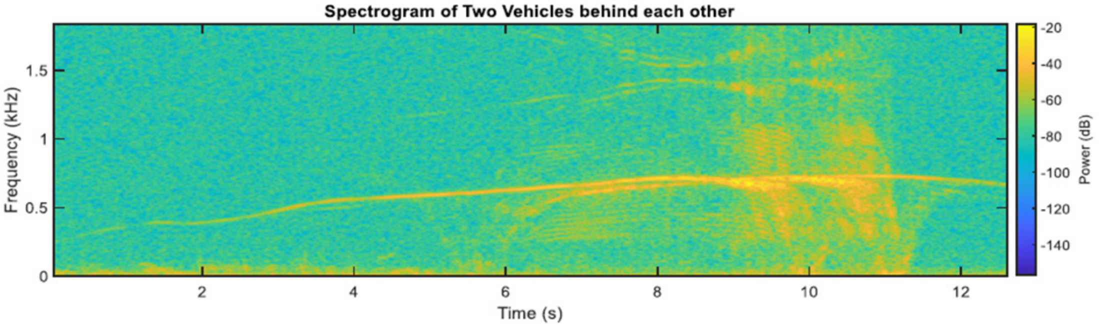

Figure 13: Spectrogram of two vehicles travelling behind each other

3.4 Antenna Sidelobes

To demonstrate the effect of antenna sidelobes, the radar will be rotated from north to illustrate the importance of the radiation pattern and the radar setup, and the influence that they have on the measurements. Table 2 indicates the radars measurable range before and after adding the horn antenna. A considerable difference is noted in the measurable range of the radar, at the radiation points of 30 and 60 degrees, before and after adding the horn antenna. The horn antenna has a more focussed radiation pattern. Which minimises the unwanted effects from the sidelobes. Figure 14 illustrates how radiation patterns with and without horn antenna differs.

Table 2: Measurable distance of radar

Degrees West of North	Without Horn Antenna	Horn Antenna
0 °	62 m	85 m
30 °	52 m	32 m
60 °	30 m	21 m

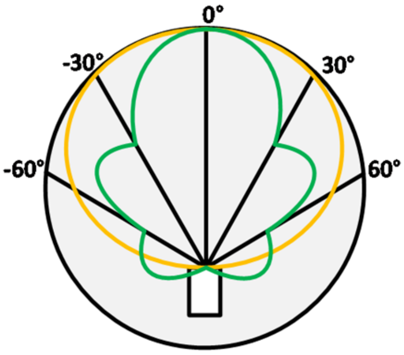

Figure 14: Comparison of radiation patterns between HB100 and Horn Antenna

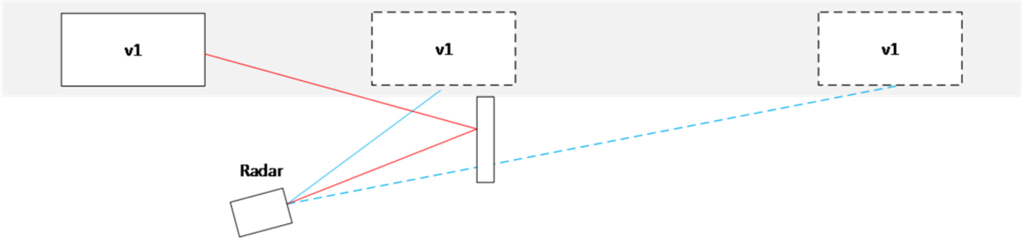

Figure 15: Multiple path reflection setup

3.5 Multiple Path Reflection

The multiple path reflection setup, which was developed for this study, is illustrated in Figure 15 with a billboard within the range that the radar detects. The red lines indicate that the radar is measuring the reflection from the billboard. The blue line shows when the radar measures the vehicle and then the blue striped line is to indicate when the radar is incapable of measuring the vehicle. The measured spectrogram is illustrated in Figure 16. It indicates the vehicle is measured while it is still traveling behind the radar. The vehicle then passes by the radar, where saturation occurs and then passes behind the “billboard”, where the radar does not detect the vehicle. Once the vehicle is far enough away from the radar it is able to measure the vehicle again. The vehicle is measured behind the radar at 37m, approximately half the measurable distance of the radar.

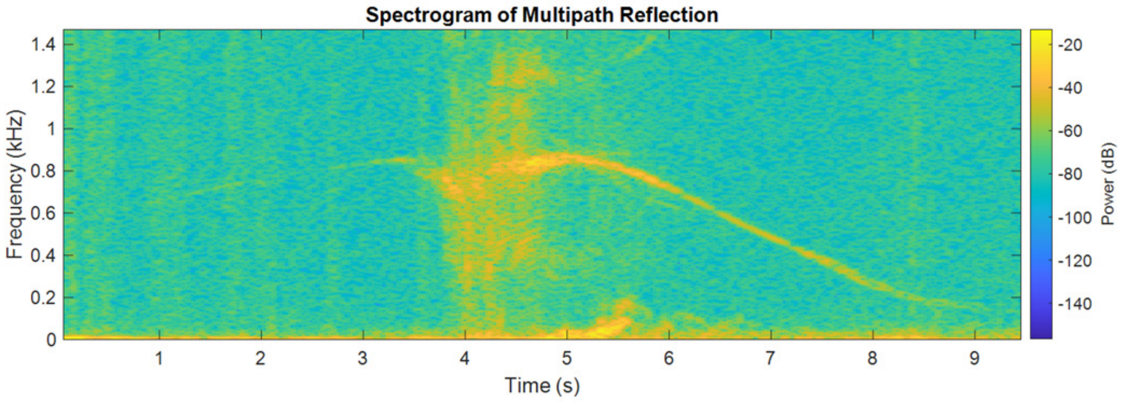

Figure 16: Spectrogram with multiple path reflection

3.6 Radar Receiver Saturation

The radar is subject to saturation whenever a vehicle drives closely by the radar. For a moment the radar will lose the ability to track the vehicles. Figure 17 illustrates the spectrogram of two vehicles, one moving towards the radar from the direction it is pointing in, and the other is moving away from the radar. The saturation causes the radar to lose its tracking of the first vehicle for a moment. The radar is then locked on to the second vehicle until the first vehicle passes by the radar and the phenomenon occurs again.

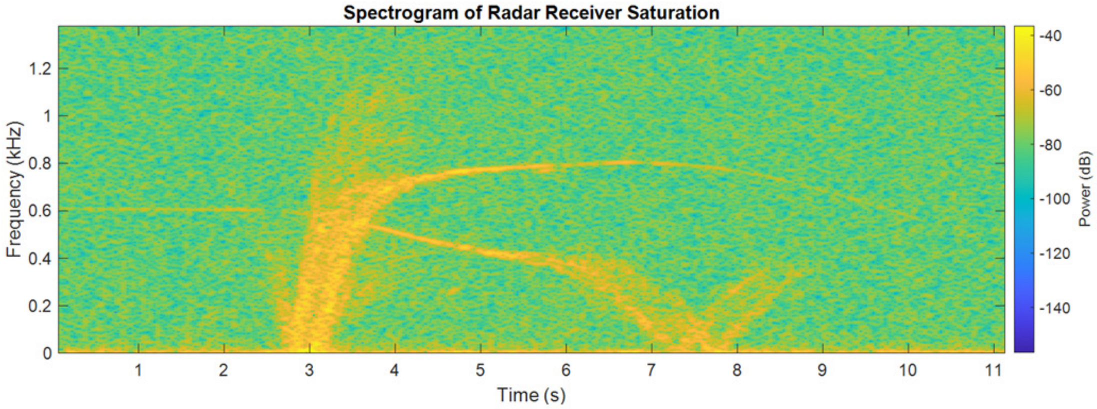

Figure 17: Spectrogram of radar receiver saturation

4. CONCLUSIONS

The operational parameters for speed limit enforcement attempt to limit the impact of the limitations of the CW Doppler in speed measurement, particularly that the radar should only be used to measure one vehicle at a time. The first limitation, of those documented in section 1.2, that is accounted for is the effect of multiple path reflection. The law, documented in section 1.1, specifies that no flat surface should be in the direction of the intended measurement. The next two laws state that only one vehicle should be measured for a measurement to be valid. The law however does not consider the difference in a vehicle's RCS size. A CW Doppler radar cannot determine the RCS of a vehicle and therefore this limitation cannot be corrected. The last law states that a vehicle is required to be tracked before a measurement is accurate. The tracking of a vehicle does not deter any of the limitations as a vehicle can be tracked even if it is not the only vehicle in the range of the radar. Figure 13 illustrates the phenomenon where two vehicles are travelling at the same speed and are tracked as one vehicle. The laws make no notice of the cosine effect, receiver saturation or the accuracy and acceleration limits. These limitations are mostly constricted to the radar designed and they should be addressed before the radar is certified for use. The antenna sidelobes are not considered but the limitation can be eliminated with a very directive antenna.

A CW Doppler radar can accurately measure a vehicle's speed. The accuracy of the measurement is limited to only one vehicle travelling in a single lane. After the investigation into the limitations of a CW Doppler radar, it is clear stricter operation laws are required.

Possible future work can be a limitation study on a FMCW Doppler radar and its limitations to vehicle measurement and enforcement. FMCW Doppler radars have the added capability of range resolution. FMCW Doppler radars are also popular in vehicle measurement, and it would be significant to see if an FMCW Doppler radar solves the limitations of a CW Doppler radar.

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