Design and simulation of signal processing algorithm in FMCW RADAR for Adaptive Cruise Control

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Abstract. Driving a vehicle in heavy traffic and maintaining safe distance to the preceding vehicle is always a difficult task. A small fault can lead to accidents and traffic jam in the current city traffic scenarios. The effort and stress of the driver in safe driving is much more. This issue can be easily solved using the adaptive cruise control (ACC). With the help of automatic speed control of the vehicle, the ACC helps to maintain safer distance between two vehicles. This is possible through the Radar technology for the target detection. In this work, we have used 77GHz FMCW waveform for the range and velocity detection of the target. The radar is generally installed on the front side of car. This radar can detect any possible target with in its maximum range in the proposed scenario. In this proposed work, we have created 5 different target objects with varying velocity and range for scenario simulation. Also, the range-velocity estimated by the proposed method is discussed with the help of Range-Doppler Map. The pros and cons of FMCW radar is discussed with the help of simulation results.

Keywords: ACC, Radar, FMCW, Range-Doppler Map

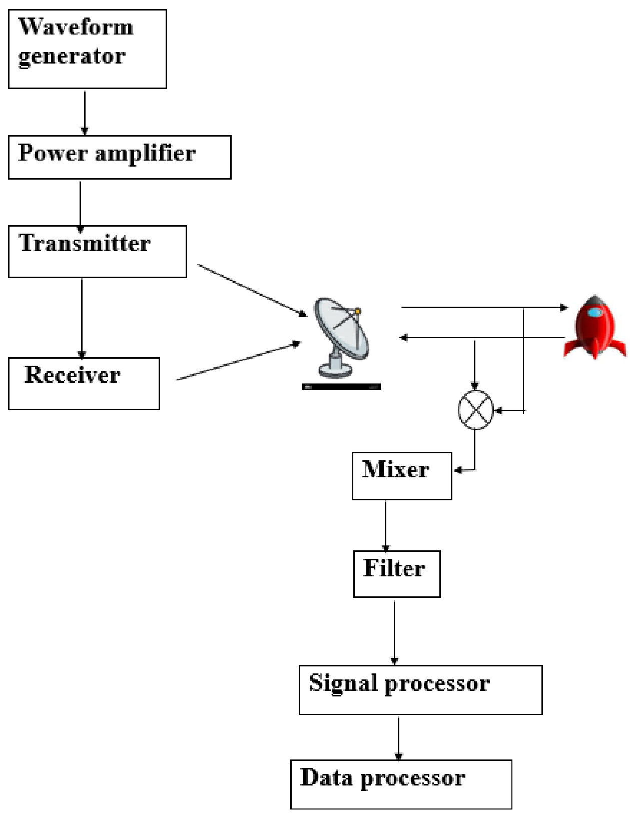
1 Introduction

The technology improvement and fast-moving lifestyle creates inevitable automobile traffic on the road. The traffic increases the probability of road accidents and traffic jams. The most of the incidents are from the driving errors in maintaining optimal separation between two preceding vehicles and speed control. The future generation autonomous vehicles and intelligent systems promises passenger convenience, safety through the technology adaptive cruise control (ACC) [1]. The radar in ACC promises brake control through predicting the preceding vehicle speed and distance.

The developing radar technology in ACC promises the range and velocity of the preceding vehicle. The radar (Radio detection and ranging) uses the radio waves to detect and track the target objects. The range and velocity collected from the radar helps to control the brake system of the automobile automatically. In this proposed work, we use the frequency modulated continuous wave (FMCW) for detection and ranging. The FMCW invented mid of 1960s yields high resolution in the ACC [2].

1.1 RADAR Working Principle

Radar is a detection system that uses the radio waves to determine the distance, angle, and radial velocity of objects relative to the object. It is made of antenna (transmitter and receiver), mixer, filter, signal processor and data processors. The Fig.1 shows the block diagram of radar system. The Radar system design [3] can be broadly classified into the following groups.



Target information (velocity, range)

Fig. 1. Basic block diagram of Radar

- **Antenna:** The radar antenna is a device that transmits the radio waves through transmitter and receives the echoes of the waves at the receiver. The antenna's performance is based on the ability to detect the exact direction and position of an object. The most common type of antenna is the parabolic antenna. It has a small feed at the focus of the dish which transmits and receives the signals. The signals are reflected by the dish and focused into a narrow beam.

- **Mixer**: Mixer are three port devices with two inputs and one output port. It takes two input frequencies and produce a sum or difference frequencies at the output port. They combine the transmitted signal and the returned signal. The frequency of the output signal is known as beat frequency.
- **Filter:** It removes the unwanted components or features from the signal, it includes noise, clutters, etc., so as to obtain the purer waveform.
- **Signal processor:** it converts the received radar signals into an optimised image that can be displayed for the operator. Based on the doppler content and amplitude characteristics the radar signal processor separates target from the clutter. With fast Fourier transform, the target states can be derived from the beat frequency of IF signal.
- **Data processor:** It concerns the information about a target. Mechanically, the information of if signal is processed and the parameters such as velocity, range and angular position are output of the processor.

1.2 Radar Classification

The radars were primarily used in military affairs. The main basis of classification of radar systems was by the band designation. Also, there is another basis of classification, which is based on type of waveform- pulse radars and CW radars [4].
Pulse radars: This type of radar produces series of rectangular waveforms. The system mentioned here are categorised based on Pulse Repetition Frequency (PRF)- low PRF, medium PRF and high PRF.
CW radars: It produces continuous sine waves which is mainly used for range measurements and uses doppler shift frequency to measure relative velocity of moving targets. In this system we use saw-tooth waveform

1.3 Radar Equations

To estimate the target range, the primary radar equation helps us to complete the radar design. [5].
The parameters are,

- *Transmitted signal energy* (P_t): The power of transmitted waveform. [6]
- *Received signal energy* (P_r): The power received waveform after reflection from target. [6]
- *Antenna aperture* (A_e): The effective area of receiving antenna that collects the returned power (P_r).It is the surface near or on the antenna for calculating the field values at external points [6].
- *Gain of antenna* (G): Gain of the antenna is defined as $G = \frac{4\pi A_e}{\lambda^2}$, where λ is the wavelength of radar signal in meters (m). The power density of the radar which radiates the received power from the antenna, is given by $\frac{P_t G_t}{4\pi R^2}$.

- *RCS* : RCS denotes the radar cross section, to emphasise on target characteristic. It depends on physical size, shape, orientation and material. The received energy of signal is related to target characteristics. The radar equation is given by,

$$P_r = \frac{P_t G_t}{4\pi R^2} \cdot \frac{\sigma}{4\pi R^{2.}} \cdot A_e$$

Where, P_r is the received signal power (Watts)
P_t is the transmitted power (Watts)
G_t is the gain
R is the distance of the target
σ is the radar cross section of the target (m^2)
A_e is the effective area of returned signal (m^2)

Here we are making one assumption which is, the received signal is equal to minimum detective signal (S_{min}). Now the maximum range can be related as

$$R_{max}^4 = \frac{P_t G_t \sigma A_e}{(4\pi)^2 S_{min}}$$

$$R_{max}^4 = \frac{P_t G_t \sigma A_e}{(4\pi)^2 k T_0 B_n F_n \left(\frac{S}{N}\right)_1} \cdot \frac{1}{L_{loss}}$$

1.4 Radar Cross Section

Echo signal is also known as radar reflection. A radar reflection takes place when a wave transmitted from a transmitter encounters any object or our specific target (in our case, any debris) causes a portion of the incident energy to be returned back to the receiver where it can be sensed by a receiver. The RCS is the projected area of a metal sphere that would return the same echo power as that of the target, if it has been replaced by a sphere [5].

When any object gets exposed to an EM waves, it scatters incident wave energy in all directions. The energy dispersed back to the receiver constitutes the radar echo of the object. Basically, RCS is the measurement which tells the characteristics of the target such as nature of material with which it is made, size, shape and orientation the target. The RCS (σ) is given by

$$\sigma = \lim_{R\to\infty} 4\pi R^2 \frac{|E_s|^2}{|E_0|^2}$$

Here E_0 is the electric field strength of transmitting wave hitting the target and E_s is the electric field strength of the scattered wave at radar. RCS can also be expressed in decibels(dB)

$$\sigma(\mathrm{dB}) = 10\log_{10}(\sigma(\mathrm{m}^2))$$

If the object is larger, the radar reflection is stronger and hence the RCS is greater. We can say that a larger RCS value indicates that the target can be more easily detected.

1.5 Power Allocation

Power received, depends on the factors such as the antenna gain, signal-to-noise ratio, size of antenna and propagation losses. Hence power analysis is important to evaluate performance of the system before the design of the radar system. The relationship between the receiver effective area and gain is given by $A_e = \frac{G_r \lambda^2}{4\pi}$, where G_r is the gain of the receiver antenna. Now the radar equation can be written as $P_r = \frac{P_t G_t G_r \lambda^2 \sigma}{(4\pi)^3 R^4}$. After the received power has been derived, we analyze the factors that decides receiver power.

1. Noise power – noise power is defined as interfering and unwanted electromagnetic energy in an electromagnetic process. It is also called as thermal noise power and expressed by N (watts) given by $\boldsymbol{N = kT_0\, B_n}$. There exists additional noise too, hence practical noise power can be expressed $\boldsymbol{N0 = kT_0\, B_n\, F_n}$, where N0 is the total noise power(watts) and Fn is the noise figure.
2. Signal to noise ratio – defined as ratio of signal power to ratio power.

$$\frac{\mathbf{S}}{\mathbf{N}} = \frac{\boldsymbol{received\ signal\ power}}{\boldsymbol{noise\ power}} = \frac{\boldsymbol{P_r}}{\boldsymbol{N_0}}$$

1.6 FMCW Waveform

A FMCW radar transmits a continuous signal in which its frequency is varied over a time period and across a specified bandwidth. The input signal given is in the form of chirping that hits the target and received back with a time delay due to change in velocity and relative range. A match filter is been used to combine the transmitted and received signal, which produces a frequency called beat frequency and between the two signals, and intermediate frequency range is also obtained [7].

The Doppler effect is a change in the frequency of a signal that is transmitted and received by a radar system. This effect occurs when a moving object is relative to the radar system. The frequency of the received signal will increase when the target moves towards the radar, and decrease when the target moves away from the radar.

The FMCW radar can accurately measure short range distances with low computational complexity. It supports simple integration of targets output. Also, it is providing low sensitivity to interfering with extremely high degree of range resolution.

In this work, we propose saw-tooth FMCW for moving target detection. For the sawtooth waveform, if **R** is the initial range of target, the time delay is calculated as $\tau = \frac{2R}{c}$. The echo signal come back to receiver with certain delay before the next chirp. The chirping time is usually around 5.5 times higher than the $\boldsymbol{\tau}$. Hence, the sweep time is $t_s = 5.5\ \tau$. And the sweep slope is given by $\boldsymbol{k = \frac{B_w}{t_m}}$.

2 Simulation Setup

In this section, we discuss about the simulation setup for Radar and the multiple moving targets [8 – 11].

2.1 Radar Simulation setup

In ACC system simulation, the following simulation parameters have been considered for simulating the scenario. Based on the power budget analysis, the following parameters are considered for the simulation scenario. The following parameters in Table 1 are calculated with the help of section 1.

We assume a radar installed on a moving object (car) with the speed of 90Km/h with an isotropic transmit and receive antenna.

Table 1. Radar setup parameters.

Name of Parameter	Value
Antenna aperture (Ae)	6.06×10^{-4} m^2
Antenna gain	27.0042 dB
Transmitted Power (Pt)	3.2 mW
Transmitter gain (Gt)	36.0042 dB
Receiver gain (Gr)	42.0042 dB
Receiver noise figure (Fn)	4.5 dB
Carrier frequency (fc)	77 GHz
Bandwidth	150 MHz
Maximum target range (m)	200
Range resolution (m)	1
Maximum target speed (km/h)	250
Sweep time (ms)	7.33
Sweep Bandwidth (MHz)	150
Maximum beat frequency (MHz)	27.30
Sample rate (MHz)	150

2.2 Moving Targets Setup

In simulating the road scenario, we have considered five moving targets such as car, trunk, cycle, bike and pedestrian. By considering the basic characteristics of each target, their specific values such as their range, speed and RCS are been set up as shown in Table 2. In this simulation, we assume the target velocity shouldn't be higher than 250Km/h.

Table 2. Moving Target parameters.

Moving Target	Quantity	RCS (dB)	Velocity (Km/h)	Initial Range (m)
bike	1	20	40	100
Pedestrian	1	3	5	30
Ordinary car	1	20	50	115
Trunk	1	23	85	125
Bicycle	1	3	12	60

3 Results and Discussion

With the simulation setup narrated in section 2, the simulation has been carried out. The FMCW signal of 150 MHz bandwidth is generated from the radar as shown in Fig. 2. The generated FMCW signal reaches the monostatic radar after reflection from the targets in the radar range.

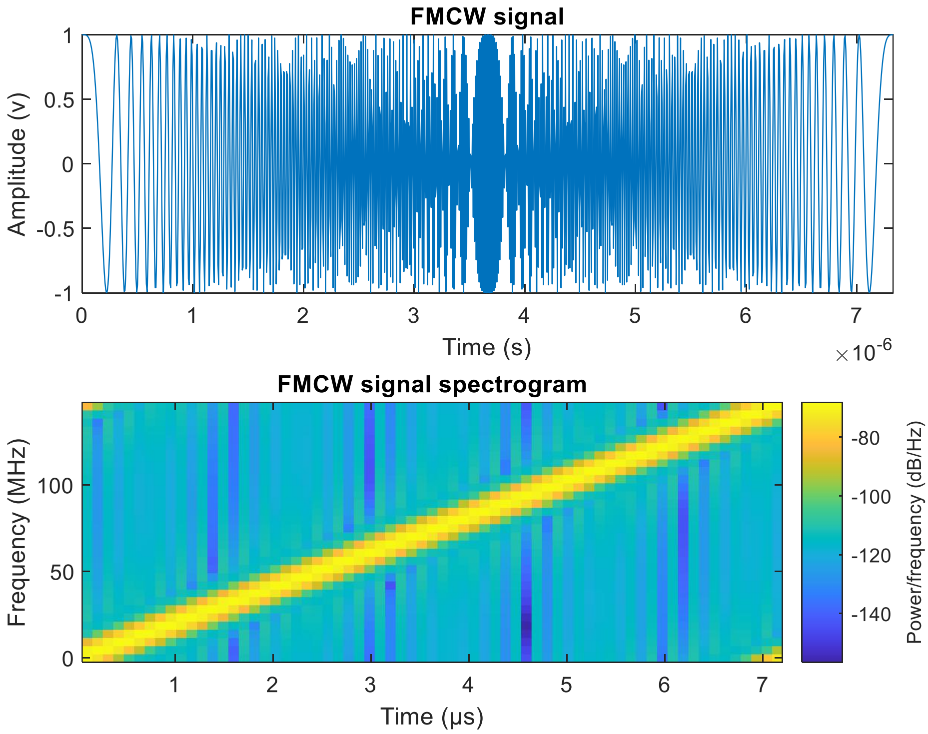


Fig. 2. Generation of FMCW- sawtooth waveform

Fig. 3 shows the power spectral density (PSD) of the signal generated from the Radar. From the simulation scenario, it is been reflected from five of the moving targets and reaches the radar. Since, the targets are located at different range and moving with different velocity, the signal transmitted will attain unique time and frequency shift from each target. The radar integrates the received signal from all the moving targets before converting into the IF signal using the matched filter.

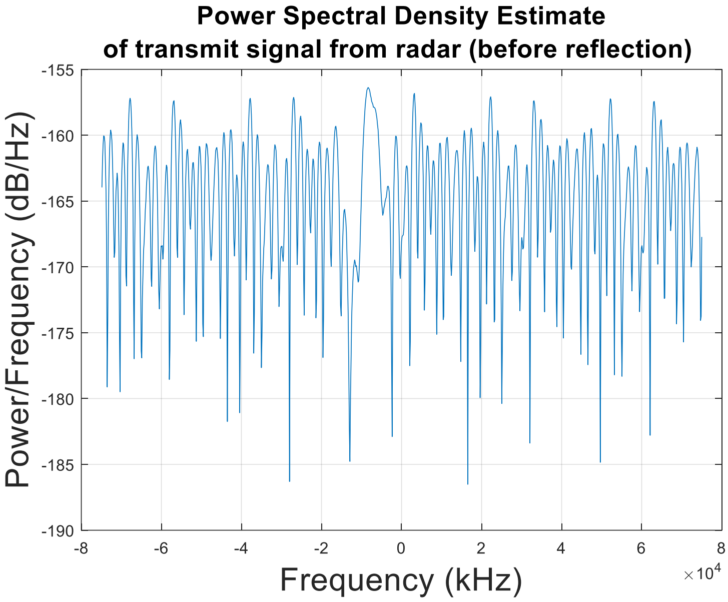


Fig. 3 PSD of transmit signal (before Reflection)

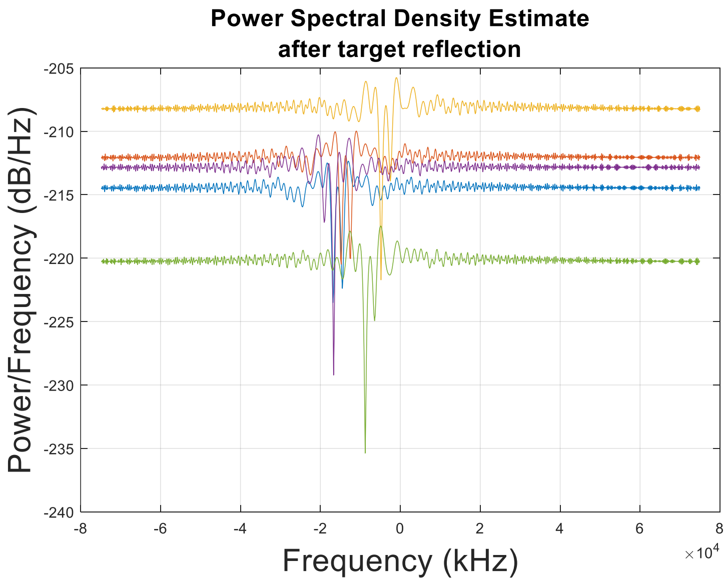


Fig.4 PSD of signal (after target Reflection)

The integrated signal from each target at the radar is shown in Fig. 4. The five different signal from each target is clearly visible in PSD of the received signal at radar. Once the integration is over, the matched filter calculates the correlation between the transmitted and received radar signal. The matched filter operation is otherwise termed as dechirping. The dechirped signal is shown in Fig. 5. The five targets are clearly indicated using 5 peaks. If the target is no detectable or else target is out of scope of the radar, the peak will be missing in the PSD.

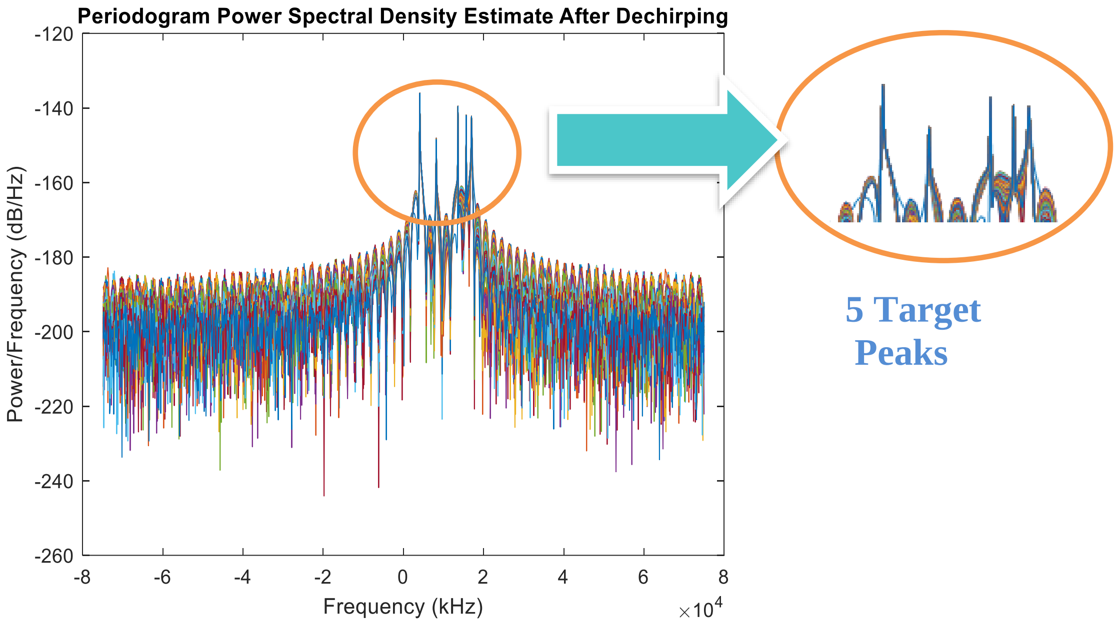


Fig. 5. PSD after dechirping

Also, the spectrum of the transmitted and received signal in radar is shown in the Fig. 6. The five peaks depict the five moving targets in the scenario. From the received signal it is observed that the received radar signal shifts in time and frequency due to the delay from the reflection and moving target doppler shift.

For the target range and doppler measurement, the beat frequency is calculated from the IF signal using FFT. From the obtained beat frequency, we can calculate the range and velocity. The obtained range and velocity of the moving target is shown in Fig. 7 Range – Doppler Map. It is clear from the Fig. 7 that, the obtained target velocity and range are matching with the simulation setup with the following deviation. Fig. 8 shows the beat frequency extracted from the received signal after match filtering.

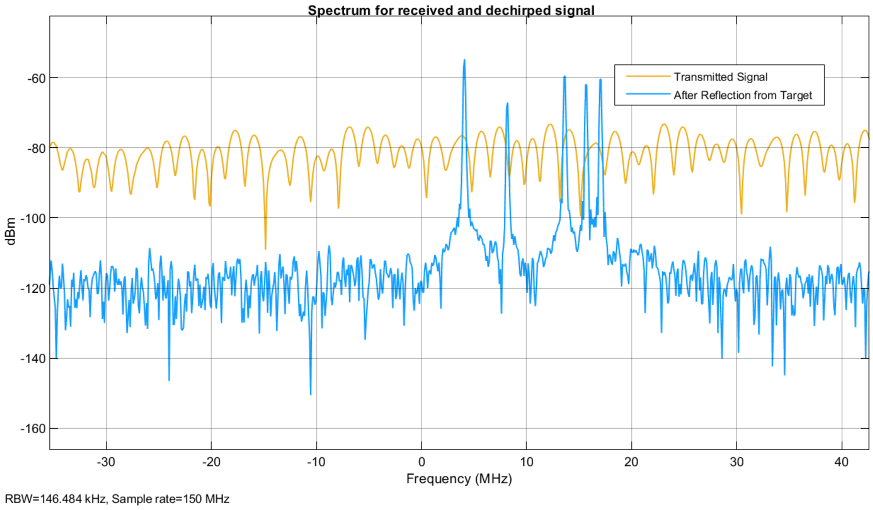


Fig. 6. Spectrum of Transmitted vs Received Signal in Radar

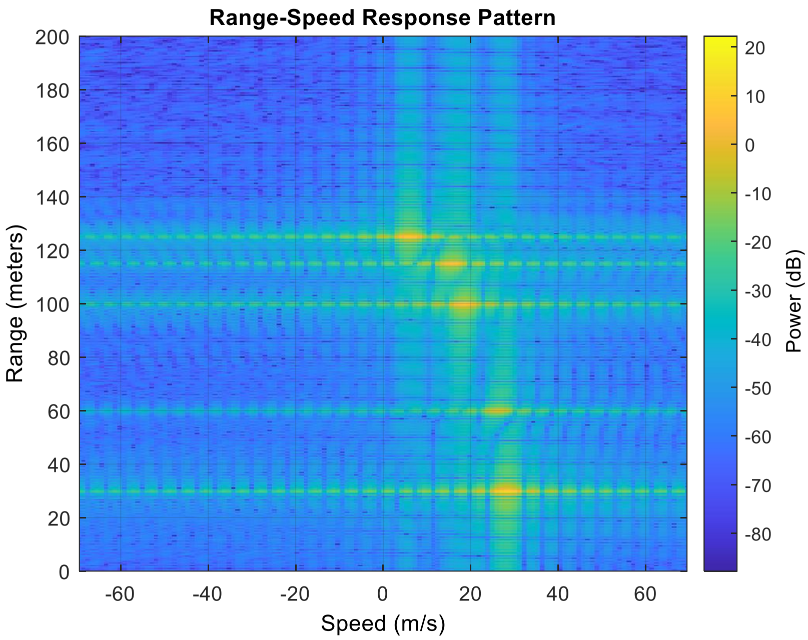


Fig. 7. Range Doppler Map

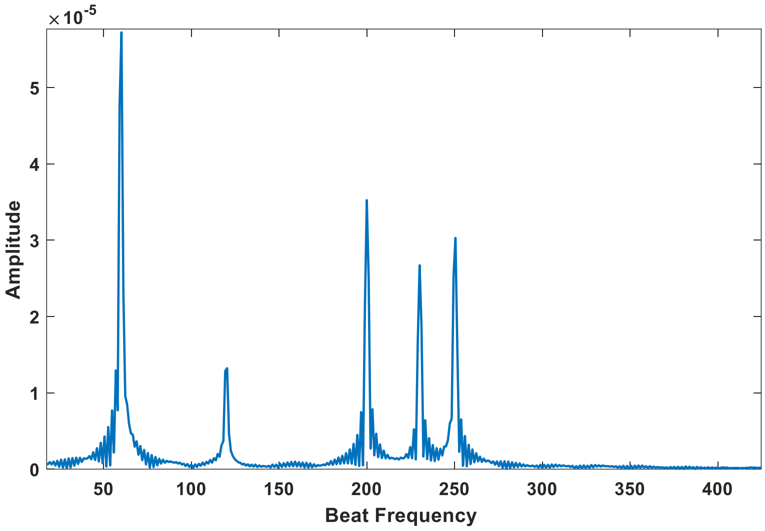


Fig. 8. Beat Frequency Identification from the received signal.

It is found that when the small target (small RCS) is moving with high velocity or in long range, it becomes difficult to track its characteristics. It is generally observed that target (corresponding peak) is missing in the dechirped signal. Also, deviation is observed in the velocity calculation of fast-moving long-range target.

4 Conclusion

In this work, we have assumed a vehicle mounted radar for moving target detection in real time road scenario. The FMCW sawtooth waveform of 77GHz with the bandwidth of 150MHz is proposed for the target detection. Five moving targets have been considered with varying range and velocity. The simulation result shows that the proposed method can able to predict the range and velocity of the target accurately. However, the following observations also made. When the low RCS target is in long range or moving with higher velocity, the prediction of target presence itself not guaranteed. Also, in the case of fast-moving target, the velocity mismatch is observed.

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