Performance Assessment of a 77 GHz Automotive Radar for Various Obstacle Avoidance Application

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This thesis titled

Performance Assessment of a 77 GHz Automotive Radar for Various Obstacle Avoidance Application

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ABSTRACT

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Human safety is one of the highest priorities in the automotive industry. The demands made for reliable safety systems have been increasing tremendously in the past decade. The radar sensors used for safety systems should be capable of detecting not only automobiles but also motorcycles, bicycles, pedestrians, roadside objects and any other obstacles the vehicle may come in contact with.

This thesis investigates several performance aspects and test procedures for a 77 GHz long range radar sensor with different test target objects. This assessment helps to investigate the potential to use these radar sensors for obstacle detection and/or avoidance for smaller objects like bicycles, humans, traffic barrels, 4" poles, metal sheets, and also for bigger objects like vans, motorcycles, aircraft, etc. For these purposes, different test cases were developed to evaluate the performance. The different test cases used to test a 77 GHz radar sensor includes: finding maximum range, range accuracy, finding maximum field of view, detection (& separation) of two target objects (similar & different) at different radial distances, and maximum range for detecting an aircraft. Observations were made with the radar sensor mounted on a moving cart and the measurements were logged. The results from these tests will provide insight into analyzing the possibilities and limitations of these radar sensors for different applications.

The tests were successfully conducted on a flat, open field at Ohio University Airport, Albany, OH.

Approved: ____

Chris G. Bartone

Professor of Electrical Engineering and Computer Science

To my parents Vara Prasad, Alivelu
sister Kalyani, brother Rakesh
and cousins Sunil, Anusha

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ACC	Adaptive Cruise Control
ADC	Analog to Digital Converter
CAN	Controller Area Network
CAPL	Communication Access Programming Language
DSP	Digital Signal Processor
ESP	Electronic Stability Program
FFT	Fast Fourier Transforms
FMCW	Frequency Modulation Continuous Wave
FOV	Field of View
HF	High Frequency
ICD	Interface Control Document
IDE	Interactive Development Environment
LF	Low Frequency
LO	Local Oscillator
LRR	Long Range Radar
PRF	Pulse Repetition Frequency
RADAR	Radio Detecting and Ranging
RCS	Radar Cross Section
RDU	Radar Decision Unit
RF	Radio Frequency
SGU	Sensor Gateway Unit

SRR	Short Range Radar
UHF	Ultra High Frequency
USB	Universal Serial Bus
VCO	Voltage-Controlled Oscillator
VHF	Very High Frequency

CHAPTER 1: INTRODUCTION

1.1 Background

For safety, security, and comfort applications of the automobile users, monitoring the surroundings of vehicles with sensors is very useful. Radar sensors are one of the best sensors as others like laser, ultrasound, and video may have difficulties in bad weather conditions or range.

Radar technology has been employed in automobiles for various functions since the early 1980s. Initially, microwave radars (i.e., 10 – 24 GHz) were used for collision warning applications on commercial vehicles [1]. Radar has advantages over other types of sensors, as it performs equally well during the day & night and also in most weather conditions. By making use of scattering signature information, radar is used for target identification and for detecting road conditions [2]. Radar sensors are an integral part of sensor fusion technology which is used for autonomous vehicles. After implementation for several years in the trucking industry, the 77 GHz long range radar (LRR) sensors finally migrated into the automobile market as part of adaptive cruise control (ACC). The heart of an ACC system is a 77 GHz radar system that is referred to as long range radar in the automotive industry. For automotive applications, a long range radar sensor is one that has an operational range on the order of several hundred meters.

As driving is a highly demanding activity, both mentally and physically, the driver must maintain a high level of concentration and be vigilant to act within a split second to changing traffic situations. The driver has to constantly assess the distance and relative speed of the vehicles in front and adjust his own vehicles speed accordingly. The design and development of safety systems technology provides the driver with a warning of incipient danger and if necessary take much quicker action than an unaided human could. The ACC radar can now perform these tasks and relieves the driver by constantly monitoring the distance to the vehicle in front and controls its own vehicles speed, so as to maintain a safe driving distance. In simple words, ACC is an extension of a regular conventional cruise control system with additional qualities. An ACC system can adapt to the changing traffic conditions by braking, accelerating, to the set cruising speed.

Two frequency bands have been allocated for land-based automation. They are 24 GHz and 77 GHz. The 24GHz band is used by Short Range Radar (SRR) for short range (0-20m) applications. The SRR uses a pulse radar principle with very short pulse lengths. They are mostly used in detection of blind spots, cut-in and stop-go scenarios, pre-crash detection, and parking aids [3].

The 77 GHz band is used by LRR for long range (0-200m) applications. The LRR sensor uses Frequency Modulated Continuous Wave (FMCW) modulation. The LRR are mostly used in collision warning/avoidance systems giving warning signals and/or taking control of automobile vehicle functions when there is a collision anticipated in order to reduce the risk of injury. With the use of silicon-germanium technology in radar sensors for high-frequency module, the latest 3rd generation LRR3 sensor is not only used in high end vehicle models but is also being featured more and more in medium and compact class cars. The detailed information about these two radars is given in the later chapters.

1.2 Objective

The primary purpose of this research work is to investigate, evaluate, and assess the performance of a LRR sensor for various obstacle detection and/or avoidance application. Target object detection is an important issue for radar sensor systems. This research work also discusses several different test procedures for testing a LRR with different test target objects varying in size, shape, and composition. This assessment is to investigate the potential use of these LRR sensors for obstacle detection and/or avoidance for objects such as Vans, Motorcycles, Bicycles, Humans, Traffic Barrels, 4" Poles, Metal Sheets, etc.

The radar detection zone depends upon many factors which include 1) the type and configuration of the radar antenna, 2) the size, shape, and material of the target object, and 3) the mounting height (i.e., aspect angle) of the radar antenna with respect to the target. The last two factors can be controlled by the users depending upon the test requirements. In this test, the normal height of the car bumper was chosen to mount the radar on a mobile cart.

The radar sensor used in this thesis was a 77 GHz LRR2 donated by Robert Bosch GmbH for the research work at the Ohio University. Its serial number is 0265B60133. The test experiment has been successfully conducted on a flat, open field at the Ohio University Airport, Albany, OH.

1.3 Organization of the Thesis

Chapter 2 introduces various basic concepts of radar sensors. It lays out a foundation for understanding different theoretical concepts. It presents information pertaining to different radar frequencies used along with their nomenclature, the modulation techniques used by the evaluated radar, and the limitations of radar are discussed.

Chapter 3 provides details on different types of radars used in the automobile industry. It presents an overview of various configurations used in different radars for various applications. Detailed information is provided for the antenna beams along with their characteristics, the modulation technique used, and an explanation as to how the radar is able to obtain the distance, and the speed information. This chapter also discusses the application of the LRR for driver assistance systems which includes the speed control system i.e., the ACC.

Chapter 4 illustrates the test setup used in the experiment for this thesis. This chapter lays out step by step procedures for the hardware setup and software configuration settings for logging measurements from the LRR2.

Chapter 5 presents the measurements observed in the test experiment. Different test cases are presented along with their observed values in different scenarios. A detailed analysis is presented for each test case.

Chapter 6 provides the summary, conclusions, and recommendations for future work on LRR sensors for various obstacle detection and/or avoidance applications.

CHAPTER 2: GENERAL RADAR BACKGROUND

This chapter provides background information about the radar - its working principle, frequencies and equations necessary for the remainder of this document. It lays a basic understanding of the radar sensor used in this thesis with different theoretical concepts. The modulation techniques and the external factors affecting the performance of the radar are also presented.

2.1 Basic Radar

Radar is an electromagnetic system which is used for detection and ranging of target objects such as vehicles, ships, aircraft, spacecraft and the natural environment [5]. RADAR is an acronym for “RAdio Detection and Ranging”. It operates by radiating radio frequency signals and detecting the echo signals which are reflected from a target object. The received echo signals are then compared with the transmitted signals by the radar to get the target related information such as distance, velocity, angular position etc. Radar systems can measure target distance with high accuracy in a wide variety of conditions irrespective of weather which is one of its most important attributes.

Figure 1 illustrates the basic principle of a mono-static radar in which a transmitter generates an electromagnetic signal which is radiated in a specific direction by a directional antenna. A portion of this transmitted energy impinges upon and is echoed back by the target object, which is collected by the radar antenna. This echoed signal is processed to detect the presence of the target and its location along with other target-related information.

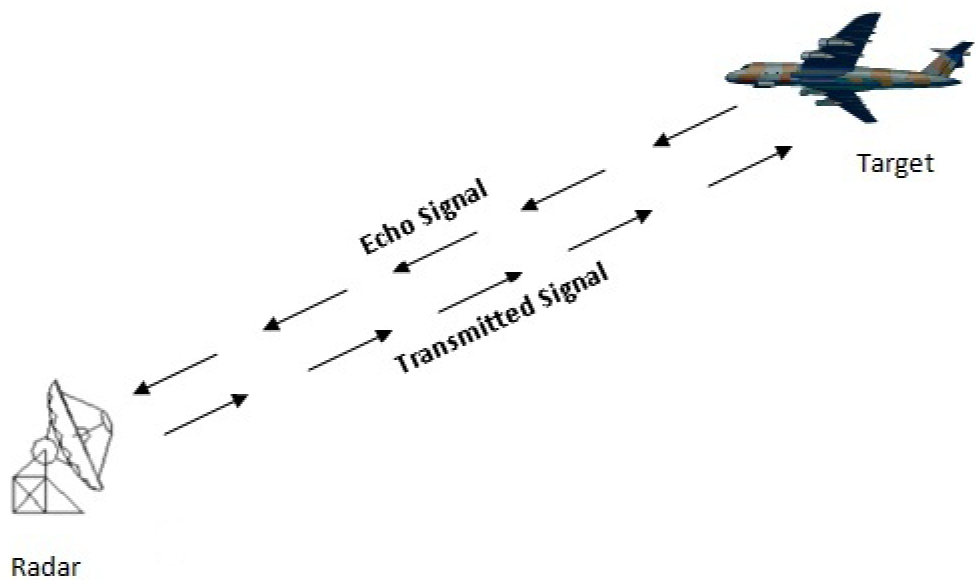


Figure 1: Basic Principle of Radar [5]

The distance to a target is determined by the total time T_R [s] it takes for the radar signal to travel the two ways between the radar and the target. In a free space environment, the electromagnetic signals travel at the speed of light $c = 3 \times 10^8 m/s$, thus the target range R can be given as [5]:

$$R = \frac{cT_R}{2} \qquad [\text{m}] \qquad (2.1)$$

While there are many types of radar systems, pulse modulated and FMCW are very common. Considering a pulse modulated radar, the rate at which radar transmits pulses is determined by the maximum range at which the targets are expected and the number of radar pulses on target are desired. If the time difference between the pulses is too short, an echoed signal from a long range target might be mistakenly associated with the next pulse transmitted by the radar rather than the actual pulse transmitted earlier. These kinds of echoed signals are called s*econd-time-around echoes* and can be misleading if not detected as a second time around echoed signals. These echoed signals can be detected by an equation which gives *maximum unambiguous range* R_{un} beyond which signals appear as second time around echoes is given by [5]:

$$R_{un} = \frac{c}{2f_p} \quad [\text{m}] \tag{2.2}$$

Where f_p is the Pulse Repetition Frequency (PRF) (Hz). Figure 2 shows the plot for maximum unambiguous range R_{un} as a function of PRF f_p.

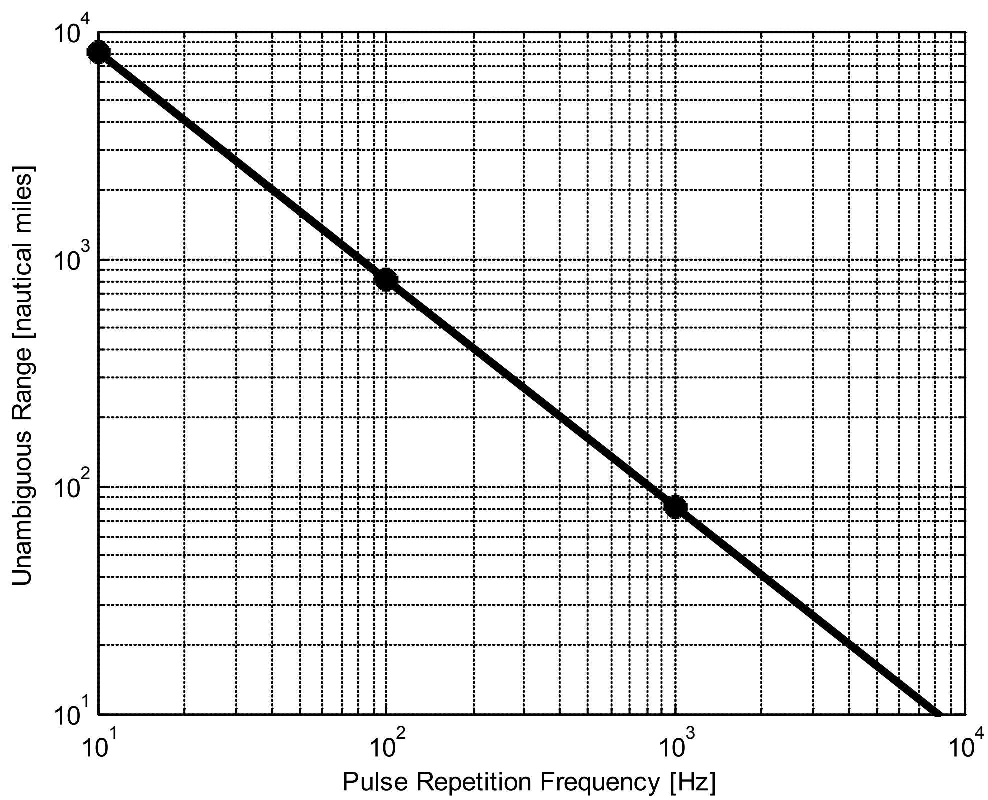


Figure 2: Plot for Maximum Unambiguous Range as function of Pulse Repetition Frequency

The radar receiver also detects weak echo signals which have a similar affect as increasing the received noise. These weak echo signals affect the radar receiver, so in order to eliminate these signals, a cut-off threshold called amplitude detection threshold is established. The radar detects a target only if the received signal amplitude is large enough to exceed this detection threshold and if the received signal amplitude is not sufficient to exceed this threshold, the radar assumes it to be only noise.

If the target object detected is moving with relative speed V_{rel} with respect to radar, then the echoed signal undergoes a frequency shift f_D (i.e., Doppler Shift) relative to the transmitted signal. The frequency shift f_D is given by [9]:

$$f_D = \frac{2 f_c V_{rel}}{c} \quad [\text{Hz}] \qquad (2.3)$$

Where f_c = Signal Carrier Frequency [Hz].

V_{rel} = Relative speed between radar and target [km/hr].

= "+" value when the relative distance is decreasing

= "-" value when the relative distance is increasing

c = Speed of light [km/hr].

For ACC applications, a LRR which has a carrier frequency of 76.50 GHz has frequency shift of approximately 141.66 Hz at a relative speed of 1 km/hr [9].

Radar systems typically obtain azimuth information of target objects by using a directional antenna with a very narrow beam which is mechanically or electronically scanned. In electronic beam scanning, the beam is effectively moved by switching between a set of sources, or by comparing the phase difference and amplitude between the signals received. In mechanical beam scanning, the beam is effectively moved 1) by moving the entire antenna in a desired direction; 2) the reflector can be moved relative to a fixed source, or 3) the feed source can be moved relative to the fixed reflector [26]. The electronic beam scanning is quicker and more agile than the mechanical method of scanning. Electronic beam scanning also helps radar to change or steer the beam polarization and shape. To produce a combination of beam scanning patterns like circular scans, the electronic scanning and the mechanical scanning are often combined.

The LRR2 sensor uses directional antenna which is not mechanically or electronically scanned to transmit the power in a particular direction. It has four antenna beams and depending upon the energy received by the beams, it can basically determine some level of azimuth information. The transmit power can be increased in the direction of the target object as compared to an isotropic antenna by the gain of an antenna. The azimuth resolution performance of radar is typically driven by the antenna beam width, which is a function of frequency and the physical size of the radar antenna.

2.2 Radar Equation

The simple form of the radar range equation relates the range of a target to the characteristics of the transmitter, antenna, receiver, target and the environment. It is useful not only to determine the distance to the target object, but it can also serve as a means of understanding radar system design, and the factors affecting radar performance in the operational environment [5].

The simplified form of the radar equation for calculating the maximum range R_{max} for a target in terms of important key parameters is as follows [5]:

$$R_{max} = \sqrt[4]{\frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 P_{r,min}}} \quad (2.4)$$

Where P_t = Peak Transmitted signal power [W]

$P_{r,min}$ = Minimum Received signal power [W]

G = Transmitter/Receiver antenna gain (monostatic)

λ = Wavelength [m]

σ = Radar cross section of the target [m^2]

Beyond the maximum range, the radar cannot detect the target object and this occurs when the received echo signal power is equal to the minimum detectable signal $P_{r,min}$. This simplified version of the radar equation does not explicitly include other important factors like the losses due to cables, antenna mismatches, atmospheric attenuation, etc [5].

2.3 Radar Frequencies:

Most conventional radars operate in the microwave region between 0.4 and 40 GHz [7]. The IEEE has adopted a list of radar frequency letter band designations which has been used since World War II. These are assigned by the International Telecommunications

Union (ITU) for radiolocation [5]. Appendix A contains technical specification information about different radar frequency bands and its usage. It should be noted that sensors used for automotive land applications should comply with FCC regulations. The operation within the band 76.0 – 77.0 GHz is restricted to LRR sensors mounted on automotive vehicles [FCC 15.253]. The operation in 24 GHz band is for SRR sensors for automobile application [FCC 15.245, 15.249].

2.4 Radar Cross Section of Targets

The Radar Cross Section (RCS) σ depends upon the property of a scattering target object, which is a variable in the simplified radar equation (2.4). The RCS depends upon, in part, the dimensions of the target object compared to the wavelength, the composition of the target, as well as the look aspect angle. When the radar wavelength is small compared to the target object's dimensions, the scattering is said to be in the *Optical region* [5]. This will be the case with the LRR and target objects used, where the LRR wavelength is much smaller than the physical dimension of a target on interest.

2.5 Principles of Frequency Modulated Continuous Wave

The direct measurement of time interval between the transmitted signal and received signal is often complicated, and for that reason, it is normally measured indirectly. FMCW is a measuring technique for range and velocity to compare the frequencies of the transmitted signal and the echoed signal. The prerequisite for the measurement is a transmitted signal that altered its frequency over time.

A voltage controlled oscillator is commonly used to modulate the transmitted signal frequency at a linear rate according to a varying direct current voltage applied. This signal is transmitted through the antenna and also acts as the reference signal required to produce a beat frequency. The time interval and distance to the target object is established indirectly by determining the frequency differences between the transmitted and received signals (i.e., beat frequency) and it is obtained by the means of a mixer and a low-pass filter. The signal is digitized and converted into a frequency spectrum with the help of a Fast Fourier Transform where the peak in the spectrum corresponds to the target object distance [9]. Figure 5 shows the simple block diagram of LRR FMCW radar.

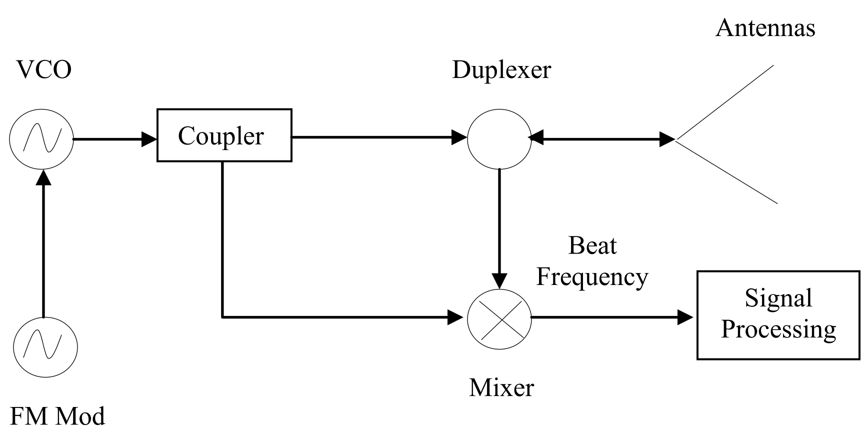


Figure 3: Simple block diagram of LRR FMCW radar [2]

In FMCW radar systems, the transmitter frequency is varied linearly as a function of time. Typically the transmitted wave signal frequency is a triangular waveform as shown in the Figure 4. If there is a target object, an echoed signal in a free space environment will be returned after a time τ. The frequency of the echoed signal lags behind the transmit signal in time in a static system where the transmitter and target objects are stationary. The propagation delay time is given by:

$$\tau = \frac{2R}{c} \tag{2.5}$$

In a pulse modulated radar system, the range measurement is obtained through the propagation time delay between when the pulse is transmitted to the detection of an echo return. But in FMCW radar systems, the range and velocity measurements have to be calculated through the frequency difference between the transmitted and received signals which is known as the beat frequency f_b (ignoring the Doppler shift on the received signal for now). This frequency is proportional to the range between the transmitter and target objects and can therefore be represented as the range frequency f_r. Figure 4a shows the triangular modulated FMCW radar waveform with transmitted signal in solid blue line and received signal in dashed red line. Figure 4b shows the beat frequency for triangular waveform and stationary target.

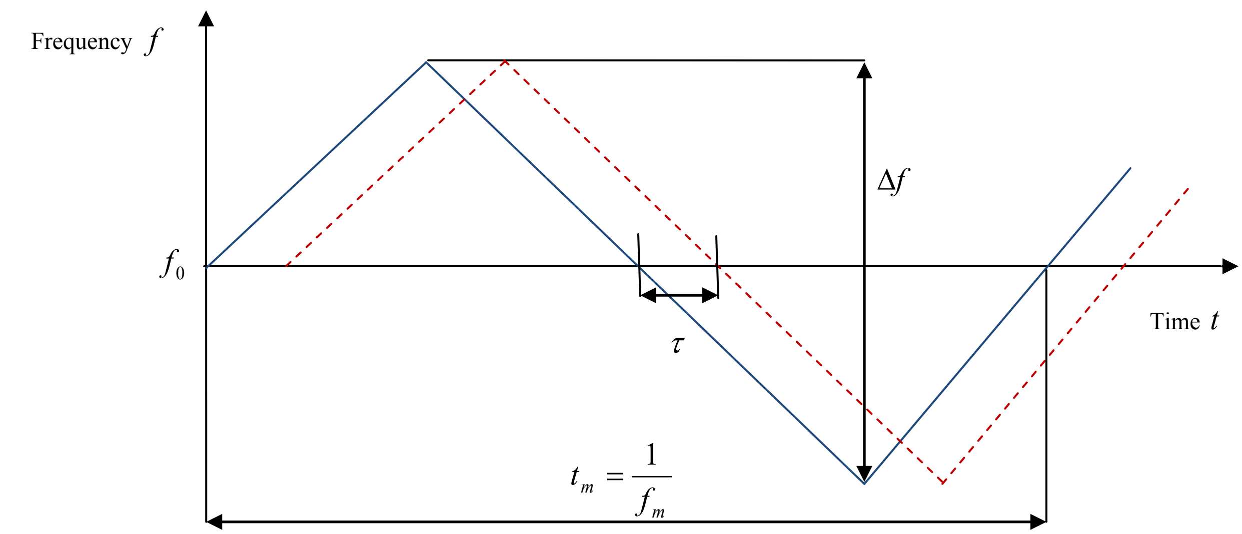


Figure 4a: Triangular modulated FMCW waveform for stationary target.
Transmitted Signal (solid blue) and Received Signal (dotted red)

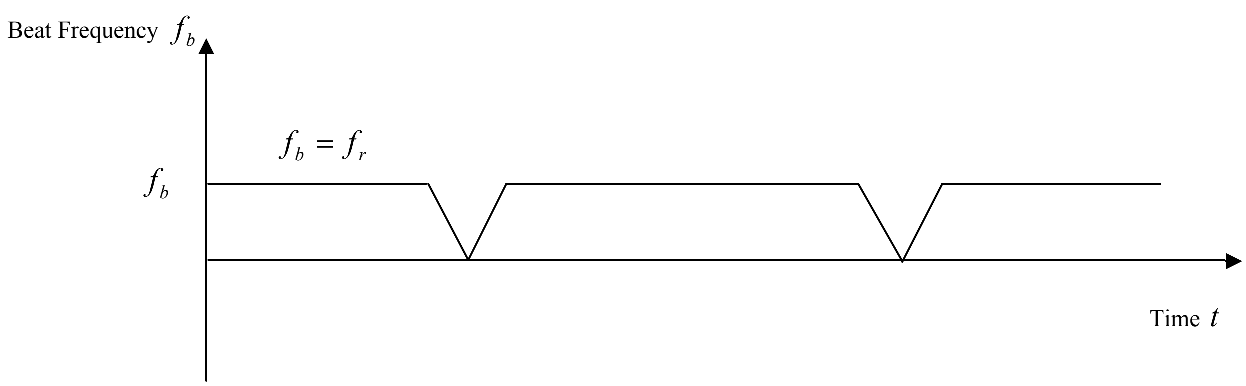


Figure 4b: Beat Frequency for triangular waveform for stationary target.

If the transmitted signal is modulated at the rate f_m over the frequency range of Δf then the beat frequency can be written as [4] [8]:

$$f_r = \frac{\Delta f}{\frac{t_m}{2}} \tau \qquad (2.6)$$

Substituting the value of propagation delay time τ from Eq. 2.5, the beat frequency is directly related to the target range by the equation:

$$f_r = \frac{4R\Delta f}{t_m c} \qquad (2.7)$$

Now since the beat frequency is measured, Eq. 2.7 can be use to solve for the range to the target.

For a moving target, the echoed signal will contain a Doppler frequency shift along with the frequency shift due to the propagation time delay τ. Due to Doppler frequency shifts, there will be a change in the received frequency. Under the assumption that the range frequency will be greater than the Doppler frequency (i.e., $f_r > f_d$), then the Doppler frequency shift term subtracts from the range frequency during the up ramp and the two terms add up during the down ramp waveform as given in the Eq. 2.8 and Eq. 2.9 [4] [6]. Figure 5 shows the beat frequency for triangular waveform and moving target.

$$f_b^{+} = f_r - f_d \, , \qquad (2.8)$$

$$f_b^{-} = f_r + f_d \qquad (2.9)$$

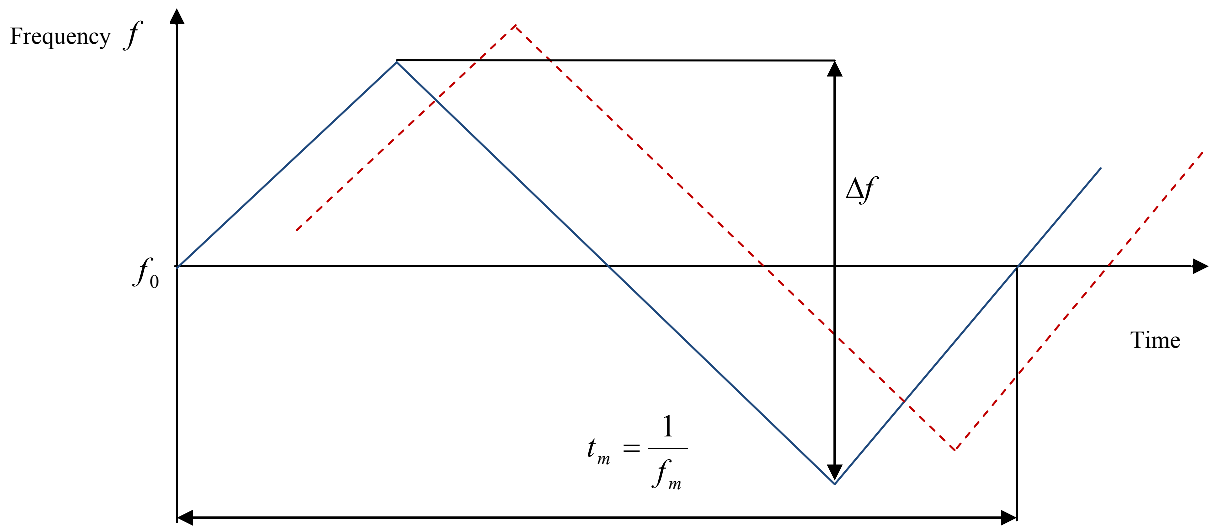


Figure 5a: Triangular modulated FMCW waveform for moving target. Transmitted Signal (solid blue) and Received Signal (dotted red)

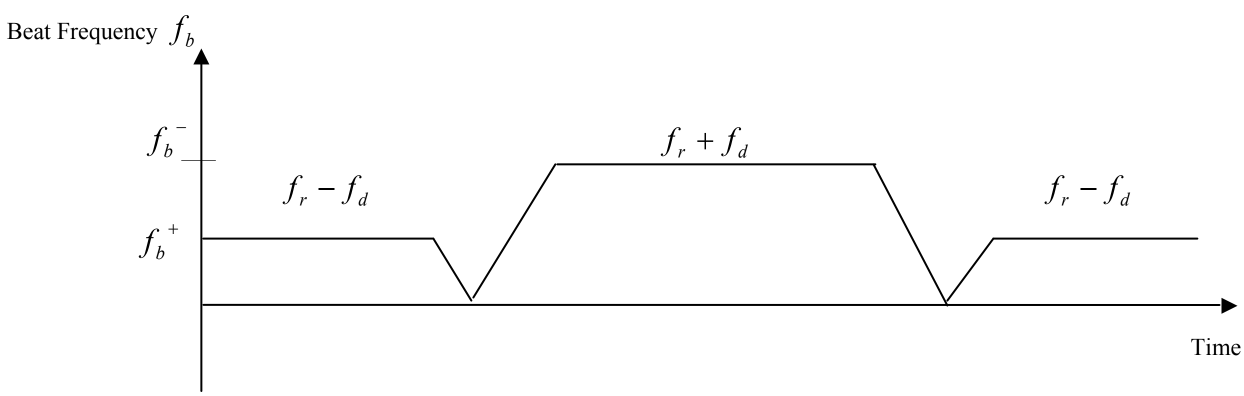


Figure 5b: Beat Frequency for triangular waveform for moving target.

Thus the beat frequency in the presence of a Doppler shift is given by the Eq. 2.10:

$$f_r = \frac{f_b^+ + f_b^-}{2} \tag{2.10}$$

And the Doppler frequency shift is given by:

$$f_d = \frac{f_b^+ - f_b^-}{2} \tag{2.11}$$

Thus, the beat frequency is averaged over the interval t_m, and the range is determined. With the modulation parameters t_m and Δf along with the Doppler frequency shift, the range is computed by averaging Eq. 2.8 and Eq. 2.9, using Eq. 2.10 and then solving for the range:

$$R = \frac{t_m c}{4\Delta f} f_r \tag{2.12}$$

The relative velocity of the target is computed by subtracting Eq. 2.8 and Eq. 2.9, to obtain f_d and then computing:

$$v_{rel} = \frac{\lambda f_d}{2} \tag{2.13}$$

Where λ = Wavelength of the radar [m]

Thus, the frequency modulation rate and maximum frequency deviation of the FMCW radar are design parameters for the expected dynamics of the radar application.

2.6 Atmospheric Attenuation

The electromagnetic energy losses affect the overall performance at each stage, in both the transmitting and receiving portion of the system. There are also atmospheric losses caused by absorption of molecules in the atmosphere [10]. The atmospheric gases (water vapor, oxygen, carbon dioxide, ozone etc) in the clear atmosphere can attenuate the radar electromagnetic energy when the frequency of radar is in close proximity to the resonant frequency of these molecules. The electromagnetic energy attenuation due to water vapor varies with time and place and also depends upon the amount of moisture present in the atmosphere. The resonance peak for water vapor is at 22.2 GHz and for oxygen molecules are at 60 GHz and 118 GHz. The maximum attenuation for 77 GHz radar systems is about 1 dB/km [5]. So these types of radar systems hardly have any affect due to atmospheric gases as they typically have short range 200 m. Additionally other forms of attenuation in the atmosphere like rain, snow, fog are typically very small too because the radar range is small.

CHAPTER 3: COMMON TYPES OF AUTOMOTIVE RADARS

This chapter provides information on popular types of radars used for automotive applications -- SRR (i.e., 24 GHz) and LRR (i.e., 77 GHz). SRR are used for short range (0 - 20m) applications, whereas LRR are used for long range (0 – 200m) applications. Section 3.1 provides a brief description of SRR, its characteristics, and applications. Section 3.2 provides a description about LRR -- a more detailed explanation of antenna beams, modulation techniques, and target object characteristics.

3.1 Short Range Radar 24 GHz

The 24 GHz radar systems are used because they have a broad antenna beam width. They typically have fixed antenna. The main manufactures of these 24 GHz SRR sensors are M/A-Com, Delphi, Hella, etc. The 24 GHz SRR typically use a pulse radar principle with very short pulse length of 350 ps and a PRF of 4 MHz as their measurement technique. Table 1 below shows the main features of these types of SRR sensors [3].

Table 1: Short Range Radar 24 GHz features [3]

Parameter	Minimum	Typ.	Maximum	Unit
Range	0.15		20	m
Pulse Width	300	350	400	ps
Duty Cycle		0.175		%
Average Power	-22	-20	-19	dBm
Peak Power	4	5	6	dBm
Effective Isotropic Radiated Power			20	dBm
S/N	30	32	34	dB

The 24 GHz SRR sensor measures the target range with high resolution over a complete range of up to 20m and with an accuracy of +/- 3cm. The velocity is estimated from the range rate. Angle information can be derived by triangulation techniques in a network consisting of 2 to 6 radar units with a central tracking processor [13]. These radar dimensions are typically small (e.g. $6cm \times 10cm \times 2cm$) with its own integrated signal processing unit and transmits detected target object information on the Controller Area Network (CAN) bus to the Radar Decision Unit (RDU). The RDU get the target information from all possible radar sensors in the system and performs the multilateration to get the position and velocity of the tracked target objects [3].

Figure 6 shows the block diagram of a typical 24 GHz radar sensor. The 4 MHz PRF generator triggers a high speed switch for transmitting very short pulses with a pulse length less than $1ns$. By using ultra-short pulses, a very high range resolution of approximately $10cm$ is achieved. In the mixer, the received pulses are mixed with the delayed transmit pulses. With the help of conventional envelope detection and special filtering, the range information of all detected target objects is sent to the RDU for data fusion and azimuth angle estimation [3].

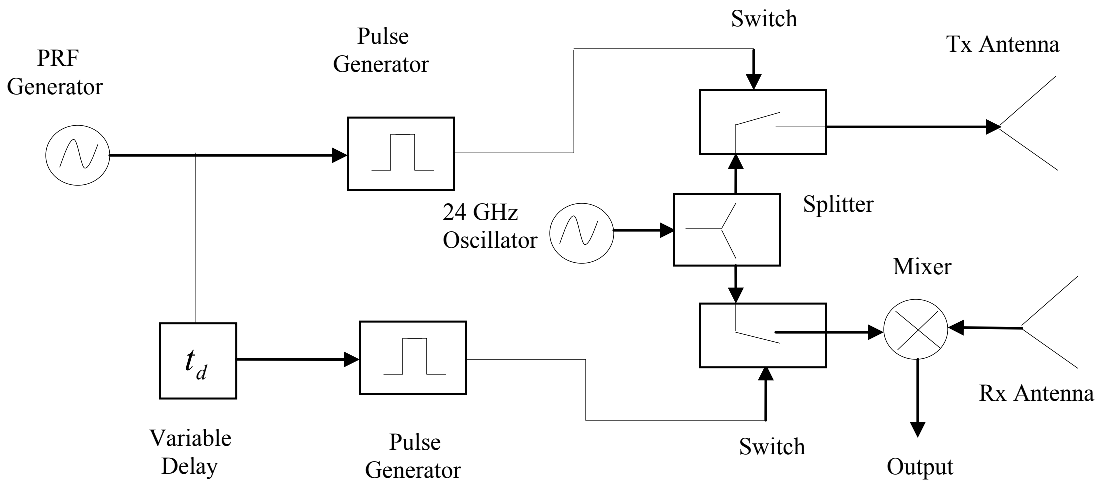


Figure 6: Block diagram of 24 GHz Short Range Radar Sensor [3]

3.1.1 Applications of Short Range Radar

For some automotive security and comfort applications the 24 GHz radar sensor is a good choice since it has good performance in range and azimuth angle measurement for short range use. Figure 7 shows the applications of SRR. The application of these radar sensors are typically in parking aids with higher update rates than conventional ultrasonic systems. It supports a long range ACC system in the short range up to 20m for cut-in situations and stop & go traffic due to the fact that these SRR can have a larger beam-width than the forward looking 77GHz LRR sensors. But it should not be seen as a replacement/substitute of LRR system. The SRR has high detection update rates which make it well suited for pre-crash detection and blind spot detection surveillance and warning for rear end collision [3].

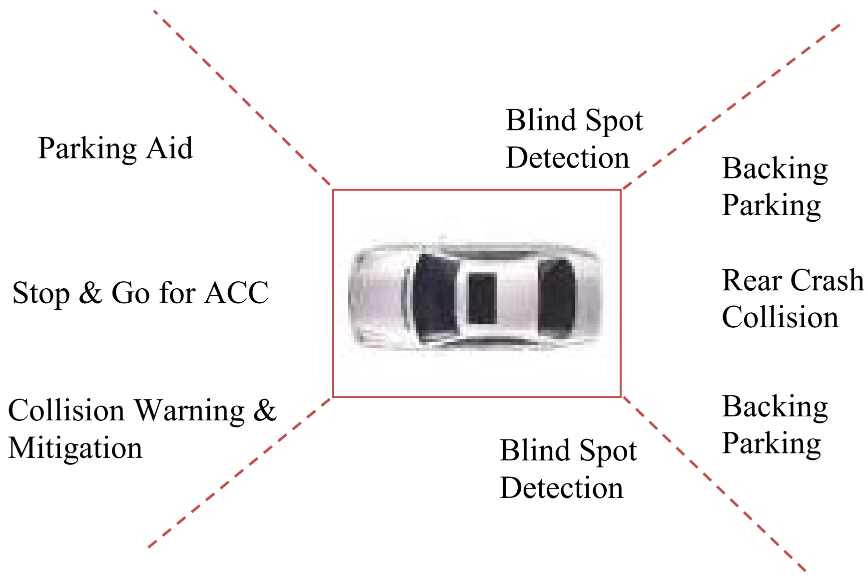


Figure 7: Applications of Short Range Radar [14]

3.2 Long Range Radar 77 GHz Generation 2

The LRR is the centerpiece of the automatic distance and speed control system for ACC and predictive emergency braking systems. These systems network the radar sensor with electronic stability program system. ACC uses information from the radar sensor to maintain a safe driving distance by controlling the vehicles speed by automatically braking and/or accelerating. The predictive emergency braking systems triggers appropriate collision avoidance/mitigation measures by continuously monitoring the situation in front of the vehicle. The system automatically triggers emergency braking, if it predicts that an unavoidable collision is about to occur, so that it can avoid or at least minimize consequences of an impact and to reduce the risk of injury.

The 77 GHz LRR has limited Field of View (FOV) because of its antenna configuration. The antenna system utilizes narrow beam physically fixed antennas, which manufacturers make to keep the size and cost of antenna low which affects the overall performance of the LRR. Manufactures of these 77 GHz LRR sensors are Bosch, M/A-Com, Delphi, Hitachi, Fujitsu Ten, Desno, TRW, etc. Bosch has manufactured different versions of these radars over the years for long range applications, i.e., the LRR (first generation), LRR2 (second generation) and LRR3 (third generation). The LRR has a range of 0 – 120 m with a sensor beam width of 8 degrees, whereas LRR2 has a range of 2 – 200 m with a sensor beam width of 16 degrees and the LRR3 has a range of 0.5 – 250 m with a beam width of 30 degrees. The Bosch radar used in this thesis was the LRR2. It has dimensions of only $74 \times 70 \times 58mm^3 \left(H \times W \times D\right)$ and a weight less than 300g. It can detect up to 32 different target objects and each has a unique message identifier as reported by the radar. Appendix B contains technical specification information of the LRR2. Figure 8 shows the Bosch 77 GHz LRR2 used in ACC applications.

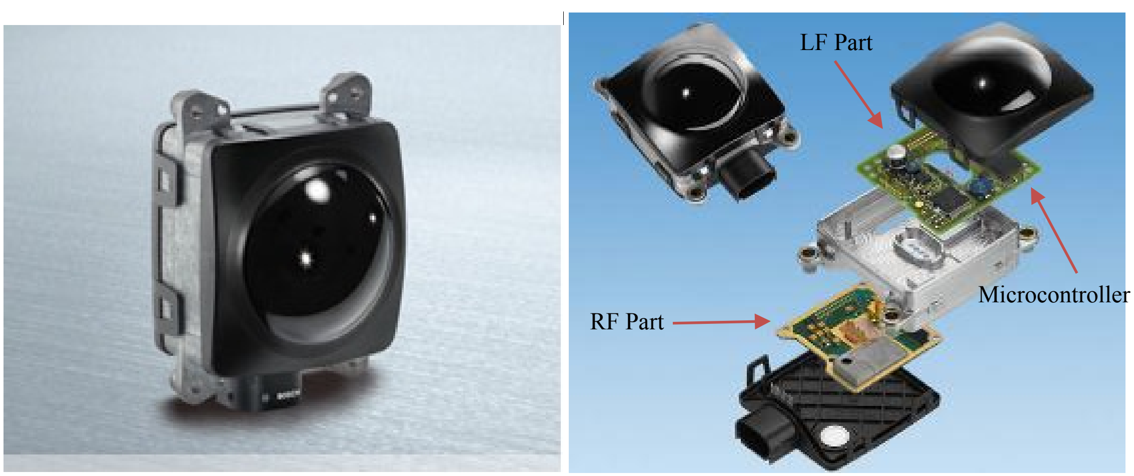


Figure 8: Bosch 77 GHz Long Range Radar Generation 2 used in ACC application [15] [19]

In the hardware implementation, this Bosch LRR2 is divided into different functional blocks. They are High Frequency RF block, Low Frequency (LF) block, voltage supply, and the housing with lens & plug connector [17]. The RF block comprises of four parts, each of which includes other sub components: gunn control, gunn oscillator, mixer, and pre-amplifier. The LF block comprises of two parts: analog-to-digital converter, signal processing and system control. The third block comprises of power supply, lens, and the network interface with the automobile [16].

Figure 9 shows the block diagram of the Bosch LRR. The frequency of this radar can be varied in the range of 76-77 GHz by altering the applied DC voltage to the gunn control circuit. The generated high-frequency signal is passed to a divider circuit through a waveguide which is integrated in the oscillator [9]. The signal generated by the gunn oscillator is routed to the mixer and then through a circulator to the antenna. The transmitted signal is multiplexed and combined with the received signal by means of a circulator. This results in a differential signal, designated as the beat frequency [16]. This signal is then amplified with a pre-amplifier and filtered by a band pass filter and then passed through a four-channel Analog-to-Digital Converter.

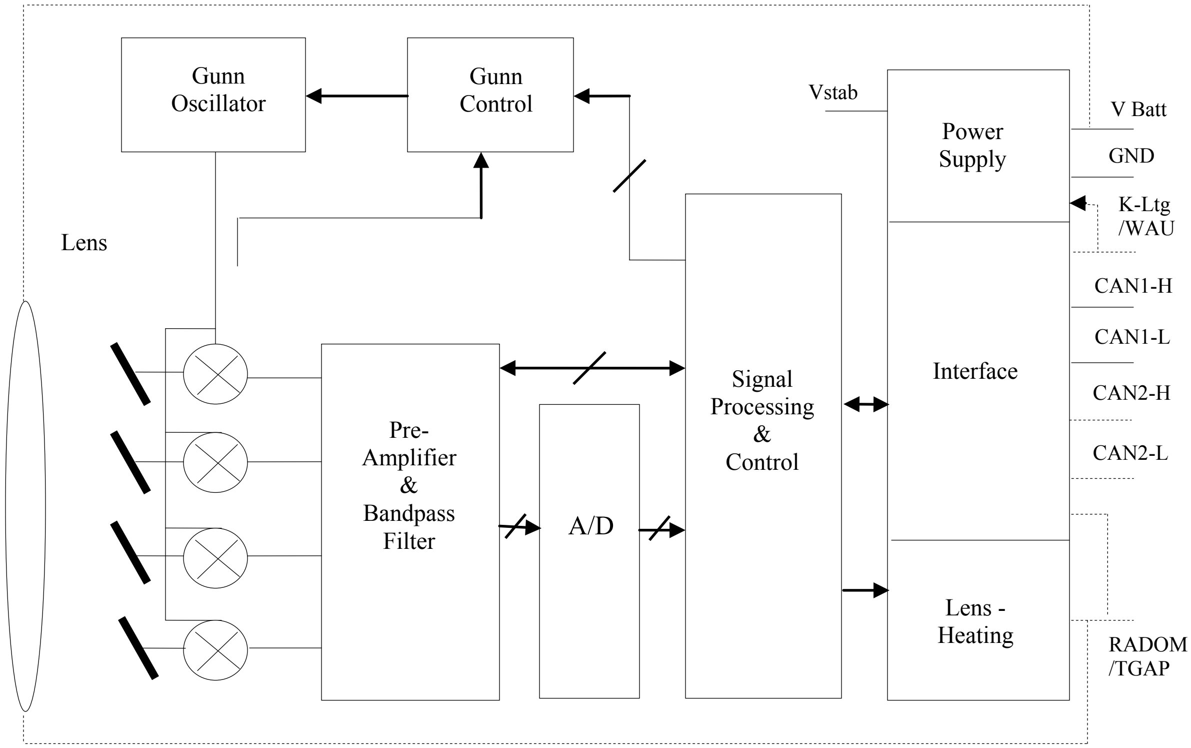


Figure 9: Block Diagram of Bosch Long Range Radar Generation 2 [24]

3.2.1 Antenna Beam

The LRR antenna transmits the radio electromagnetic energy into free space and receives the backscattered electromagnetic energy from the target objects. The LRR2 antenna design is simplified to get it on the printed circuit device and it is not mechanically or electronically scanned. Keeping in mind the very short wavelength of 3.8 mm at 77 GHz, the LRR2 antenna circuitry consists of four feeding poly rods attached directly to four patch elements on the RF board illuminating dielectric lens. The total angular coverage of +/- 8 degrees is obtained by the four single receiving beams partially overlap in azimuth.

Figure 10 shows the total angular coverage is about 16 degrees and the antenna characteristics with respect to the horizontal azimuth angle [15].

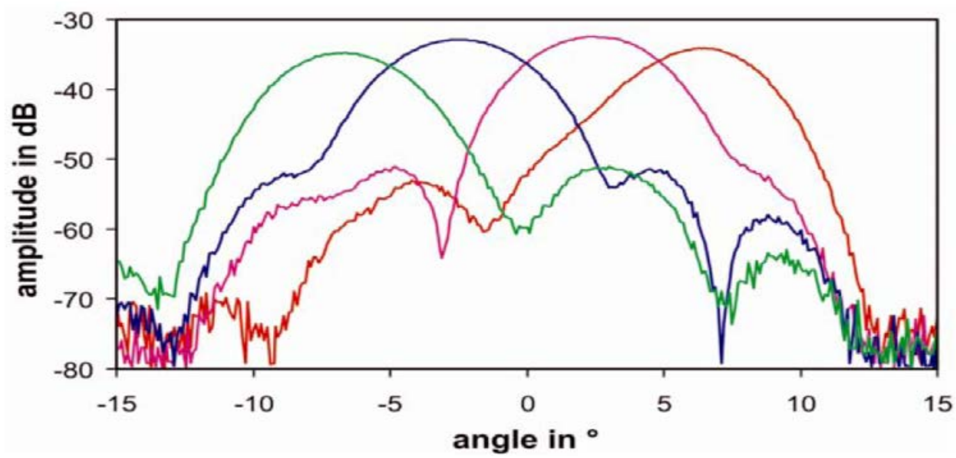


Figure 10: Receive Antenna Beam Patterns for Long Range Radar, 2nd Generation [15]

During transmission, the same radar signals are sent to the four antennas and emitted simultaneously and coherently to produce a transmitted signal. At the receiving end, the separation of the signals from each of the four radar beams takes place with the help of four separate, identical receiving channels [17]. The antenna processing algorithm determines the azimuth of the target. The parameters - distance, relative speed, azimuth angle are determined directly and the derived parameters such as relative acceleration, relative lateral velocity, and the relative lateral offset are also computed. LRR2 sensor can also provide secondary functions such as misalignment angle detection, alignment adjustment support, and blindness detection (probability that radar sensor is dirty) [17]. Figure 11 shows the summary of digital signal processing in the LRR2.

Frequency Modulation	Generation of 3 Linear Frequency Ramps with different Slopes
Spectral Analysis	Windowing, FFT, Calculation of 12 Spectra (4 Beams, 3 Ramps)
Peak Detection	Adaptive Detection Threshold, Search for Maxima in Spectra, Interpolation
Frequency Matching	Frequency Matching of different Modulation, Calculation of Distances and Velocities
Angular Measurement	Comparison of Complex Amplitudes, Matching with Normalized Antenna Patterns
Object Tracking	Plausibility Check, Analysis of Time Sequence of Detections

Figure 11: Summary of digital signal processing in LRR2 [17]

3.2.2 Object Detection Characteristics

The LRR2 uses FMCW radar principle, for a single modulation lasting for a few milliseconds. The signal processing takes place in the frequency domain instead of the time domain as the time measurements are converted into frequency measurements. The Doppler frequency shift and the transit travel time of the radar wave are used to calculate the distance and the relative velocity. The frequency modulation generates three linear frequency ramps with different slopes which are needed for determining the distance and the relative velocity for detection of multiple target objects [17]. Figure 12 shows the FMCW signal transmitted by LRR2 with three different ramps.

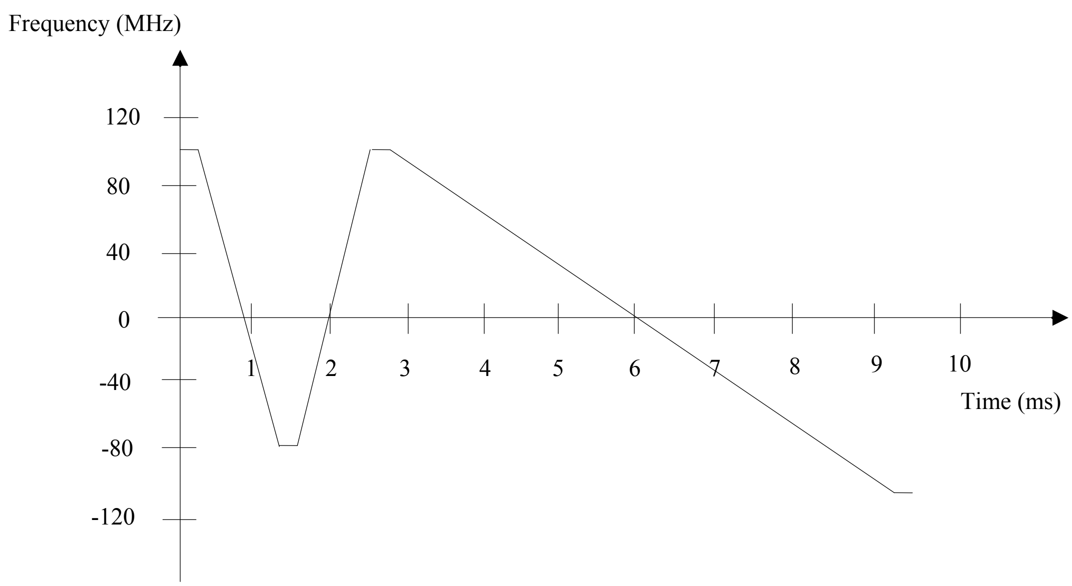


Figure 12: Frequency Modulated Continuous Wave with 3 modulation ramps [16]

The transmit signal is transmitted through each of the four antennas simultaneously. Each antenna acquires a received signal which is then combined with the current transmit signal to form a beat frequency signal. This results in twelve beat frequencies (one for each ramp in each antenna) which are analyzed for location of potential objects. An adaptive threshold is overlaid on the beat frequency signal, to filter out the noise contained in the spectrum. The potential target objects are processed to determine their position; the signals below the threshold are thus excluded. The peak close to zero frequency is also excluded because it is from reflections of the lens [16]. Each of these twelve filtered beat frequency are sampled in the ADC and then processed through a digital signal processor using FFT.

3.2.3 Controller Area Network Bus Interface

The communication protocol used in the LRR2 is CAN. It is a two wire, half-duplex, high-speed serial data communications system for real-time applications that is far more reliable, superior, cost effective to conventional serial technologies such as RS-232, TCP/IP etc. CAN was originally designed for the automotive industries. With the kinds of benefits that were reaped, it has paved its way and became popular in industrial automation, domestic appliances as well as other in applications [21].

The LRR2 detects and tracks the target objects within its FOV, this real-time target data is transmitted over the CAN bus to be used by other systems on the CAN bus. The update rate of the CAN messages for LRR2 is 80 – 120 ms and it has messages stored in Intel format [24]. LRR2 doesn't output raw measurements as all the target decisions are made by an algorithm internal to it. The information on the CAN messages logged for this test are discussed in detailed in the following chapter (refer to 4.3).

CHAPTER 4: EXPERIMENTAL SETUP

This chapter illustrates the test setup used in the experiment for this thesis. It lays out step by step procedures for the hardware setup and software configuration settings for measurements logged from the LRR2.

4.1 CANcaseXL USB

For the tests, CANcaseXL USB 2.0 was used as the interface from the CAN bus of LRR2 to the USB port on a laptop. It is manufactured by Vector GmbH and is based on a high-performance 32 bit microcontroller as shown in Figure 13. It has two completely independent CAN bus channels (Channel 1, Channel 2), is powered from the USB port and has a status display including three LED's per channel (receive, transmit, error) [23].

Figure 13: Vector CANcaseXL USB 2.0 [23]

4.2 CANalyzer Software

CANalyzer 7.0 software, also developed by Vector Software GmbH is an analysis tool that was used to display statistical information and log radar data. It has a computer graphic block diagram display which depicts the data flow from the CAN bus for various screen evaluation windows. Blocks can be inserted at any point on the data flow and the user can program the functions with the help of application-oriented C-like language, which is Communication Access Programming Language (CAPL). It has an interactive development environment which makes it easy to create, modify and compile CAPL programs. In the project database, there is an option to assign project-specific names, conversion formulas, physical units, etc for the CAN messages and their data segments. This database helps to represent CAN messages and their data parameters on the application level (e.g., target distance = 77 m, vehicle speed = 80 mph). Data logging is used to record the entire data measurements or parts of measurements into the multiple files [22].

4.3 Configure Radar Messages using CANalyzer Software

The Interface Control Document (ICD) for the LRR2 provided by Robert Bosch GmbH describes all the input, output and control messages [24]. This document provides the header information (contents of messages & norm of their signals) for all the radar messages available over the CAN network. Using this ICD as a reference, a database was created for all LRR2 messages desired to be logged, analyzed and recorded in the CANalyzer software. *ACC_T01* (0×792) *and ACC_T02* (0×793) are the two CAN messages which give information about the target object detected by the LRR2. *ACC_T01* message gives distance, relative speed, relative acceleration of the target object and lateral distance of the target object relative to vehicle (*ACC_T02* message gives some more additional information about the target object which is not used in this thesis). The range until which LRR2 shows the target information with constant message ID (0×792) is considered to be a good target. LRR2 keeps lock on the target with constant message ID (0×792) which is closer in range, while the other target has varying message ID (i.e. $0 \times 6B6 - 0 \times 6D5$). Figure 14 illustrates the database that was built for the LRR2 CAN messages in CANalyzer software.

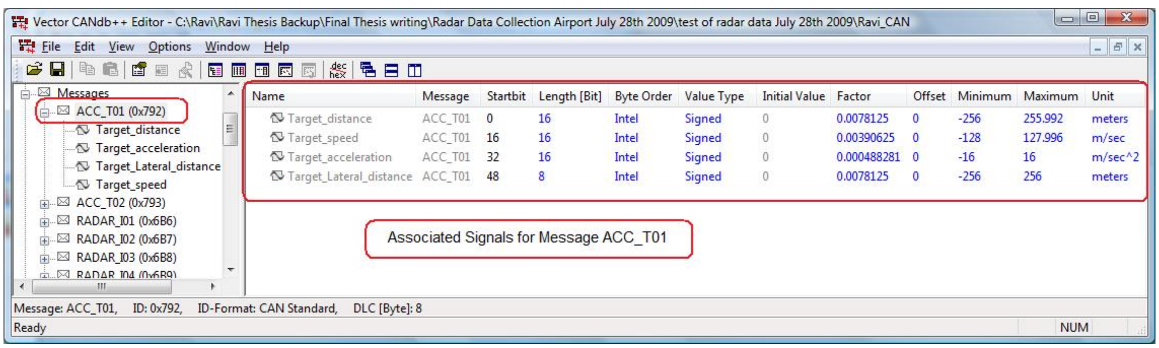


Figure 14: Database for LRR2 CAN messages in CANalyzer software

During each cycle, the LRR2 sensor unit transmits three messages (*RADAR_INFO1, RADAR_I01-RADAR_I32, RADAR_INFO2*) to the CAN network. The control unit in radar waits up to an internal cycle duration of 150 ms for the above three messages [24]. The message *RADAR_I01-RADAR_I32* contains the object information of 32 detected targets. After receiving *RADAR_INFO2,* the control unit continues to send its messages (*CU-I0, CU_REQUEST, CU_I1*) within a time range of 20 ms. If one of the *CU_XX* messages has not been received within the stipulated 20 ms time duration then an error message (*ACC_SGU_STATUS*) is generated with the corresponding error flag [24].

For data integrity and safety reasons, the measurement number from the *RADAR_INFO1* message has to be copied into the control message *CU-I0*. If there is a discrepancy between the measurement number received from control unit and the former measurement number sent, an error message (*ACC_SGU_STATUS*) will be generated [24]. For this to be implemented, a CAPL based program was written in the CANalyzer software [25] (Refer to Appendix C). Figure 15 shows the measurement setup with CAPL node for the messages to be send to the LRR2 in the CANalyzer software.

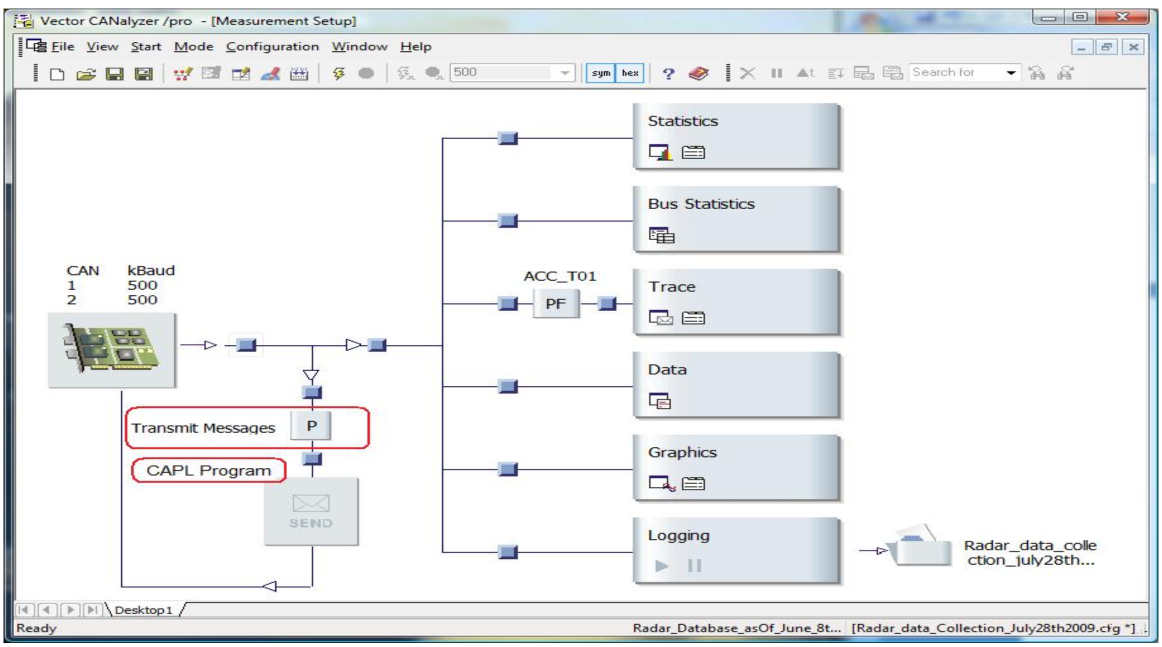


Figure 15: Measurement setup with CAPL node for the messages to be send to LRR2 in CANalyzer 7.0 Software

4.4 Setup on Mobile Cart

The experimental setup consists of the Bosch LRR2 ACC radar mounted on the front side of a moving cart. The LRR2 was connected to laptop with the help of the Vector

CANcaseXL USB 2.0 interface. A Compaq Presario V2000 laptop was used to collect the data and an uninterrupted power supply with internal battery storage was used to supply power to equipment on the moving cart. The equipment could operate for approximately 2 hrs before the batteries in the UPS were depleted. As the LRR2 tracks and detects different objects within its FOV, real-time target objects information was transmitted over the CAN bus, which was collected in the laptop with the help of the Vector CANcaseXL USB 2.0 interface. The Vector CANalyzer 7.0 software tool was used to collect/log the data and to display the real-time statistical information about the target objects. Figure 16 shows a photograph of the LRR2 setup on the moving cart.

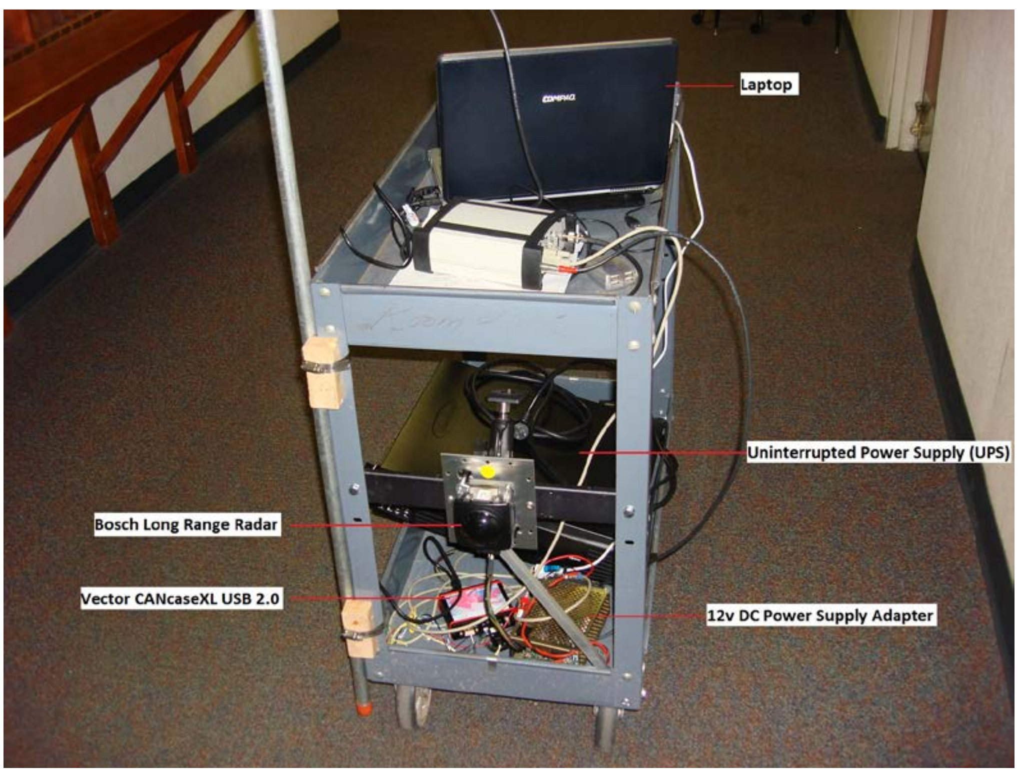


Figure 16: Experimental Test Setup of LRR2 on moving cart

The measurements were aimed at performance assessment for this LRR2 for various obstacles avoidance application. For these initial tests, a simple operational environment was desired. Thus, a flat open field test area was selected on a taxiway at the Ohio University Airport, Albany, OH. The test cart was moved along the taxiway lane marker (yellow line) in Figure 17, with target shown is Van. The length distance markers were placed along the yellow taxiway lane marker to verify range measurements of the radar to the target. These length distance markers were measured with a measuring tape and considered the true range for data analysis to follow.

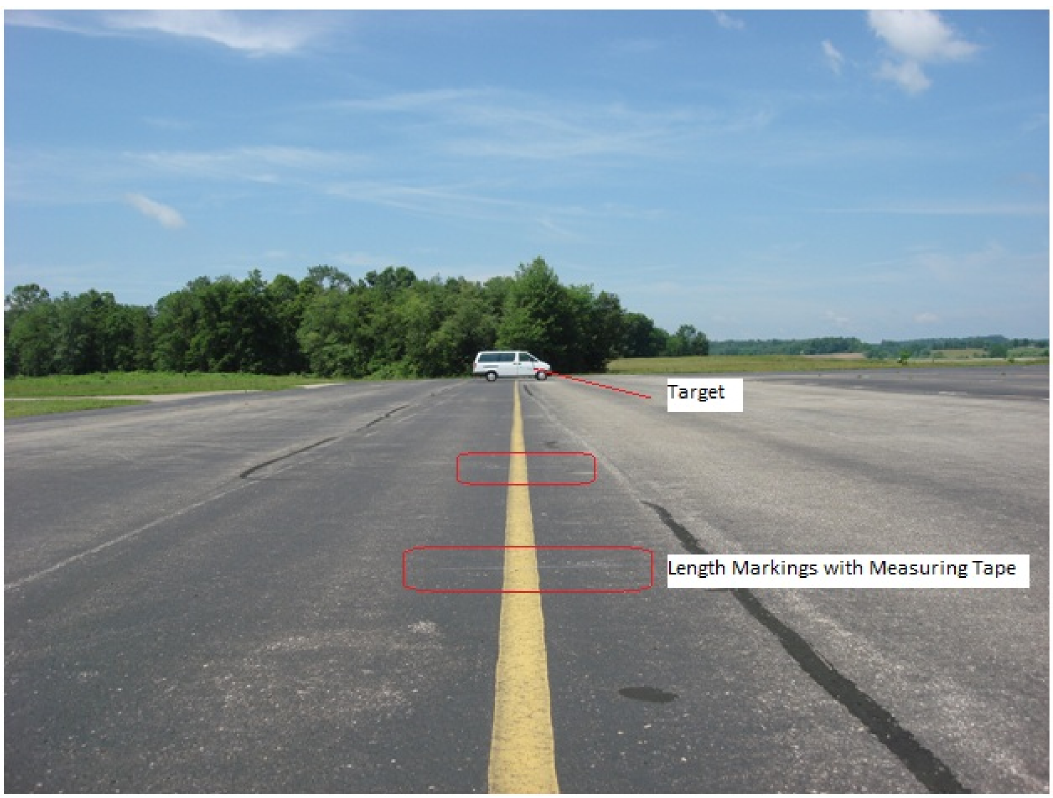


Figure 17: Ohio University Airport Taxiway where test data (Radar Measurements) was collected

4.5 Target Objects List & Dimensions

To evaluate the LRR2 for various obstacles avoidance application, various targets were selected, as shown below.

1. **Human:** Adult Male, 6’1”, approximately 190 lbs
2. **2 Circular Metal sheet:** 2 ft in diameter made out of aluminum 0.5” thickness, mounted on dielectric wooden stand, ~1m up from ground
3. **Van:** 1998 Ford Aerostar passenger van
4. **Bicycle/Human:** 26" Men's Roadmaster Mountain Sport Bike with metal frame
5. **Motorcycle/Human:** 2006 Triumph Speedmaster Motorcycle - height 46.6”, width 37.6”, length 95.4”
6. **Traffic Barrel:** Material used is impact resistant polyethylene. It is orange and white striped with ultraviolet stabilizer to inhibit color fading with 4” bands of retro reflective strips. Height: 42.5" overall, width: 18" top, 23.5" base, 18" minimum diameter.
7. **4’’ Pole:** 6’ height, 4” diameter made of carbon steel
8. **Aircraft:** Beechcraft bonanza V35

An airfield is a very busy place with constant motion of many different vehicles such as baggage carts, security vehicles, catering trucks, refueling trucks and the aircraft etc. Therefore, it may be beneficial for the moving vehicles to be equipped with some system to detect and warn the drivers of any possible collision with other object in its vicinity. So the aircraft was also chosen as a target object to see how far the LRR2 could detect aircraft on the taxiway for possible runway incursion mitigation. The Metal Sheet as a target was chosen because it has a very well defined known RCS. The Pole is chosen as people might hit while driving. The Human as target was chosen as pedestrian is a typical obstacle which has to be detected by the collision avoidance systems. For the Motorcycle/Bicycle as a target objects, Human was also present along with them in the radar's detection zone. Figure 18 shows pictures of various targets objects used in this test.

a. Van

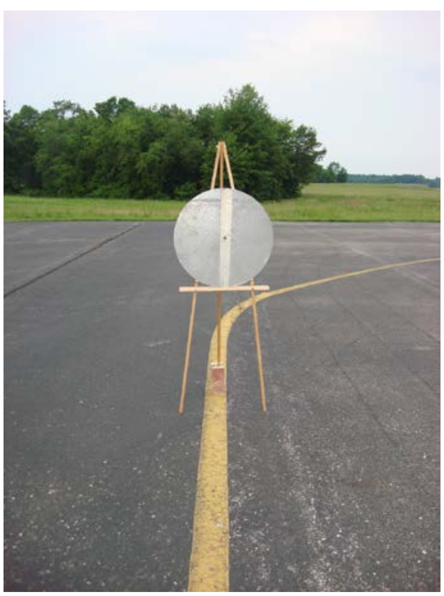
b. Motorcycle (Human not shown)

c. Bicycle (Human not shown)

d. Aircraft

e. Traffic Barrel

f. 4” Pole



g. Circular Metal Sheet

Figure 18: Various Target Objects used in the Test Experiment

CHAPTER 5: MEASUREMENTS & ANALYSIS

The performance of a radar system is affected by many factors which include the size, shape and the composition of the target objects. This thesis mainly discusses five test cases on several target objects. The measurements for performance assessment of LRR2 sensor were divided into five testing categories. These five test cases include – 1) finding maximum range, 2) range accuracy, 3) finding maximum FOV, 4) detection (& separation) of two target objects (similar & different types) at different radial distance and 5) radar's maximum range for detecting an aircraft. The target objects used in these tests were as described in the previous chapter. The tests were performed July 28, 2009 on a sunny day with temperature of 75 degrees Fahrenheit.

The test setup consisted of a LRR2 sensor mounted in the front of a moving cart. An initial test for false detection was done before starting with the data collection. With the detection zone totally clear, the moving cart with LRR2 was moved in the direction of sensing to determine if there were any false alarms and if a false alarm occurred, the root cause had to be determined and noted. Then, the system settings were adjusted or relocated to a different test area where false alarms were minimum or none. The radar detects and tracks the target objects within its FOV, where the real-time target data is transmitted over the CAN bus to the laptop through the CANcaseXL interface for data logging and display purposes.

As presented in Section 4.2, the CANalzyer 7.0 software application was used for data measurement and logging purposes. Figure 19 shows a real-time screen shot of this software application with target objects information as detected by the LRR2.

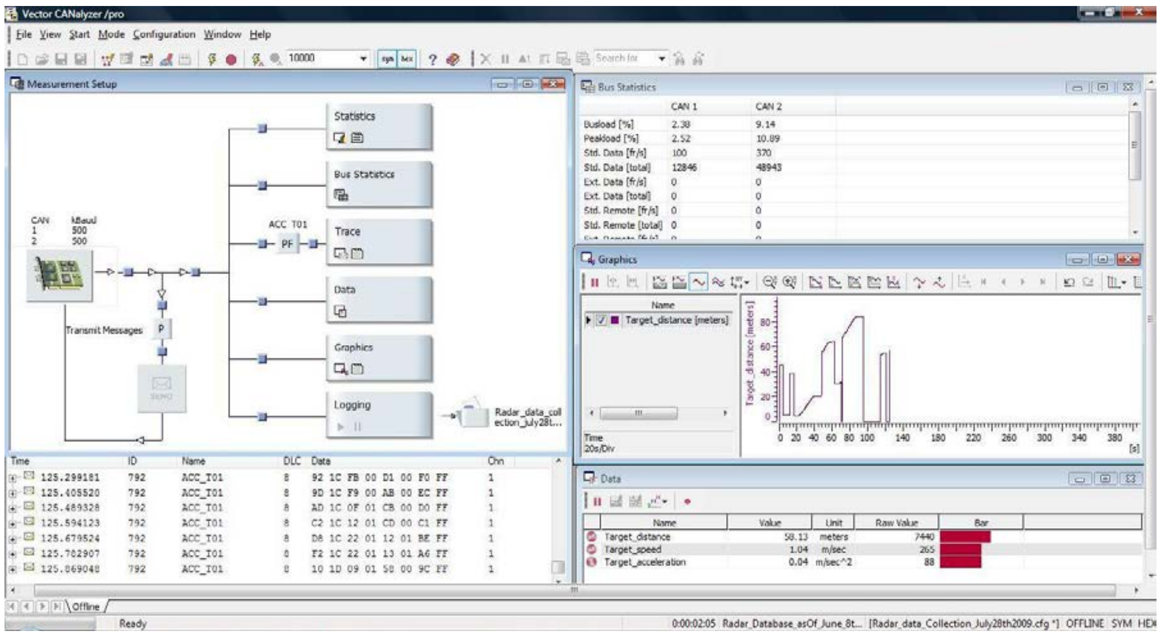


Figure 19: CANalzyer Software with target objects information as detected by LRR2

5.1 Test Cases

The performance of the radar will varies whether the vehicle is moving towards or away from the target as it is a function of the detection algorithm. If a target is already there and the signal power is lost, often that is going to happen faster than if the vehicle is approaching a target and then it has to exceed the threshold. The radar performance also depends upon the relative velocity between the target and the radar. If the vehicle is moving away slowly, the time to detect the target in the algorithm is typically not a concern. In these tests, good solid target object was detected initially and as the cart was moved away from the target (as the range was increased), the target was lost. The criteria for when a target was declared was until the radar stopped reporting a consistent message ID (0×792) from the CAN bus. This criterion was used for all tests. It has to be recognized that this doesn't exactly represents an operational scenarios with the fast moving automobiles. Those types of operational tests would be done in the future tests.

5.1.1 Maximum Range

The purpose of this test was to determine the maximum range of the LRR2 to detect various target objects. According to the specifications (see Appendix A) given by the manufacturer, the LRR2 can detect target objects up to 200 m; however, the RCS of the target is not explicitly specified to achieve this range. This test was divided into two categories. The first category was when the target objects were perpendicular to the radar along the center of the FOV and the second category was when the target objects were parallel to the radar along the center of its FOV. The Radar Range was compared with the True Range measured by means of a measuring tape (Refer to Figure 17). The point at which LRR2 stopped reporting target information with a consistent i.e., non-changing message ID (0×792) was taken as the maximum range of the target object. The True Range is the range measured by measuring tape, the Radar Range is the range measured by LRR2 sensor, and the Range Measurement Error is the difference between True Range and Radar Range.

Perpendicular:

Figure 20, 21 shows the target object (Van) on the taxiway kept stationary perpendicular to the radar along the center of its FOV, while the radar cart was moved away from the target along measured markings (yellow colored lines) in a straight path until the radar losses lock on target. Table 2 shows the results of radar maximum range for the various target objects tested.

Figure 20: Target object (Van) on the taxiway field placed perpendicular to the radar

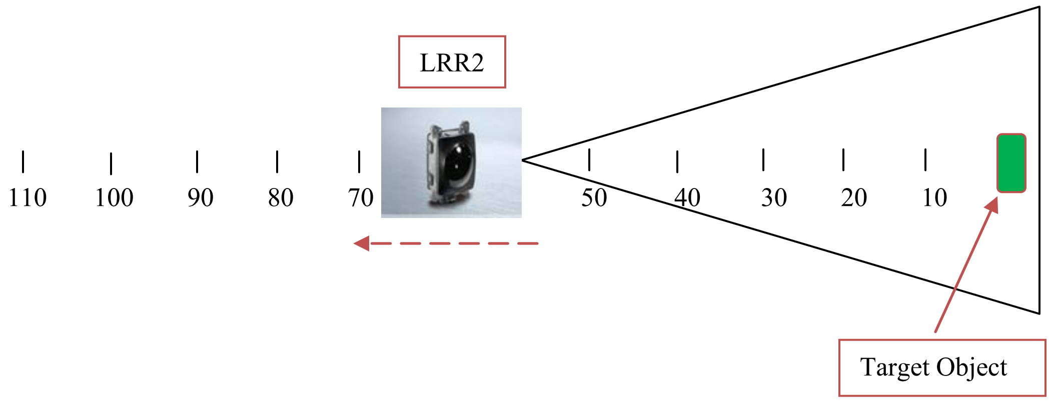


Figure 21: Target object placed perpendicular to the radar, as the radar cart was moved along measured markings in a straight path

Table 2: Radar maximum range measurements when target objects are perpendicular to radar along the center of its FOV

Target Object	True Range (m)	Radar Range (m)	Range Measurement Error (m)	Range Measurement Error (%)
Van	105.00	105.13	0.13	0.12
Motorcycle/ Human	100.00	100.16	0.16	0.16
Bicycle/Human	90.00	90.13	0.13	0.14
Traffic Barrel	85.00	84.92	-0.08	-0.09
Human	95.00	95.20	0.20	0.21
Metal Sheet	70.00	70.31	0.31	0.44
4 inch Pole	40.00	40.07	0.07	0.17

Parallel

The target object was kept stationary parallel to the radar along the center of its FOV, while the radar cart was moved away from the target along measured markings (yellow colored lines) in a straight path until the radar losses lock on target. Figure 22 shows the target object (Van) on the taxiway field placed parallel to the radar. Table 3 shows the results of radar maximum range for the various target objects tested.

Figure 22: Target object (Van) on the taxiway field placed parallel to the radar

Table 3: Radar maximum range measurements when target objects are parallel to radar along the center of its FOV

Target Object	True Range (m)	Radar Range (m)	Range Measurement Error (m)	Range Measurement Error (%)
Van	95.00	95.20	0.20	0.21
Motorcycle/ Human	85.00	85.26	0.26	0.30
Bicycle/Human	75.00	75.24	0.24	0.32
Human	65.00	64.81	-0.19	-0.29

As the target objects (Traffic Barrel, 4” Steel Pole, and Metal Sheet) were symmetrical in shape, they were tested only in one case (i.e., perpendicular). The radar was able to detect the Van (target object) from a longer distance because of its relatively larger cross section area than other target objects. The maximum range detected by the LRR2 for targets differ slightly when they are placed perpendicular than when placed parallel to the radar along the center of its FOV because of its larger area of cross section of the targets in the perpendicular position. From the observed measurements as in Table 2, the LRR2 was able to detect up to 105 m (Van as a target object) without losing lock on the target and for other target objects, the maximum radar detection range was less than 100 m.

5.1.2 Range Accuracy

The range accuracy is a degree of conformance between the measured range to a target at a given time as compared to the targets true range. It is used as a statistical measure of the system error. In order to investigate the range accuracy of the LRR2 at various true range distances, the target object was kept at one location perpendicular to the radar along the center of its FOV and the radar cart was moved away from target along measured markings (yellow colored lines) in a straight path in increments of 5m, as shown in the Figure 17. Table 4 shows the results of the radar range measurement error investigation for the various targets used.

Table 4a: True Range vs. Measured Radar Range for targets (Van, Motorcycle/Human, Bicycle/Human) in increments of 5 m.

True Range (m)	Van		Motorcycle/Human		Bicycle/Human	
	Radar Range (m)	Range Measurement Error (m)	Radar Range (m)	Range Measurement Error (m)	Radar Range (m)	Range Measurement Error (m)
5.00	4.98	0.02	4.91	0.09	5.05	-0.05
10.00	9.92	0.08	9.83	0.17	10.07	-0.07
15.00	14.95	0.05	14.87	0.13	15.02	-0.02
20.00	19.91	0.09	19.82	0.18	20.05	-0.05
25.00	24.95	0.05	24.87	0.13	25.06	-0.06
30.00	29.96	0.04	29.91	0.09	30.03	-0.03
35.00	34.89	0.11	34.81	0.19	35.04	-0.04
40.00	39.91	0.09	39.85	0.15	40.05	-0.05
50.00	49.87	0.13	49.91	0.09	50.01	-0.01
60.00	59.90	0.10	59.80	0.20	60.10	-0.10
70.00	69.88	0.12	69.81	0.19	70.06	-0.06
80.00	79.91	0.09	79.85	0.15	80.07	-0.07
90.00	89.86	0.14	89.79	0.21	90.06	-0.06
100.00	99.93	0.07	99.81	0.19		
	Average Error (m)	0.08		0.15		-0.05

Table 4b: True Range vs. Measured Radar Range for targets (Human, Traffic Barrel, Metal Sheet, 4" Pole) in increments of 5 m.

True Range (m)	Human		Traffic Barrel		Metal Sheet		4" Pole	
	Radar Range (m)	Range Meas-urement Error (m)	Radar Range (m)	Range Meas-urement Error (m)	Radar Range (m)	Range Meas-urement Error (m)	Radar Range (m)	Range Meas-urement Error (m)
5.00	4.99	0.01	5.03	-0.03	5.02	0.02	5.01	-0.01
10.00	9.96	0.04	10.07	-0.07	10.05	0.05	10.02	-0.02
15.00	14.95	0.05	15.02	-0.02	15.06	0.06	15.02	-0.02
20.00	19.94	0.06	20.07	-0.07	20.09	0.09	20.03	-0.03
25.00	24.93	0.07	25.06	-0.06	25.11	0.11	25.06	-0.06
30.00	29.93	0.07	30.04	-0.04	30.10	0.10	30.08	-0.08
35.00	34.90	0.10	35.03	-0.03	35.14	0.14	35.09	-0.09
40.00	39.90	0.10	40.09	-0.09	40.12	0.12	40.11	-0.11
50.00	49.91	0.09	50.12	-0.12	50.16	0.16		
60.00	59.89	0.11	60.10	-0.10	60.11	0.11		
70.00	69.90	0.10	70.08	-0.08	70.14	0.14		
80.00	79.87	0.13	80.12	-0.12				
90.00	89.82	0.18						
Average Error (m)		0.09		-0.07		0.10		-0.05

Figure 23 plots the LRR2 range accuracy for different target objects at different distances. From the measurement observations, the average radar range error for different targets at different distances was less than +/-0.2 m, which is far better than what was stated in the manufacturer's specifications [24]. The radar range errors are within these values and there is very little increase in its value proportional to the range as shown in Figure 23.

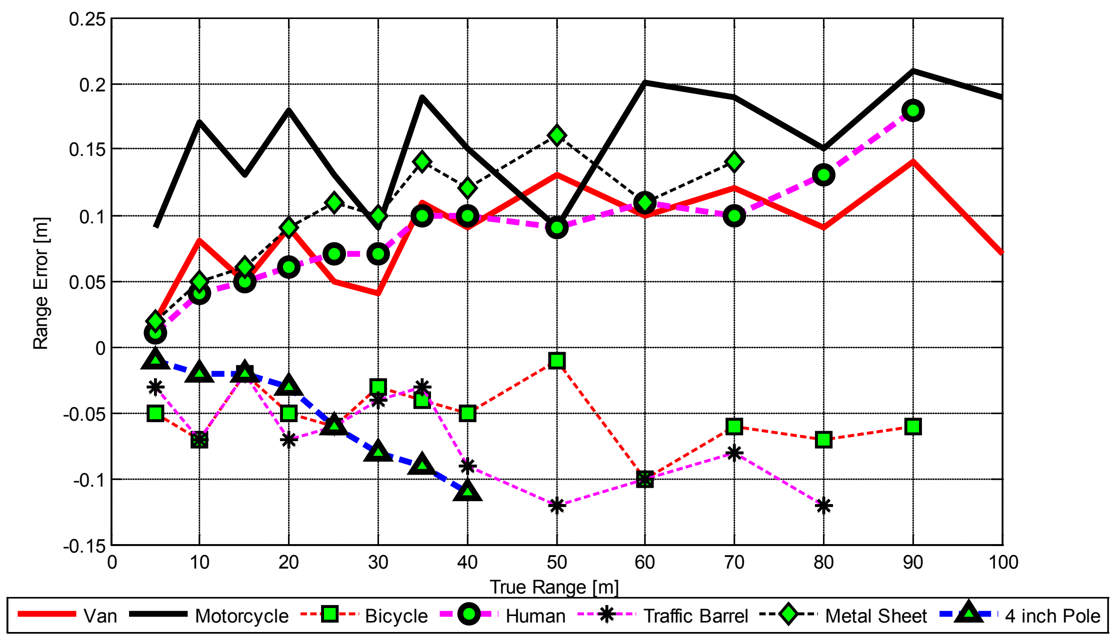


Figure 23: LRR2 range accuracy for different target objects

5.1.3 Maximum Field of View for a Single Target

The FOV measurement test provides information on the effectiveness and extent of area the LRR2 can observe targets in front of it. This test was done with various target objects. The procedure used to determine the FOV was to measure the maximum distance on both sides (i.e., left & right) of the center line of the FOV where the radar was able to detect the target object. The targets were moved from the center line to both, left and right sides, until they disappeared from the radar's detection zone and then they were brought back until they reappeared. Figure 24 below shows the FOV setup and measurement. The FOV values were calculated by using simple trigonometric equations.

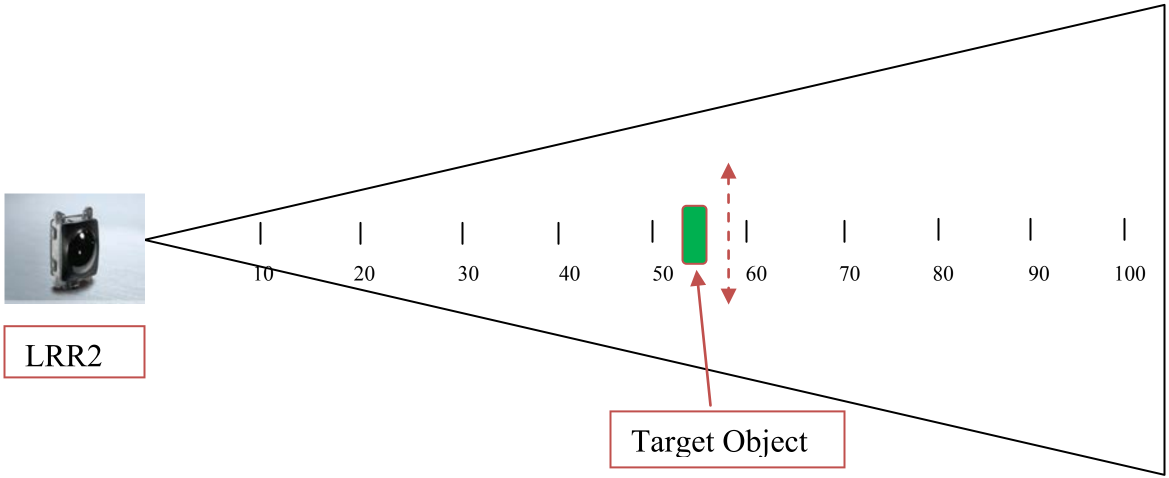


Figure 24: FOV setup and measuring method

From the observed measurements listed in Table 5, the average FOV of the LRR2 in detecting a human as target was $15°$, a metal sheet as the target was $12°$ and a traffic barrel as target was $18°$. The observed LRR2 FOV measurements were close to the value specified by the manufacture i.e., $16°$ but that depended upon the target size, material used, and it's RCS. The traffic barrel has a larger FOV compared to other targets due to its larger cross sectional area and most importantly it is white striped with ultraviolet stabilizer to inhibit color fading with 4" bands of retro reflective strips surrounding them.

Table 5a: Distance measured by LRR2 with Human as target to determine FOV

Human					
True Range (m)	Left Distance (m)	Left FOV (deg)	Right Distance (m)	Right FOV (deg)	Total FOV (deg)
15.00	2.33	8.83	1.74	6.60	15.43
20.00	2.98	8.48	2.36	6.74	15.22
25.00	4.05	9.21	3.13	7.14	16.35
30.00	4.72	8.93	3.48	6.61	15.54
35.00	5.20	8.44	4.22	6.88	15.32
40.00	5.95	8.46	4.95	7.05	15.52
				Average FOV	15.56

Table 5b: Distance measured by LRR2 with Metal Sheet as target to determine FOV

Metal Sheet					
True Range (m)	Left Distance (m)	Left FOV (deg)	Right Distance (m)	Right FOV (deg)	Total FOV (deg)
15.00	1.78	6.77	1.12	4.27	11.04
20.00	2.66	7.58	1.39	3.98	11.55
25.00	3.42	7.78	2.03	4.64	12.42
30.00	4.30	8.16	2.97	5.65	13.81
				Average FOV	12.21

Table 5c: Distance measured by LRR2 with Traffic Barrel as target to determine FOV

Traffic Barrel					
True Range (m)	Left Distance (m)	Left FOV (deg)	Right Distance (m)	Right FOV (deg)	Total FOV (deg)
15.00	2.33	8.83	2.34	8.85	17.68
20.00	2.58	7.36	2.54	7.22	14.58
25.00	4.43	10.05	4.56	10.34	20.39
30.00	5.92	11.15	4.88	9.23	20.38
35.00	7.23	11.67	5.58	9.06	20.73
				Average FOV	18.75

5.1.4 Range Resolution in Detecting Two Similar Targets

The ability of the radar to detect two close target objects at different radial ranges along the center of the FOV is defined as the Range Resolution. For this test, the ability of the LRR2 to resolve similar and different types of targets was investigated; this section will present results when using two similar targets, and the next section will present results using two different targets.

To investigate the LRR2 ability to resolve two targets of the same type, pair of metal sheets were used in this test case. First, the LRR2 was positioned by having the metal sheets at the same height; both were 2 feet above the ground at different radial distances (i.e., up to 5m), but the LRR2 was able to detect only one metal sheet closer to it and was not able to separate both the metal sheets.

The next test case positioned the target objects at different heights. One metal sheet was kept slightly above the ground while the other metal sheet was kept at 2 feet above the ground at a different radial range as shown in Figure 25.

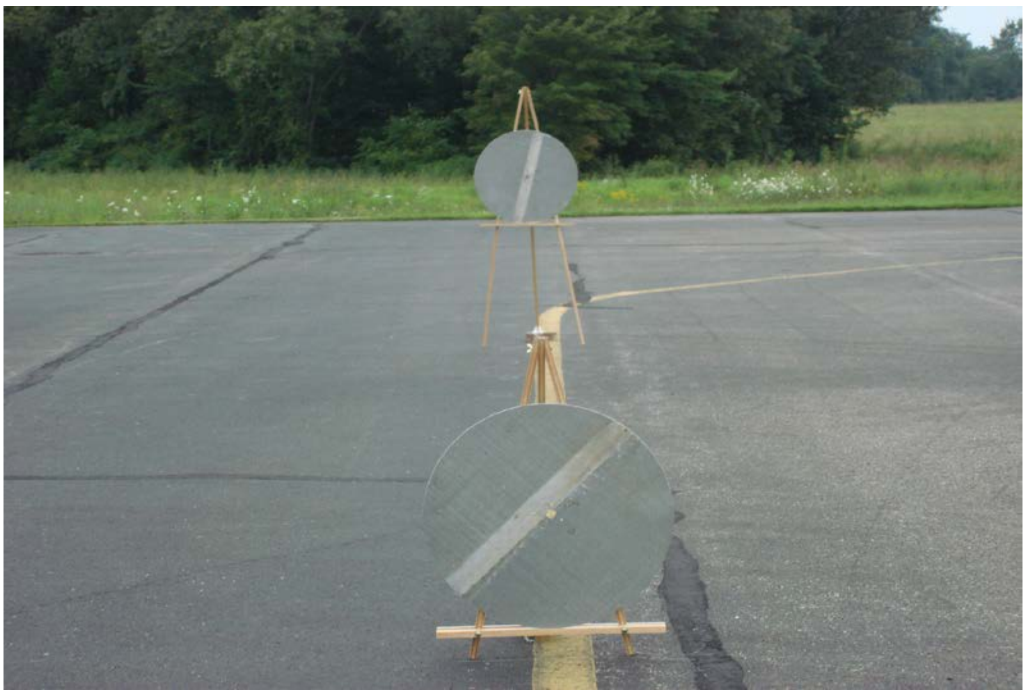


Figure 25: Pair of the similar target objects (Metal Sheets) kept at different height at a different radial range.

Radar Target Separation is the difference in distance in horizontal plane between both the target objects as measured by the radar. Radar Target Separation Measurement Error is the difference between the Radar Target Separation and True Target Separation as measured by a measuring tape.

Table 6 shows the range resolution between a pair of the same target type objects for two metal sheets. The True Range in Table 6 is the True Range to the closet target. As seen from the measurements, the range resolution decreases (error increases) with the range of the radar from the target. With the radar target separation less than 5 m, the radar was not able to distinguish the two target objects, as the radar was able to detect only one target closer to it. But as the separation continued to grow (at or above 5 m), the radar was able to distinguish the two similar target objects (metal sheets).

Table 6: Range Resolution between a pair of the similar target objects (2 Metal Sheets).

True Range (m)	Target 1 (Metal sheet) Radar Range (m)	Target 2 (Metal sheet) Radar Range (m)	True Target Separation (m)	Radar Target Separation (m)	Radar Target Separation Measurement Error (m)
5.00	5.02		4.00		
5.00	5.03	10.07	5.00	5.04	0.04
8.00	8.10	15.17	7.00	7.07	0.07
10.00	10.11	20.21	10.00	10.10	0.10

5.1.5 Range Resolution in Detecting Two Different Targets

The two different target objects were kept at different radial ranges along the center line of the radar's FOV and were moved away from each other (Figure 26). The minimum distance at which the two targets were detected as two different targets corresponds to

Range Resolution. The radar distinguishing the two target objects is a function of RCS area and the relationship of which target is in front of radar.

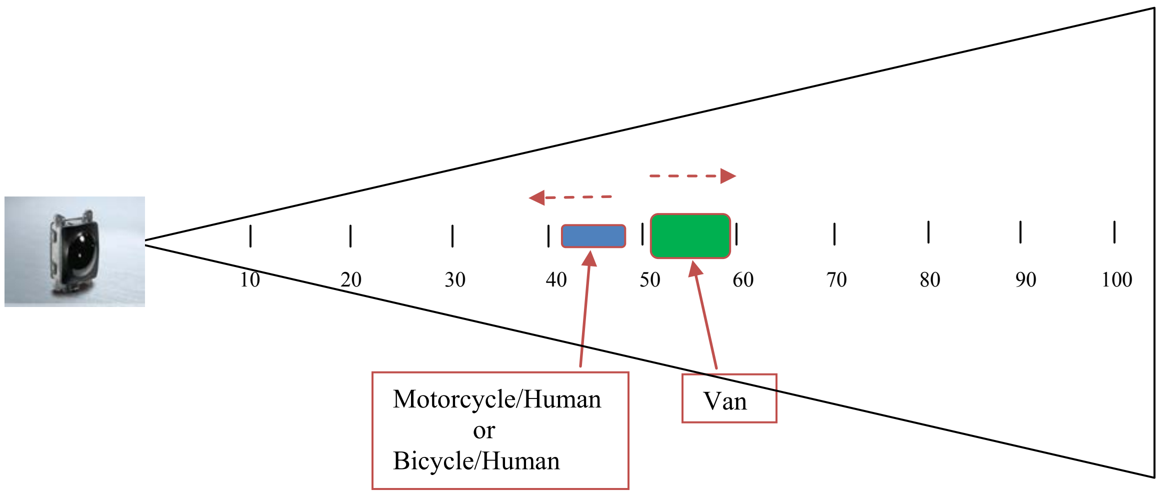


Figure 26: Setup for measuring range resolution between two different target objects.

Target 1 radar range is to the Motorcycle/Human (or Bicycle/Human), and Target 2 radar range is to the Van. Radar Target Separation and True Target Separation (measured by measuring tape) is the difference in distance between both the target objects (from their respective rear bumpers). The targets are kept stationary in a parallel configuration to the radar along the center of its FOV. From the measurements listed as in Table 7, with the Radar Target Separation less than 6 m, the radar was not able to distinguish the two target objects. It was able to detect only one target closer to it. But as the separation continued to grow (at or above 6 m), the radar was able to distinguish the two different target objects (from their respective rear bumpers).

Table 7a: Range Resolution between two different targets objects (Bicycle/Human and Van).

True Range (m)	Target 1 (Bicycle/Human) Radar Range (m)	Target 2 (Van) Radar Range (m)	True Target Separation (m)	Radar Target Separation (m)	Radar Target Separation Measurement Error (m)
5.00	5.06		5.00		
5.00	5.08	11.12	6.00	6.04	0.04
10.00	10.09	17.15	7.00	7.06	0.06

Table 7b: Range Resolution between two different targets objects (Motorcycle/Human and Van).

True Range (m)	Target 1 (Motorcycle/Human) Radar Range (m)	Target 2 (Van) Radar Range (m)	True Target Separation (m)	Radar Target Separation (m)	Radar Target Separation Measurement Error (m)
10.00	10.07		5.00		
10.00	10.05	16.10	6.00	6.05	0.05
15.00	15.08	22.15	7.00	7.07	0.07

As a final note, although not tested, if the order of targets was to reverse by having a bigger target (Target 2) in front of radar, it expected to mask out the smaller target (Target 1). Then the ability of the radar to resolve these two targets will then expected to be greater in the Radar Target Separation stated above.

5.1.5 Angular Resolution

The ability of the radar to detect two close target objects at the same radial range at different azimuth positions is defined as the Angular Resolution. The LRR2 sensor has limited performance in azimuth because of its narrow beam physically fixed antennas, which manufacturers make to keep the size and cost of the antenna system low. The angular resolution of a radar is typically driven by the antenna beam width, which is a function of frequency, configuration and physical size of the radar antenna. As such LRR2 cannot separate two target objects in azimuth i.e., at same radial range at different azimuth positions; this operational test could be further investigated in future testing. However, the LRR2 was able to determine two similar targets once separation became 5m or more (as per data in Table 6), it is believed that if two targets are separated by distance greater than 5m and if they are at two different bearing, still within the FOV of radar, it is anticipated that radar would be able to distinguish them.

5.1.6 Maximum Range of Aircraft

The maximum range measurement values were taken with LRR2 directly pointing on the nose of the aircraft and also with the radar sensor pointing on the broadside of the aircraft. In order to investigate this maximum range, the cart was placed close to the aircraft and the cart with the LRR2 was moved away from the aircraft until the radar losses lock on target. Figure 27 shows the aircraft used for these tests and as described previously in Section 4.5.

Figure 27: Setup for measuring the maximum range of LRR2 in detecting an aircraft

Table 8 shows the LRR2 maximum range observed when pointing directly on to the nose of the aircraft at 71 m and at 100 m when the radar was pointing onto the broadside of the aircraft. This difference in maximum Radar Range value is due to the larger RCS when looking at the broadside of the aircraft. From the data presented in Table 8, along with the data presented earlier in Table 2 & 3, it can be consider that the vehicles on the airfield could be equipped with a LRR2 sensor system to detect and warn the drivers of any possible collision with the other objects like vehicles, traffic barrels, poles, humans etc in its vicinity. Also aircrafts could be equipped with these types of radar sensors to detect other vehicles/aircrafts on the taxiway for possible runway incursion mitigation.

Table 8: Maximum range measurements of LRR2 in detecting an aircraft on both sides

Nose of Aircraft		Broadside of Aircraft	
True Range (m)	Radar Range (m)	True Range (m)	Radar Range (m)
71.00	71.63	100.00	100.75

CHAPTER 6: CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

The Bosch LRR2 was designed for the ACC applications and it performs those functions very well. The purpose of this work was to investigate the potential to use these type of LRR sensors for various obstacle avoidance applications.

From these tests, the LRR2 sensor had a maximum detection range of 105m for Van as the target object. For smaller target objects tested like the Bicycle/Human, Human, Traffic Barrel, 4" Pole, and Metal Sheet, the maximum radar detection range was less than 100m and it varied depending upon the RCS of the target object. The Range Accuracy of LRR2 for different target objects was less than +/-0.2 m which was significantly better than what was listed in the manufacturer's specifications. The observed LRR2 FOV measurements for various targets were close to the value specified by the manufacture i.e., $16°$ but that depended upon the target object size, material used, and it's RCS. The average FOV of the LRR2 in detecting a traffic barrel as target object was$18°$, which was significantly better compared to other targets because the traffic barrel is white striped with ultraviolet stabilizer to inhibit color fading with 4" bands of retro reflective strips surrounding them and also has larger cross sectional area.

The results show that the LRR2 sensor requires radial range separation of 5m or more to distinguish between similar target objects (i.e., same target type of 2 Metal Sheets). Also seen from the measurements, the range resolution decreases (error increases) with the range of the radar from the target. For two different target objects (Motorcycle/Human or Bicycle/Human) depending upon their size, material, and RCS, the radar requires 6m (from their respective rear bumpers) to separate and distinguish the two targets. For these tests, the smaller RCS target was closer in range than the target with the larger RCS (i.e., Van)

The data results also supports that the LRR2 sensor detects aircraft and has different maximum range detection values depending on whether it is pointing directly on to the nose or to the broadside of the aircraft. LRR2 maximum range was 71 m when pointing onto the nose of the aircraft and was 100m when pointing onto the broadside of the aircraft. So from the tests, it can be consider that the vehicles on the airfield could be equipped with a LRR2 sensor system to detect and warn the drivers of any possible collision with the other objects like vehicles, traffic barrels, poles, humans etc in its vicinity. Also aircrafts could be equipped with these types of radar sensors to detect other vehicles/aircrafts on the taxiway for possible runway incursion mitigation.

The LRR2 sensor is suitable for performing ACC functions and with the clear intent to detect objects that are in front of the vehicle. It is clear from these tests that LRR2 is suitable for doing certain types of obstacle avoidance. To further investigate LRR2 performance in obstacle avoidance more testing needs to be done in range measurement with respect to operational environment, equipping LRR2 on moving automobiles with stationary/moving targets, angular resolution etc. One main consideration is that all these test measurements were performed on stationary targets and the measurements could well differ (range measurement error may increase) for moving radar and/or moving target objects.

6.2 Future Work

The work described in this thesis has demonstrated that the LRR sensors are capable of detecting not only automobiles but also other target objects like Motorcycles, Bicycles, Humans, and roadside objects like Traffic Barrels, 4" Poles, Metal Sheets, etc. In order to refine this work and extend the applications of LRR sensors to a broader range of applications, additional development and testing is recommended as follows.

- The performance of the radar will varies whether the vehicle is moving towards or away from the target as it is a function of detection algorithm. So additional tests with the LRR sensors mounted on the fast moving automobiles has to be done to evaluate it performances in the real-time operational environment. This data will provide additional insight into the radar target detection algorithms and its ability to rapidly detect targets with small RCS.
- The angular resolution could be improved by advanced algorithm, so that LRR sensor can detect and separate the target objects at the same radial distance at different positions. This could lead to improved antenna and processing algorithms.

- An electronically scanned antenna positions its beam rapidly from one direction to another without mechanically moving, so as to increase the azimuth coverage of the LRR sensors.
- Ability of the internal algorithm to detect the target and put the data faster on the CAN bus thereby increasing the effective data throughput rate of LRR sensors.
- There could also be an option for the user to modify the radar sensor parameters in accordance with his needed requirements.

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APPENDIX A: RADAR FREQUENCY BANDS AND ITS USAGE [5][7]

Radar Letter Band Designation	Frequency Range	Usage
HF	3-30 MHz	Over the horizon radar
VHF	30-300 MHz	Very long range surveillance
UHF	300-1000 MHz	Very long range surveillance
L	1-2 GHz	Long range surveillance Enroute traffic control
S	2-4 GHz	Moderate range surveillance Terminal air traffic control Long range weather (200nmi)
C	4-8 GHz	Long range tracking Airborne weather detection
X	8-12 GHz	Short range tracking Missile guidance Mapping marine radar Airborne weather radar Airborne intercept
Ku	12-18 GHz	High resolution mapping Satellite altimetry
K	18-27 GHz	Little used (water vapor)
Ka	27-40 GHz	Very high resolution mapping Short range tracking Airport surveillance
V	40-75 GHz	Smart munitions, remote sensing
W	75-110 GHz	Smart munitions, remote sensing
mm	110-300 GHz	Experimental, remote sensing

APPENDIX B: TECHNICAL FEATURES OF LRR2 [9] [24]

System Parameters	Values
Frequency Range	76 – 77 GHz
Target Distance Range	2 to 200 m
Accuracy	+/- 0.5m
Resolution	2 m
Relative Speed	-60 to +20 m/s
Accuracy	+/- 0.25 m/s
Resolution	+ 1.5 m/s
Modulation	FMCW
Max. No of Detected objects	32
Azimuth FOV (Horizontal Angle)	+/- 8 deg
Accuracy	+/- 0.1 to 0.4 deg
Elevation FOV (Vertical Angle)	+/- 2 deg
Number of Beams	4
Cycle time (update rate)	10 Hz
Power Consumption	13 W
Maximum Transmit power	10 dBm
Antenna Gain	28 dBi

APPENDIX C: CAPL PROGRAM

A CAPL based program was written to control and extract data from the LRR2 (i.e., requirement below) in Vector CANalyzer 7.0 software. The LRR2 control unit continues to send its messages (*CU-I0, CU_REQUEST, CU_I1*) within a time range of 20 ms. If one of the *CU_XX* messages has not been received within the stipulated time duration of 20 ms then SGU generates an error message (*ACC_SGU_STATUS*) with the corresponding flag. More information about this requirement can be found in Section 4.3 [24].

CAPL Program for Radar messages

****

Author: Ravi Komarabathuni

Date: 07/28/09

****

```
variables
{
   message 0x6D6 final_msg;
   message 0x6B1 control_msg1; // Messages to be sent
   message 0x6B2 control_msg2; /* Messages to be sent */
   message 0x6B3 control_msg3;
   int v1;
   int v2;

}
```

```
on message 0x6B5
{
   v1 = this.byte(0);
   v2 = this.byte(1);

}


on message 0x6D6
{

   send_msg_1();
   send_msg_2();
   send_msg_3();

}


send_msg_1 ()
{

   control_msg1.dlc = 0x08;
   control_msg1.CAN = 2;
   control_msg1.byte(0) = 0x03;
   control_msg1.byte(1) = 0x00;
   control_msg1.byte(2) = 0x00;
   control_msg1.byte(3) = 0x00;
   control_msg1.byte(4) = 0x14;
   control_msg1.byte(5) = 0x00;
   control_msg1.byte(6) = v1;
   control_msg1.byte(7) = v2;
   output(control_msg1);

}


send_msg_2 ()
{

   control_msg2.dlc = 0x08;
   control_msg2.CAN = 2;
   control_msg2.byte(0) = 0x00;
```

```
    control_msg2.byte(1) = 0x00;
    control_msg2.byte(2) = 0x0A;
    control_msg2.byte(3) = 0x00;
    control_msg2.byte(4) = 0x00;
    control_msg2.byte(5) = 0x00;
    control_msg2.byte(6) = 0x03;
    control_msg2.byte(7) = 0x00;
    output(control_msg2);

}


send_msg_3 ()
{

    control_msg3.dlc = 0x08;
    control_msg3.CAN = 2;
    control_msg3.byte(0) = 0x00;
    control_msg3.byte(1) = 0x00;
    control_msg3.byte(2) = 0x00;
    control_msg3.byte(3) = 0x00;
    control_msg3.byte(4) = 0x00;
    control_msg3.byte(5) = 0x00;
    control_msg3.byte(6) = 0x00;
    control_msg3.byte(7) = 0x00;
    output(control_msg3);

}
```