

# **ESTIMATING EXPECTED LEVELS OF MUTUAL INTERFERENCE IN AUTOMOTIVE RADAR AND SIMULATING SYSTEM IMPACTS**

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## **ABSTRACT**

The primary goal of this paper is estimate the power, due to other radar transmitters, expected to be incident on the receiving antenna of a given automotive radar, and secondly, simulate the impact this may have on the performance of an example radar system. The approach uses stochastic geometric methods to weigh the spatial, temporal, and spectral overlap, for realistic scenarios with multiple radars operating in proximity. The results show that a given radar receiving antenna may face more interference power (10 to 50 dB) than what is expected from the reference target used to specify system performance. Under these conditions, a radar system, without interference mitigation strategies, will likely suffer significant degradation in performance.

## INTRODUCTION

The automotive industry is undergoing a fundamental transformation, made possible by a multitude of advancements in electronic, communication, and remote sensing technologies. Automobiles are being developed with varied levels of autonomy to increase efficiency, reduce congestion, improve safety, and provide reliable transportation to communities that formerly would be dependent on others for assistance.

This paper provides simplified expressions to estimate the environment in which automotive radars must operate, as market penetration of radar-equipped vehicles grows. Systems that operate well in environments with few other radars may suffer significant degradation of performance in radar congested environments. The results show that levels of interference based on operation of current systems in congested environments will be significant. In scenarios with many vehicles operating radars in the 76-81 GHz band, the power from other radars will likely exceed the power of echoes from targets needed for specified performance by several orders of magnitude, based on the model in this paper.

The modeling and simulation work focus on two questions:

- How much power does a given radar receive from other radar transmitters?
- How may this impact the performance of a collision warning system?

The first question is addressed by developing a model for nominal automotive radars and computing the amount of power overlapping in space, time, and spectrum. This work is done theoretically, assuming free space propagation of RF waves.

The second question is addressed by introducing the power computed for the interference, as noise, into a system simulation. This approach is common in past studies, and assumes the waveforms of the interfering radar are substantially different, so that their mutual energy does not correlate. This approach is taken here, in part, because it requires a minimum of assumptions about the signal processing chain behind the receiving radar's front end. To quantify possible system impacts, the processing functions are based on a generic model developed in cooperation with industry professionals and simulated in MATLAB's Automated Driving System (ADS) Toolbox. For this reason, the approach here does not capture the system impacts which depend on the multitude of interactions possible with different waveforms.

While radar interference is a well understood phenomena and studied for many decades, the concern of when and how this will impact the development of advanced driver assist systems and autonomous vehicles is relatively new. The European funding project MOre Safety for All by Radar Interference Mitigation (MOSARIM) began in January 2010 with the main objectives:

- Investigate possible automotive radar interference mechanisms
- Assess possible countermeasure and mitigation techniques

The MOSARIM study focused on simulation and empirical measurements to identify interference levels, evaluate mitigation strategies.

As well as the MOSARIM study, many other researchers have made contributions to the study of this problem, and were consulted for this study [1]-[6]. The novelty of this research is that it represents an end-to-end estimation of mean interference power for realistic traffic scenarios, and a modification of the MATLAB ADS Toolbox to simulate the system impact.

## RADAR MODEL

In order to compute the interference level for a radar, we must create a model for the system under test, as well as the interfering systems. The model must be of sufficient fidelity to estimate the amount of power incident on the receiving aperture. For the purposes of modeling and simulation, parameters for a generic long range automotive radar were established, based on values selected from radar specifications.

The power arriving at a receiving antenna,  $P_{Rx}$ , from a transmitter at a range  $R$ , is a function of the power of the transmitter,  $P_{Tx}$ , gain of the transmitting antenna,  $G_{Tx}$  the wavelength of the transmission,  $\lambda$ , and the gain of the receiving antenna,  $G_{Rx}$ . This is the Friis formula [7], expressed in (Equation 1).

$$P_{Rx} = \frac{P_{Tx} G_{Tx} G_{Rx} \lambda^2}{(4\pi R)^2} \quad (\text{Equation 1})$$

The monostatic radar range equation computes the power received by a radar co-located with a transmitter, observing energy returned by a target with radar cross section,  $\sigma$ . This is written out in (Equation 2).

$$P_{Rx} = P_{Tx} G_{Tx} G_{Rx} \left( \frac{\lambda}{4\pi R} \right)^2 \frac{\sigma}{4\pi R^2} \quad (\text{Equation 2})$$

The radar range equation shows the  $R^4$  path-loss for radar returns, as opposed to the  $R^2$  path-loss for transmission loss from another radar..

A long range radar for automotive radar applications is typically expected to detect and track vehicles more than 100 meters ahead. Typically, the radar performance is specified against a reference target with radar cross section of 0 dBm<sup>2</sup> at 100 meters.

The system noise for the radar is the product of the noise factor,  $f_N$ , and the thermal noise, which is the product of the operating temperature,  $T$ , the bandwidth of the receiver,  $B$ , and Boltzmann constant,  $k$ , expressed in (Equation 3)

$$N = f_N kTB \quad (\text{Equation 3})$$

The values used for this paper are shown in Table I. Based on the radar range equation and the values in Table 1, the SNR, expressed in (Equation 4) for the reference target per pulse is 14.1 dB. The SNR value is before pulse compression. Following pulse compression, the signal power is elevated by the time-bandwidth product. This is accounted for in our simulation by condensing the signal power into the target range bin and uniformly distributing the noise power across the range bins.

$$SNR = P_{RX}/N \quad (\text{Equation 4})$$

**Table 1.**  
*Parameters used for a generic long range radar to model interference level*

	Value	Units
Mean Power	1	Watts
Reference Range	100	Meters
Reference RCS	0	Decibel Meters Squared
Bandwidth	200	Mega Hertz
Range res.	0.75	Meters
Range bins	200	Unitless
Comp. Gain	23	Decibel
Carrier Frequency	76-77	Giga Hertz
Noise Factor	10	Ratio (Unitless)
Duty Factor	0.5	Ratio (Unitless)
FOV Az.	20	Degree
FOV El.	5	Degree
Antenna Gain	27	Decibel
Az. Resolution	5	Degree
Range rate limits	[-100 100]	Meters Per Second

## INTERFERENCE MODEL

This section details our approach to answer “How much power does a given radar receive from other radar transmitters?”

The expected interference experienced by a given receiver requires an estimate of the probability of intercepting (POI) other vehicles’ radar transmissions in spectrum, time, and space.

Assumptions must be made about how the radar carrier frequency and pulse scheduling are selected. For this paper, the probability of intercept, POI, is based on the assumption that the choice of center frequency is selected randomly, uniformly distributed, in band, and there is no synchronization between systems on other cars.

The spectral POI for a pair of radars is based on the amount of the available band they occupy, or channel fraction. That is, a 200 MHz system, operating in the 76 to 77 GHz band, has a channel fraction of 0.2. For many operational systems, the channel fraction could be an order of magnitude smaller because the instantaneous bandwidth is chosen to be relatively narrow. For a population of  $K$  radars, the spectral POI for each of the radars is,  $\omega_K$ , is shown below in (Equation 5)

$$\omega_K = 1 - \prod_{k=1}^{K-1} (1 - CF_k) \quad (\text{Equation 5})$$

The temporal POI for a population of  $K$  radars follows a similar derivation, but the governing parameter is the duty factor for the interfering pair,  $DF_1$  and  $DF_2$ . For a population of  $K$  radars, the temporal POI,  $\tau_K$ , is shown below in (Equation 6).

$$\tau_K = 1 - \prod_{k=1}^{K-1} (1 - DF_k) \quad (\text{Equation 6})$$

The temporal spectral overlap is then simply the product of the two, as shown in (Equation 7).

$$\xi_K = \omega_K \tau_K \quad (\text{Equation 7})$$

Mutual interference involves multiple radars. The radar under consideration is identified as the Ego radar. To compute the interference power at the Ego radar,  $I_1$ , we follow the approach of [6], shown in (Equation 8), which requires specification of the mean interferer density,  $\lambda$ , the transmitter power,  $P_0$ , the temporal-spectral overlap factor for pairs of radars,  $\xi_2$ , the minimum distance away from the Ego radar, on a road with lane spacing  $L$ , which an interferer with FOV  $\theta$  must be to illuminate the Ego receiver, is  $\delta = L/\tan(\theta/2)$ , and the frequency dependent gain term,  $\gamma_1 = G_t^2(c/4\pi f)^2$ .

$$I_1 = \xi_2 \lambda P_0 \gamma_1 (\pi - 2 \arctan(\delta/L))/2L \quad (\text{Equation 8})$$

In this stochastic geometric approach, the expected interference level is integrated over the interfering radars, so the temporal-spectral overlap is taken pair-wise. An example is computed in the Results section.

## SYSTEM MODEL

To estimate the impact of interference on a collision warning system, the study introduces the interference power, calculated in the interference model (8), and introduces the interfering transmissions as uncorrelated noise. This approach is common in past studies and assumes the waveforms of the interfering radar are substantially different, so that their mutual energy does not correlate. This requires a minimum of assumptions about the signal processing chain behind the receiving radar's front end. While the approach neglects the possible impacts of interfering signals, which generate false tracks (ghost targets), the impact of elevated noise is less dependent on hardware architecture.

To quantify possible system impacts, the processing functions are based on a generic model developed in cooperation with industry professionals and simulated in MATLAB's ADS Toolbox. The approach can be adapted for higher fidelity models, with the specific signal processing chain for a particular brand and model of radar. However, in this study, the system model is intended to demonstrate the impact on a generic, but reasonable, radar system that can be reproduced by other researchers with access to the ADS Toolbox.

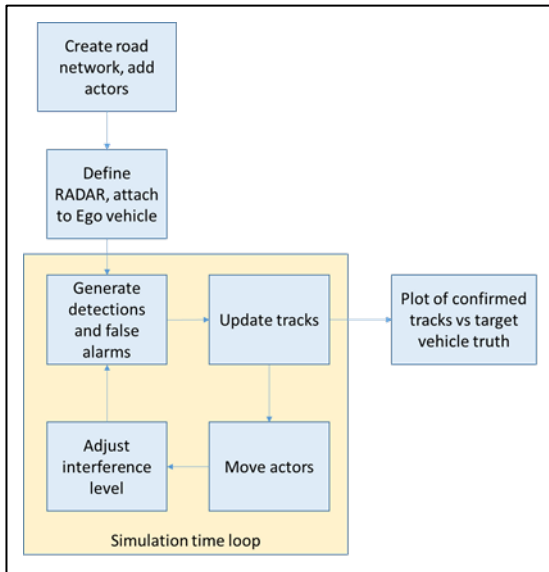
To model a vehicle with advanced driver assist sensors, it is necessary to be able to instantiate, manipulate, and support interactions between the various components within the scenario. This framework described here incorporates:

- Roadway definitions
- Scene actors, including pedestrians and vehicles
- Motion of actors within the scene
- Definition and placement of sensors on the vehicle(s)

- Sensor detection model
- Support for combining detections into tracks

The model must have the ability to extract per-time-step information relating to vehicle positions, detection and track information, and modify on a per-time-step basis the detector responses based on changing scene conditions.

For our simulations, we implemented the processing flow shown in Fig. 1.



**Fig. 1. Simulation Processing Flow**

To implement our simulations, we chose to use the MATLAB platform (from MathWorks), with the add-on ADS Toolbox. Introduced in 2017, the ADS Toolbox provided most of the capability we needed. In those instances, where it did not provide the desired interface, the implementation of the necessary extensions proved straight forward.

### Generating Roadways and Vehicles

The ADS Toolbox provides methods for defining roadways, actors (vehicles and pedestrians), and motion profiles for those actors. The roadways are constructed from two-lane road segments, defined by a set of center-points in Cartesian coordinates (x, y, z) along the segment. The center-points are connected by piecewise clothoid curves.

Three classes of vehicles are referred to in this paper:

1. The Ego vehicle is the subject of interference.
2. The Target vehicles is the object, against which, the Ego vehicle's track performance is evaluated.
3. Interfering vehicles are other vehicles in the scenario with active radars.

Vehicles are added to the roadway by specifying a set of waypoints and velocities. The waypoints, like the road centers, are Cartesian coordinates. Examples of these displays are shown in Fig. 2. In this case, the Ego vehicle is blue, and the Interferers are yellow.

### Sensor Definition and Placement

Sensors are attached to vehicles. Once a sensor is attached, it moves with the vehicle as it traverses the roadway. Each sensor has an update rate, which controls the number of detections the sensor generates, and may be different than the update rate of the scenario (i.e. movement of the vehicles).

The values of these parameters used in our simulations are shown in Table 1. An example display of an Ego vehicle radar azimuth field of view is shown in Fig. 3.

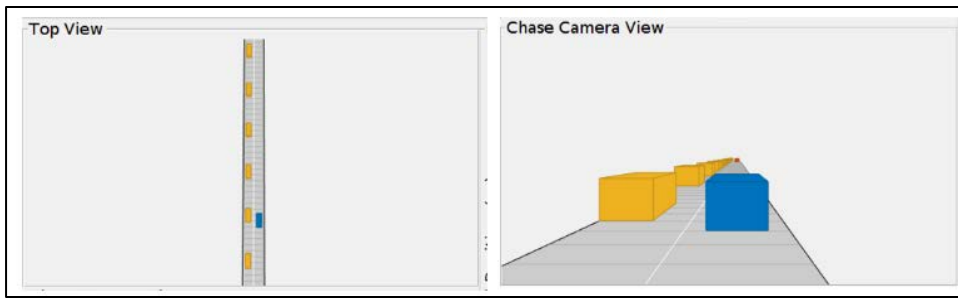


Fig. 2. Generated roadway with vehicles, where the Ego vehicle appears blue, and interferers are yellow.

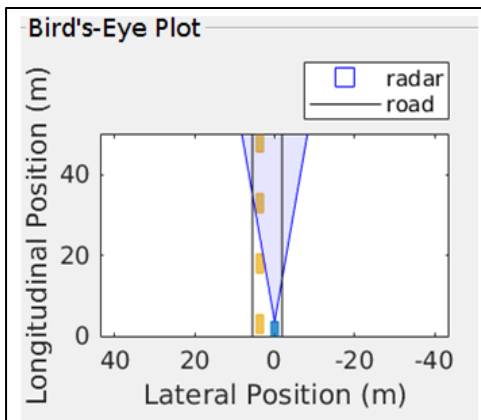


Fig. 3. Overhead view showing radar beam indicating azimuth field of view.

### Modelling Detections

Detectability of targets is governed by three inter-related parameters: Probability of false alarm (PFA), probability of detection (PD), and signal-to-noise ratio (SNR). Probability of false alarm relates to the number of false detections that are allowed to occur. To insure that detections of real targets are generated, some amount of false alarms must be allowed. For our simulations, the PFA was set to  $1e-6$ , meaning that a false alarm will occur every 1,000,000 detections. This PFA was selected to be on the low end of PFA values that are valid for Albersheim's equation ( $1e-7 < PFA < 1e-3$ ), based on industry practices of limiting false alarms. The expectation is that some false alarms will be eliminated via the tracking system, since unlike true detections from vehicles, the false alarms may not correlate with a reasonable trajectory.

Once an acceptable level of false alarms has been set, the relationship between the PD and SNR is defined via a Receiver Operating Characteristic (ROC) curve. The ROC is derived from well understood radar reflection phenomenology. In the ADS Toolbox, radar reflections are assumed to be from non-fluctuating targets, with non-coherent pulse integration, generated via Albersheim's detection equation [8]. While this model for reflections is adequate for many uses, with more time and effort, this equation could be replaced with a richer model from Snidman's equations [8], based on Swerling models that provide for fluctuating responses generated from collections of potentially non-homogeneous scattering mechanisms of targets.

Detections are generated on a per-time-step basis. First, actors within the scenario are moved to their current position. Next, point targets are generated for the scene. The region-of-interest (ROI) is defined by the orientation and field-of-view of the radar. This ROI is sub-divided based on the minimum spacing defined by the azimuth and range resolutions as demonstrated in Figure 5, (in these simulations, elevation resolution is infinity, i.e. responses cannot be separated by height). Actors are represented as 6-sided cuboids. At most three sides of an actor are visible to the radar at any time. Point targets are generated wherever the side of an actor occupies one of the sub-divisions of the ROI.

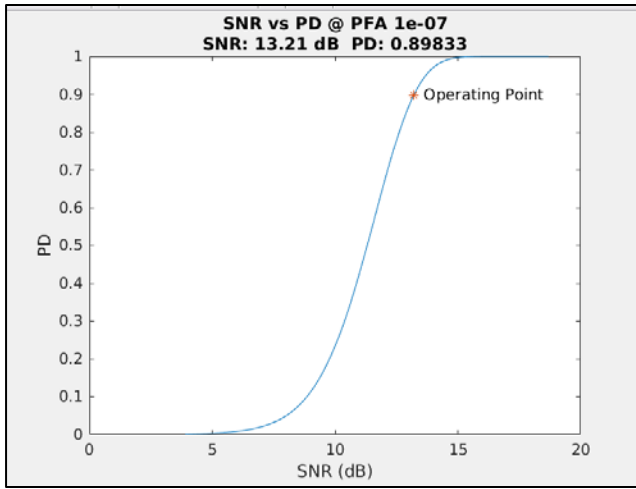


Fig. 4. Example ROC curve relating SNR and PD given desired PFA

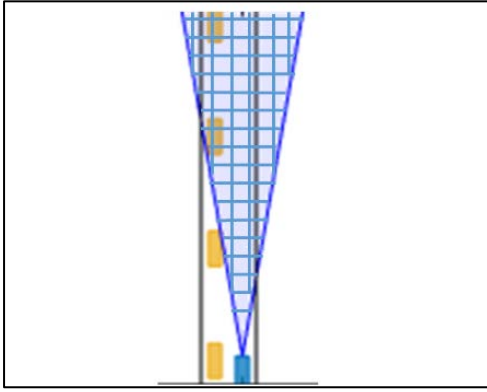


Fig. 5. Example of subdividing radar beam to identify point target responses

Each point target is assigned a radar cross section (RCS) value. This is the idealized response of the target at the given angle, without accounting for distance between the sensor and the target. Each actor is assigned a set of RCS values, which can differ with illumination angle. These set of RCS values are interpolated to get the point target response given the per-time-step illumination angle of the target. For our simulations, all vehicles are assigned an RCS value of 10 dBsm for all angles, which has been found in previous work [8] to be a good estimate of vehicle cross-section.

Point targets are then eliminated based on range rate. Range rate is a measure of the radar's ability to discern changes in relative range between the Ego and target vehicles. The limit on this ability comes from the rate at which the radar can transmit pulses, driven by an engineering tradeoff between expected maximum vehicle velocities, maximum range extent, and cost of the radar system. Point targets outside the minimum/maximum range rate are considered spurious and ignored.

Since the RCS of the target does not account for the distance between the sensor and point target, this number must be converted into the SNR at the point target. The SNR for each point target,  $SNR_T$ , is adjusted by the product of two ratios, the target RCS to reference RCS, and the two-way propagation loss ( $R^{-4}$ ), at the target's range relative to the reference range, shown in (Equation 9).

$$SNR_T = SNR_R (RCS_T / RCS_R) (Rng_T / Rng_R)^{-4} \quad (\text{Equation 9})$$

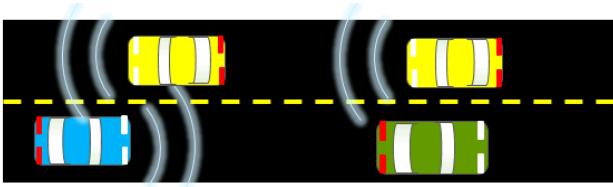
The total number of false alarms generated are chosen by calculating the total number of resolution cells for one sweep of the radar and multiplying that number by the false alarm rate. If false alarms are generated, the range and azimuth locations of the false alarms are chosen at random from a uniform distribution. False alarms are assumed to be marginal detections, therefore the SNR of each false alarm is set by applying Albersheim's equation, from [8], at the detection threshold level. Finally, the false alarms are grouped together with the target detections into one set of radar detections.

The radar detections are then fed into a tracking algorithm in order to attempt to group the current detections with previous detections and tracks. Any current detections that cannot be assigned to previous tracks are used to create new tracks. Previous tracks that are assigned new detections are updated and confirmed. Any tracks that did not get a new detection are initially coasted and, if they continue to fail to obtain detections in the future, are eventually deleted. The default tracker used in the ADS Toolbox, and in this paper, is a constant velocity linear Kalman filter.

The main metric used in determining the ability of the radar to detect a target in the presence of interference and noise is the terminal track range. This is the maximum range of a continuous track of the target. In other words, this is how far out the radar was able to initially detect the target and maintain that track through the completion of the simulation.

### EXAMPLE SCENARIO

Consider a two lane highway with interference caused by forward looking radars on cars travelling opposite directions, as shown in Figure 6, below. The interference is measured at the Ego vehicle, shown in blue. The source of the interference is the radars on the yellow cars, *interfering vehicles*, travelling in the opposite direction. The impact of the interference on the system will be evaluated by how well the Ego vehicle can detect and track the green car, the Target vehicle.



**Fig. 6.** Example scenario is represented schematically above. The Ego vehicle, in blue, operates a forward looking radar, following a target vehicle, in green. The Ego vehicle suffers from the interference of radars on the yellow cars travelling in the opposite direction.

The Ego vehicle is travelling at 80 kilometers per hour, and the Target vehicle is 200 meters ahead, travelling at a speed of 20 kilometers per hour. The two vehicles will collide after 12 seconds. The Interfering vehicles are Poisson distributed in the opposing lane with mean separation of 15 meters. The lane spacing is set at 3.7 meters, which is a nominal center to center spacing of US road ways.

### RESULTS

The interference can be computed as a function of the density of the opposing traffic, by substituting in the values for all the other parameters determined by the lane spacing and radar parameters. Replacing the variables in (4) with the values that follow:  $\xi_2 = 0.1$ ,  $P_0 = 1 W$ ,  $\gamma_1 = 2.794 \times 10^{-2} m^2$ ,  $\delta = 20.98 m$ , and  $L = 3.7 m$ , we have an expression for the interference power at the Ego radar,  $I_1$ , as a function of the mean spacing of interfering vehicles,  $\bar{x}$ , in the opposing lane, in (Equation 10).

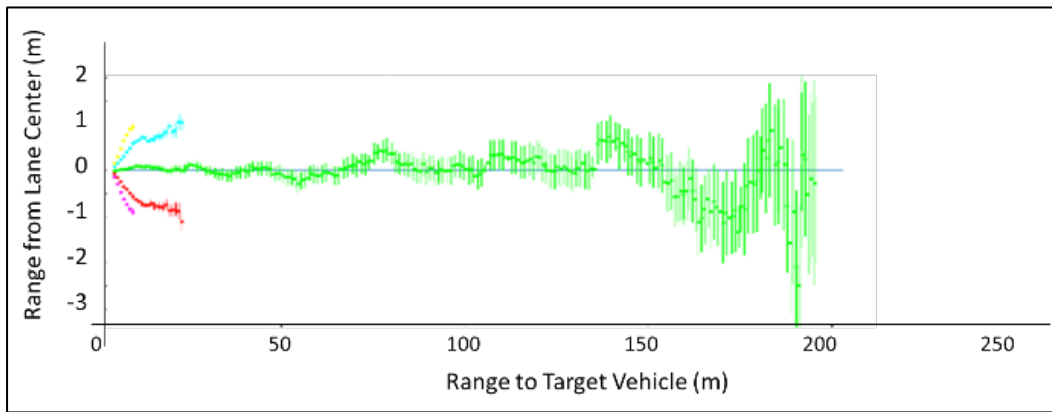
$$I_1(\bar{x} = \lambda^{-1}) = 1.32 \times 10^{-4} (W m) / \bar{x} \quad (\text{Equation 10})$$

For this situation the interference power is inversely related to the spacing of the interfering vehicles. If the mean spacing between the vehicles in the opposing lane is 15 meters, the interference power in (5) is estimated to be -51 dBW. For convenience, we assume the radar pair use significantly different waveforms, and following pulse compression, the power is uniformly spread over the 200 range bins. Thus, each range bin suffers approximately -73 dBW of interference power. The reference target is a 0 dBsm target at 100 meters, which using the same radar parameters has a return power of -107 dBW in the range bin at 100 meters.

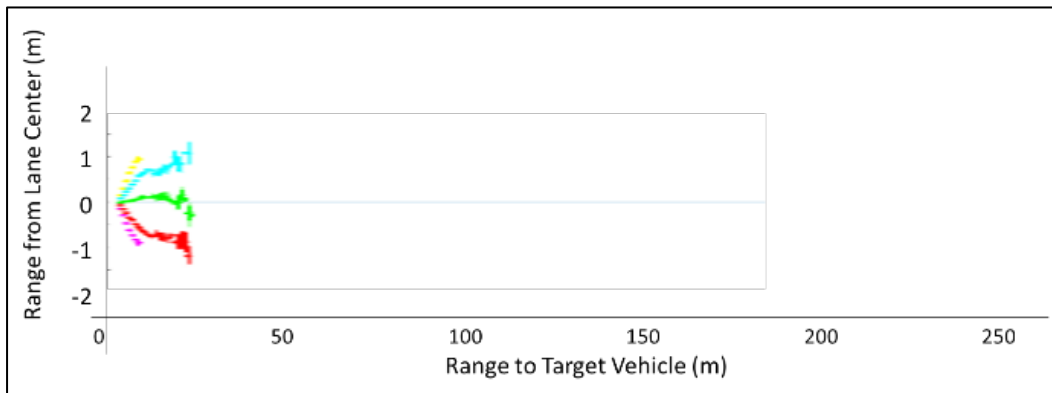
The impact on performance is shown graphically, for the simulated system, by observing the distance from the target at which a *terminal* track is formed. A terminal track implies that the same track is maintained until the time of collision. Without interference, a terminal track is formed for the Target vehicle at a range of 196 meters, plotted in Fig.7. With interference, a terminal track with the Target vehicle does not exist beyond 21 meters, plotted in Fig.8. In both cases, additional tracks form as the Target vehicle becomes resolved in azimuth.

The implication is, without significant interference mitigation, the example automotive radar system, will suffer significant loss of performance for ADAS applications, as the range to the target is only 11% of the reference target specification. However, it should be stressed that this example is intended to high-light the approach on a generic radar model.





**Fig. 7.** Plot of terminal target tracks from example scenario, long-range radar with no interference. The plot shows the track position and uncertainty plotted as range from the Ego vehicle to the Target vehicle.



**Fig. 8.** Plot of persistent target tracks from Scenario 1, long-range radar, with interference, for the case of 76-77 GHz band. The plot shows the track position and uncertainty plotted as range from the Ego vehicle to the Target vehicle.

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