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TRAFFIC SURVEILLANCE USING RADAR INTERFEROMETRY

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ABSTRACT

Most of the fatal accidents occur due to over speeding and to bring down accidents is strict enforcement of speed limits. In India, various steps to enhance road safety such as road furniture, road markings/road signs, introduction of Highway Traffic Management System using Intelligent Transport System, and enhancement of discipline among contractors during construction, road safety audit on selected stretches, have been undertaken by National Highways Authority of India. Traditionally, this task has been partially solved using radar and/or laser technologies radar guns, laser or LIDAR guns etc., and, more recently, are using video-camera based systems. All these systems have significant shortcomings that have yet to be overcome.

The main drawback of the laser gun is "instant on", meaning the gun isn't detectable at all times, only when it's directed to the car. The second the beam hits car, the laser instantly reads speed, and that's what causes the detector to beep. It doesn't measure the top-speed. Novel video-camera systems, based on license plate identification, solve the previous drawbacks, but they have the problem that they can only measure average speed but never top-speed. This paper studies the feasibility of using interferometric linear frequency modulated continuous wave radar to improve top-speed enforcement on roadways. Two different systems based on down-the-road and across-the-road radar configurations are presented. The main advantage of the proposed solutions is they can simultaneously measure speed, range, and lane of several vehicles, allowing the univocal identification of the offenders.

KEYWORDS: Automotive Radar, Road Traffic Control, Vehicle Traffic Detection

INTRODUCTION

Nowadays traffic surveillance system is an urgent need for the robust and reliable to improve traffic control, law enforcement, and urban congestion. The main task of this paper is to measure the top speed of the vehicles, range and number of several vehicles on road. Several works on traffic surveillance are high resolution radar, Doppler radar, LIDAR, radar guns, video camera's etc., with different solutions [9]-[11]. Using video based vehicle traffic surveillance on road detects only vehicles. It monitors the traffic using camera's which is mounted on the vehicle and fixed in traffic or driveway monitoring systems. The drawbacks of the system are it will not measure the top speed of the target.

A Radar Gun is used to send out radio waves of specific frequencies in a chosen direction. The traveling waves then bounce off objects, including vehicles, and return to the radar gun's receiving station. The radar gun computer then uses the frequency shift to calculate the speed of the moving vehicle. The laser gun is used to detect the speed by pointing a light beam to the vehicle [12]. The drawbacks are it is very expensive and it can't be used from a moving vehicle or from behind glass, and accurate aiming requires a tripod or a very steady hand. In foreign countries Doppler radar in down the road configuration has been widely used for speed enforcement. The main use of Doppler radar is only for target identification and it will not select the target because of wide beam width and the speed measurement is erroneous when there are two or more targets in the radar beam. To minimize this drawback an alternative method is the use of Doppler radar in across-the-road configuration by transmitting the micro wave beam across the road to measure the speed of the vehicle. Hence ATR configuration solves the problem of target identification and also measures two or more targets in the radar beam at the same time.

To overcome all the drawbacks of the existing system, the proposed system is two different schemes which solve the association of each echo to each target using unique radar. These two schemes based on the interferometric linear frequency modulated continuous wave (LFMCW) radar. The proposed scheme can measure speed, range, detects or identifies the targets individually, and azimuth of the targets. Hence, these schemes solve the shortcoming of target identification, allows simultaneous top-speed measurement of several vehicles with a unique system. This paper explains the Interferometric linear frequency modulated continuous wave (LFMCW) radar in two configurations which are down-the-road (DTR) configuration and across-the-road (ATR) configuration.

DOWN-THE-ROAD CONFIGURATION

Geometry

In DTR configuration, let y be the cross road position and x be the along road position. Let A and B are the two targets travels along the road is shown in figure 1. Let T_X be the transmitting Antenna and R_L & R_R be the left receiving antenna's and right receiving antenna respectively. The different targets will have different azimuth and elevation angles which is represented by (θ_L & θ_R) and (φ_L & φ_R) respectively. The above figure shows the down the road configuration.

Road Lane and Speed Detection

In conventional DTR radar, the target radial speed V_r is measured using the Doppler shift f_d caused in the received signal using (1)[2], where λ is the radar central wavelength. However, there is no way to identify which vehicle is speeding in case two of them are inside the beam. Using high-resolution radars, we can estimate motion parameters for all the illuminated targets, but we cannot determine which echo corresponds to each vehicle [7].

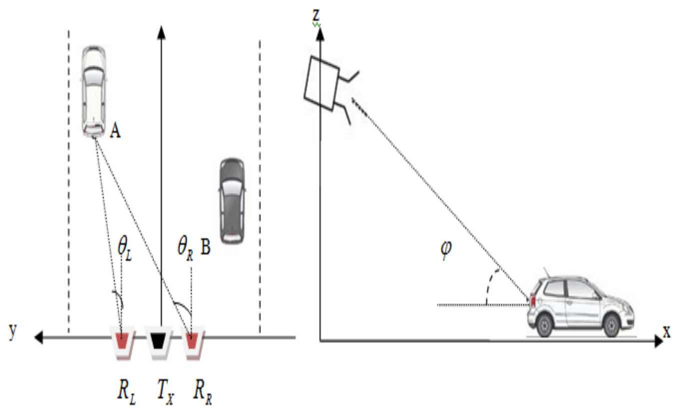

Figure 1: Down the Road Detection Geometry

Another problem with DTR high-resolution radars is that the target response is spread among multiple Doppler frequencies introduces a high uncertainty in speed measurement which increases with increasing speed.

$$V_r = -\frac{\lambda}{2} f_d \tag{1}$$

In order to identify the radar echo corresponds to the each target, the difference in the measured radial velocity from the receiving antennas have to calculate which are located in slightly different positions. The target location is calculated by the difference of the measured radial velocities between the antennas which depends on the road lane. This calculation is used to identify the vehicle lane. This difference is very small and is lesser than the Doppler resolution cell. To measure the radial velocities difference accurately, the phase difference of the received signals needs to be used. The target distance to each antenna, R_L for the left receiving antenna and R_R for the right receiving antenna, is related to the absolute phase difference between the antenna's or interferometric phase and is given by

$$\phi_I(t) = \frac{2\Pi}{\lambda}[r_L(t) - r_R(t)] \tag{2}$$

Calculating the gradient of the interferometric phase, it can be seen that it is related with the difference in radial velocities between the antennas, V_{R_L} for the left and V_{R_R} for the right one, using

$$\frac{\partial\phi_I(t)}{\partial t} = \frac{2\pi}{\lambda}\left(\frac{\partial r_L(t)}{\partial t} - \frac{\partial r_R(t)}{\partial t}\right) \equiv \frac{2\pi}{\lambda}\left(v_{r_L}(t) - v_{r_R}(t)\right) \tag{3}$$

If a target with constant velocity and no acceleration is considered, which is typical for the small dwell time of DTR radars, equation (4) is obtained, that relates radial velocity difference to along the road speed V_x and azimuth and elevation angles

$$v_{R_L}(t) - v_{R_R}(t) = V_x \cos\theta_L(t)\cos\varphi_L(t) - V_x \cos\theta_R(t)\cos\varphi_R(t) \tag{4}$$

If the target distance is greater than the height of the radar location, x>>h then the difference in azimuth angles to the interferometric phase gradient is

$$\frac{\partial\phi_I(t)}{\partial t} \approx \frac{2\pi}{\lambda} V_x(\cos\theta_L(t) - \cos\theta_R(t)) \tag{5}$$

The radar cannot measures the absolute interferometric phase, ϕ_I because it only measures the wrapped interferometric phase, ψ_I. The absolute phase difference can be obtained from the wrapped one using phase unwrapping and calibration with a phase reference point. Absolute and wrapped phases are related by (7).

$$\phi_I(t) = \psi_I(t) + 2\pi n(t) + \phi_0 \ (n \in N). \tag{6}$$

Here Interferometric phase gradient is used, so in this system there is no need to calculate absolute interferometric phase [1]. As long as interferometric phase gradient is used, absolute interferometric phase is not necessary. The absolute and measured phase gradient are equal for all phase values except when there is a $-\pi$-to-π phase shift.

$$\frac{\partial\phi_I(t)}{\partial t} = \frac{\partial(\psi_I(t) + 2\pi n(t) + \phi_0)}{\partial t} \cong \frac{\partial\psi_I(t)}{\partial t} \tag{7}$$

As viewed from the both receiving antenna's, to detect the lane of the driving target vehicle a prior knowledge of the angles of the lane limits and equation (5) must be used.

$$\cos\theta_L(t) - \cos\theta_R(t) \approx \frac{\lambda}{2\pi V_x}\frac{\partial\phi_I(t)}{\partial t} \tag{8}$$

In practical the detection scheme is based on the estimation of the target cross road position, y. Let B is the base line of the two receiving antenna's, consider x>>y and x>>B, which is true in a typical detection scenario, the cosines of the azimuth angle is approximated as,

$$\cos\theta_L = \frac{x}{\sqrt{x^2 + (y + B/2)^2}} = \frac{1}{\sqrt{1 + \left(\frac{y + B/2}{x}\right)^2}}$$

$$\cong 1 - \frac{1}{2}\left(\frac{y + B/2}{x}\right)^2 \tag{9}$$

$$\cos\theta_R = \frac{x}{\sqrt{x^2 + (y - B/2)^2}} = \frac{1}{\sqrt{1 + \left(\frac{y - B/2}{x}\right)^2}}$$

$$\cong 1 - \frac{1}{2}\left(\frac{y - B/2}{x}\right)^2 \tag{10}$$

Using equation (5), (9) and (10) the target cross road position can be related to the measured interferometric phase gradient and finally, isolate the y coordinate of target vehicle obtained

$$y \cong -\frac{\lambda x^2}{2\pi V_x B}\frac{\partial \phi_I}{\partial t} \tag{11}$$

Assume $x \cong R$ and $V_x \cong V_R$ are the initial estimation of the road lane, where R and V_R are the measured distance and radial velocity of the target in any of the receiving antennas. By correcting the cosine effect initial estimation can be done by the prior knowledge of azimuth and elevation angles for the detected distance and the lane using a better estimation of y and V_x

$$V_x = \frac{V_R}{\cos\theta\cos\varphi} \tag{12}$$

Operational Limits

In order to obtain the gradient of interferometric phase, that we need to estimate the cross-road position with (12), the phase change between consecutive samples must be smaller than π radians. This condition will set the maximum bounds for target speed to correctly detect the lane. Using (11), and replacing the continuous phase derivative by time and phase increments, we obtain (13), shown below, where the time increment is the inverse of the ramp repetition frequency (*RRF*).

$$V_x \cong -\frac{\lambda x^2}{2\pi B y}\frac{\Delta\phi_I}{\Delta t} \tag{13}$$

$$\Delta t = \frac{1}{RRF} \tag{14}$$

The restriction to correctly estimate the phase gradient is having two samples in each phase cycle. However, in order to get the best performance of this technique, and reduce phase difference variance, is better to have more samples per phase cycle

$$\Delta\phi_I = \frac{2\pi}{N_S} \tag{15}$$

In DTR configuration if two or more targets simultaneously travels with equal speed and with the same range regarding the radar, no matter where the targets are in the lane it will be indistinguishable. Some conclusion states that from equation (16) it is possible to detect for higher velocities. A higher distance to the radar means a higher detectable velocity. The maximum detectable velocity will increase if the ramp repetition frequency or the wavelength is increased. It can be also increased if the baseline or the number of samples per phase cycle is decreased. However, all these parameters will have different effects in the uncertainties so a tradeoff must be reached.

$$V_{x\,max} \cong -\frac{\lambda x^2}{By}\frac{RRF}{Ns}. \tag{16}$$

Simulation Results

In this section, there are three types of simulation results are taken place. First figure shows how the targets are placed in the road lane in the dense traffic scenario. In second figure shows the analytic formula for the uncertainty in the cross road position measurement using MATLAB simulation [3], [4] and [5]. The last figure shows how the noise interrupts the signal. In case of heavy traffic, there will be more than one target in the radar beam along the same line or different road lanes. There are four targets in the two lane highway in this simulation.

The images for the example are as shown in the figure 2. These images will allow us to estimate the targets velocity and obtain the phase difference in order to estimate the cross-road position and determine the road lane of the target. A detail of the cross-road position estimation and the road lane detection map are shown in Figure 3. The radial velocity difference detection map is shown in Figure 2(a), and the position detection map is shown in Figure 2(b).

In these detection maps, the actual and the detected values for each target have been included. The limits of the road lanes are plotted in black, the actual target value is plotted in blue, and the detected target value is plotted with a different color for each target. In order to plot all targets in the same figure, the radial velocity difference has to be normalized using the along-the-road target speed. Otherwise, a faster target will present a higher radial velocity difference.

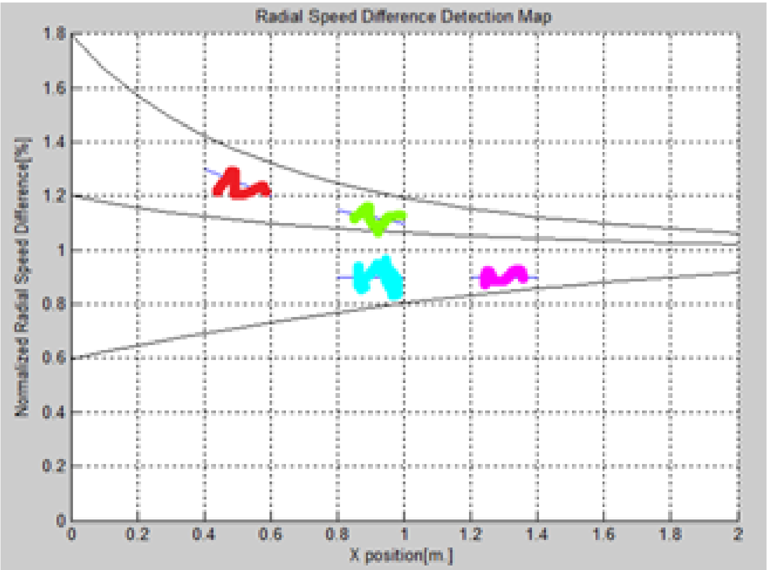

Figure 2(a): DTR Detection Maps in a Simulate Scenario (a) Radial Speed Difference Detection Map

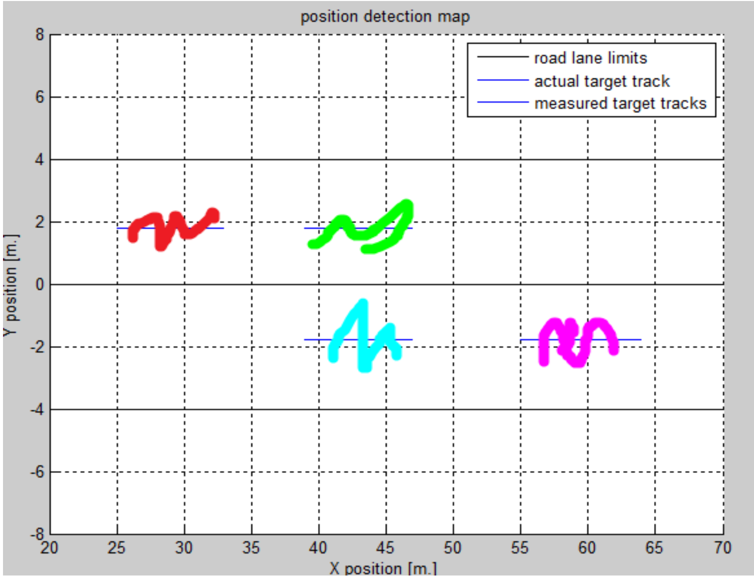

Figure 2(b): DTR Detection Maps in a Simulate Scenario Position Detection Map

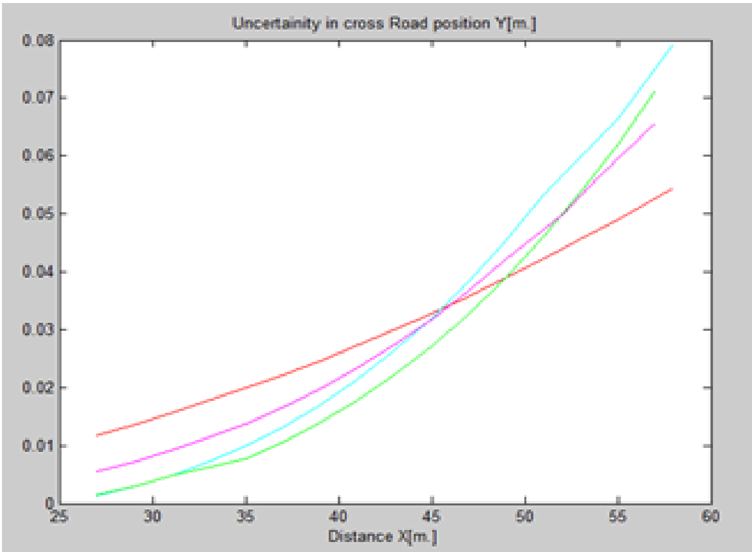

Figure 3: DTR Cross-Road Position Uncertainty

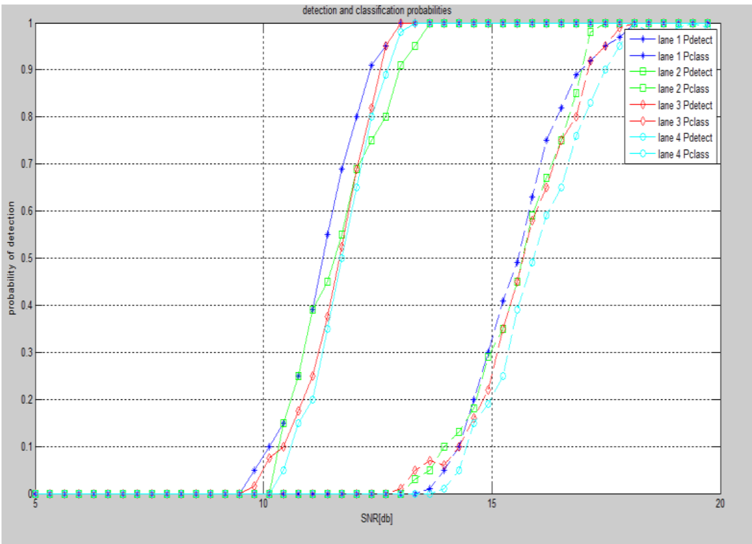

Figure 4: DTR Detection and Classification Probabilities against Noise

The performance of the DTR technique against noise is shown in Figure 4. Two kinds of curves are obtained using simulation, probability of detection, and classification against signal to-noise ratio (SNR). A target is classified when it is detected; the speed error in the measured speed is less than a threshold. A target is classified when it is detected, the speed error is below the threshold, and the road lane is correctly estimated. In the DTR configuration, Interferometry is used to estimate road lane position. It is interesting to point out that for a correct road lane classification; we need higher SNR than for just detecting it. These results are only the simulation results.

ACROSS THE ROAD CONFIGURATION

Geometry

In ATR configuration, let y be the cross road position and x be the along road position. Let A and B are the two targets travels along the road. Let T_X be the transmitting Antenna and R_L & R_R be the left receiving antenna's and right receiving antenna respectively. The different targets will have different azimuth and elevation angles which is represented by (θ_L & θ_R) and (φ_L & φ_R) respectively. The above figure shows the down the road configuration. The radar baseline can be slightly skewed from the road direction by an angle.

Road Lane and Speed Detection

In ATR configuration, to detect the target vehicle speed, the phase of the received signal in each antenna is used. To detect the road lane, the distance between the target to radar is used. The absolute phase difference between the antennas or the interferometric phase is given by

$$\phi_I(t) = \frac{2\Pi}{\lambda}(r_L(t) - r_R(t)) \tag{17}$$

The gradient of the interferometric phase is related to the difference in radial velocities between antennas.

$$\frac{\partial\phi_I(t)}{\partial t} = \frac{2\pi}{\lambda}\left(\frac{\partial r_L(t)}{\partial t} - \frac{\partial r_R(t)}{\partial t}\right) \equiv \frac{2\pi}{\lambda}\left(v_{r_L}(t) - v_{r_R}(t)\right) \tag{18}$$

Radial velocity is related to the azimuth and elevation angles of the target is shown in the equation (19) below. Consider the target having constant velocity and no acceleration, which is the correct assumption for a small azimuth beam width.

$$v_{R_L}(t) - v_{R_R}(t) = V_x \cos\alpha \sin\theta(t)\cos\varphi(t) + V_x \cos\alpha \sin\theta(t)\cos\varphi(t) \tag{19}$$

Considering the instant when the target is at the same distance from both receiving antennas, the elevation angles, as viewed from both antennas, will be equal, as shown in

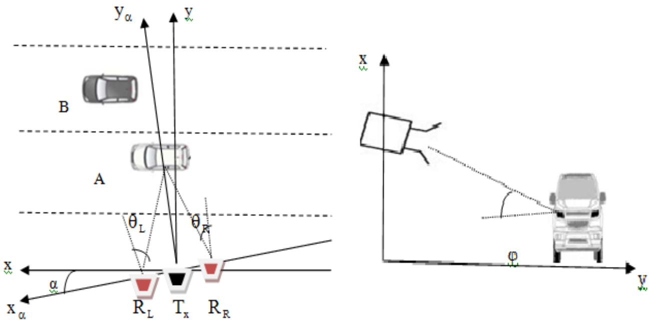

Figure 5:(a) & (b) Are the Across-the-Road Configuration Geometry

(20), below, and the azimuth angles will be identical in magnitude but with different sign, as in (21), shown below:

$$\varphi_L(t_0) = \varphi_R(t_0) = \varphi(t_0) \tag{20}$$

$$\theta_L(t_0) = -\theta_R(t_0) \tag{21}$$

$$\sin\theta_L(t) = -\sin\theta_R(t) \cong \frac{B\cos\alpha}{2y} \tag{22}$$

From equations (19)-(21) the difference in radial velocities is given by

$$v_{R_L}(t) - v_{R_R}(t) = V_x\cos\alpha\cos\theta_L(t)\cos\varphi_L(t) - V_x\cos\alpha\cos\theta_R(t)\cos\varphi_R(t) \tag{23}$$

Hence from equation (19), (22) and (23) relates the phase difference gradient and the speed of the target vehicle is obtained by

$$V_x = \frac{\lambda y}{2\pi B\cos^2\alpha\cos\varphi(t_o)}\frac{\partial\phi_I(t_o)}{\partial t}. \tag{24}$$

In order to obtain the road lane, the cross-road position of the target is compared to the known cross-road position of the road lane limits. When α is small, the cross-road position can be obtained using (25), shown below, where *r* is the distance measured by the radar in any of the antennas and *h* is the height of the radar.

$$y \cong \sqrt{r^2 - h^2}\cos\alpha. \tag{25}$$

Operational Limits

In order to obtain the gradient of interferometric phase, that we need to estimate the speed with (24), and to avoid phase aliasing, π must be smaller for the consecutive samples of each change in phase. This condition will limit the maximum speed of a target to correctly measure it. Using (24), and replacing the continuous phase derivative by time and phase increments, we obtain

$$V_x = \frac{\lambda y}{2\pi B\cos^2\alpha\cos\varphi(t_o)}\frac{\Delta\phi_I}{\Delta t}. \tag{26}$$

$$\Delta t = \frac{1}{RRF} \tag{27}$$

The restriction to correctly estimate the phase gradient is having two samples in each phase cycle. However, in order to achieve the best performance of this technique, and reduce phase difference variance, it is better to have more samples per phase cycle.

$$\Delta\phi_I = \frac{2\pi}{N_s} \tag{28}$$

If we consider Ns samples per phase cycle, the maximum speed to correctly estimate the road lane will be given by

$$V_{x\max} \cong \frac{\lambda y RRF}{B\cos^2\alpha\cos\varphi(t_o)N_s} \tag{29}$$

Another limitation of this configuration is the time the target vehicle is in the radar beam. This time must be long enough to collect *Ns* phase samples as before. This number of samples is related to the target speed and the radar beam width θ_{az}

$$N_S = \frac{2\tan\left(\frac{\theta_{az}}{2}\right)y}{V_x} RRF \cong \frac{\theta_{az} y}{V_x} RRF \tag{30}$$

Finally, considering Nssamples per phase cycle, the maximum speed to correctly estimate the road lane is the minimum of the speeds given by (29) and

$$V_{x\max} = \frac{y\theta_{az}}{N_s} RRF. \tag{31}$$

Some conclusions can be stated when looking at (29). A higher detectable velocity is possible for remote lanes compared to close ones. Increasing the ramp repetition frequency or the wavelength, or decreasing the baseline or the number of samples per phase cycle, will increase the maximum detectable velocity. However, they will have a different effect in the uncertainties, and therefore, a tradeoff must be reached.

SIMULATION RESULTS

In this there are three types of simulation results are there. First to measure the speed of the targets in Across-the-Road configuration. Using equation (24) and (25) the graph ATR uncertainty speed measurement is shown in Figure 6. Secondly the last two graphs are of the probability detection versus signal to noise ratio.

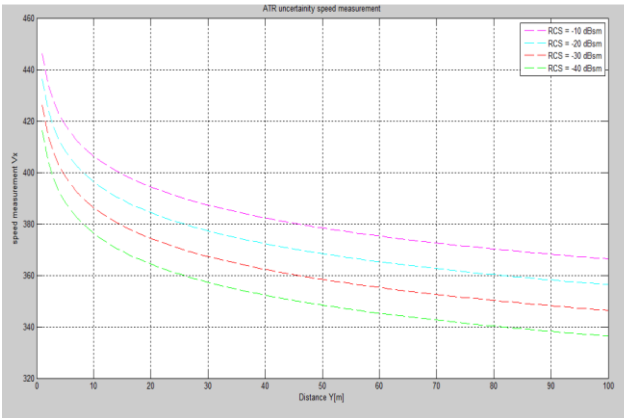

Figure 6: ATR Uncertainty Speed Measurement

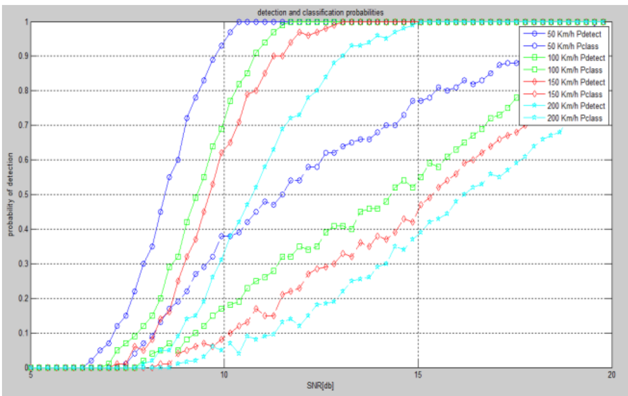

Figure 7: Detection and Classification Probabilities

In this there are three types of simulation results are there. First to measure the speed of the targets in Across-the-Road configuration. Using equation (24) and (25) the graph ATR uncertainty speed measurement is shown in Figure6. Secondly the last two graphs are of the probability detection versus signal to noise ratio.

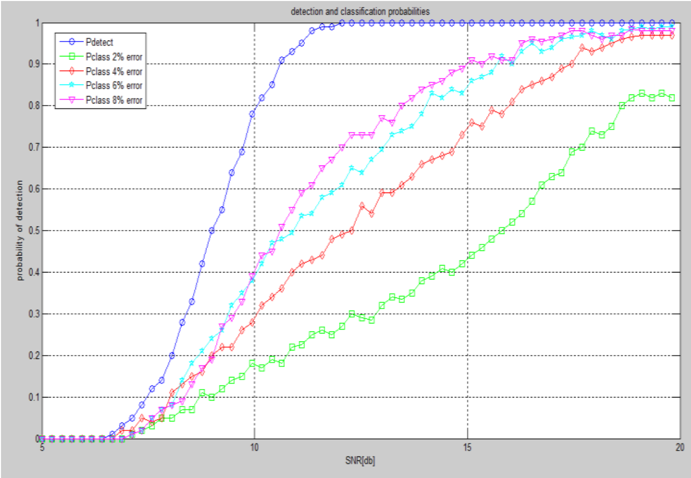

Figure 8: The Effect on Performance of the Speed Error Limit

CONCLUSIONS

In this paper there are two different interferometric systems which simultaneously measure speed, range and road lane position of several vehicles. In DTR configuration, Interferometry is used to estimate the road lane position. Without Interferometry, it is unable to identify speed of the car in the road lane if two or more vehicles are in the road beam. In ATR configuration, Interferometry is used to estimate target speed. Without Interferometry, it is unable to estimate the target speed when the radar beam is pointing nearly perpendicularly to the traffic direction. The quality of doing the proposed techniques has been successfully with the simulations.

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