Proceedings of the 8th World Congress on Electrical Engineering and Computer Systems and Sciences (EECSS'22)
Prague, Czech Republic - July 28- 30, 2022
Paper No. EEE 101
DOI: 10.11159/eee22.101

Height Estimation Methods for Object Detection in Automotive Radar Applications

Alua Musralina[1], Thomas Zwick[2], Marlene Harter[1]
[1]High-Frequency Technology and EMC Laboratory, University of Applied Sciences Offenburg, Germany
alua.musralina@hs-offenburg.de; marlene.harter@hs-offenburg.de
[2]Institut für Hochfrequenztechnik und Elektronik, Karlsruher Institut für Technologie, Germany
thomas.zwick@kit.edu

Abstract **-** In automotive parking scenario, where the curb shall be detected and classified to be traversable or not, radars play an important role. There are different approaches already proposed in other works to estimate the target height. This paper assesses and compares two methods. The first is based on Angle of Arrival (AoA) estimation of input signals of multiple antennas using the Multiple-Input-Multiple-Output (MIMO) principle. The second method uses the geometry in multipath propagation of the radar echo signal for one antenna input. In this work a modified method of calculation of the curb height based on the second method is proposed. The theory of approach is mathematically proved and effectiveness is demonstrated by evaluation of measurements with a 77 GHz Frequency Modulated Continuous Wave (FMCW) radar. In order to evaluate the performance of the introduced method the mean square error (MSE) is used in the proposed scenario. This method, using only one antenna input, produced up to 3.4 times better results for curb height detection in comparison with former methods.

Keywords**:** Curb, height estimation, radar, Angle of Arrival, multipath, Mean Square Error

1. Introduction

In automotive applications the radar sensors are applied for self-localization, as well as for estimation of targets' orientation, dimension and motion states. For the last 20 years the ultrasonic sensors are used for object detection. Since there are new requirements for autonomous parking as horizontal and vertical angle measurements of echo signals, the ultrasonic sensors for the curb detection and its height estimation are not sufficient. Multiple-Input-Multiple-Output (MIMO) radars with corresponding antenna configurations can provide both, horizontal and vertical angle measurements, so that in application as parking assistance systems radars can be used for detection and classification of obstacles [1]. Moreover, radar signals are less affected by bad weather conditions.

In general, MIMO radar sensors consist of several receiver and transmitter antenna elements, low noise amplifiers (LNA), mixers, analog-to-digital converters (ADC) and digital signal processors. The tolerances in the feeding lines of the antennas, coupling effects as well as temperature changes and aging can increase the amplitude and phase errors [2]. Those errors can be mitigated using the self-calibration technique which was evaluated in previous work [3].

A MIMO radar is capable of providing a high-resolution image, while using an antenna array with a fewer number of elements. A MIMO antenna array consisting of four receiver (RX) and three transmitter (TX) physical antennas provides a large aperture of 4x3 virtual antennas. A large antenna aperture leads to a narrow beam and hence a higher resolution.

There are various methods for the target heights' calculation with radars exist. One methods use sensor fusion algorithms to combine the radar data with information from camera [4] or with LiDAR and camera [5], whereas the other algorithms are based on finding the coordinates of targets using various methods of radar trilateration [6]. Interferometric automotive radar can be applied to obtain an object altitude information as well [7].

This paper assesses the target height estimation methods based on Angle of Arrival (AoA) estimation as well as the method based on multipath propagation of the radar echo signal, which was previously discussed in other works [8]-[12].

An evaluation board AWR1843 from Texas Instruments [13] is used for curb height estimation.

The paper is organized as follows. First, the AoA estimation-based method is explained and measurements results are presented. Afterwards, a multipath propagation model is introduced and previously available algorithms of target height estimation and their evaluation outputs are discussed. Then, a new equation for height detection in parking scenario is proposed and compared with outcome of former methods. The results in terms of mean square error (MSE) for different sensor heights are evaluated. Finally, the last section concludes the paper.

2. AoA based method for curb height estimation

The radar received (Rx) signal is a time-delayed version of the transmitted (Tx) signal. The difference of the Tx and Rx signals is known as the intermediate frequency (IF), which is used to measure the range to a target. IF signal samples in time domain are captured by an ADC and windowed with a Taylor window. The time domain samples are transformed into the frequency domain by using the Fast Fourier Transform (FFT). The peak of the FFT spectrum provides the target.

The radar which is used for measurements has 3 Tx and 4 Rx physical antennas. An antenna layout of the radar makes it possible to obtain 8 and 4 virtual antenna arrays in both, azimuth and elevation planes, respectively. During measurements the radar was rotated to 90° and for elevation angle estimation 8 antenna arrays are used. Assuming, that the peak of the 8 channel input signals corresponds to the top edge of the curb, by evaluation the peaks of the incoming signal the height of the curb can be estimated.

Even though, a curbstone has a relatively flat surface, it might have different scattering centers. In order to be sure that the radar TX signal the most probably will scatter from the top edge of the curbstone, aluminium (AL) foil line is attached on the required place as shown in Fig. 1. The measurement results are compared with the curbstone without AL.

Fig. 1: The measured curb with Aluminum (AL) foil line.

Evaluation results of the AoA estimation method are shown in Fig. 2 and Fig. 3, where *r* corresponds to a distance to the curb in meters, θ is an elevation angle from the sensor to the target. The angle to the target in degree can be converted into meters.

For detailed analysis, by calculating the absolute errors, 10 measurements are performed for each distance. The mean value of 10 height estimation results is taken, which are presented in Table 1. In case of curb with AL the results for 2.5 m and 4 m showed the absolute errors of 0.034 m and 0.05 m, respectively. The AoA estimation method in real case, where there is no AL on the curb, showed the absolute errors up to 0.06 m.

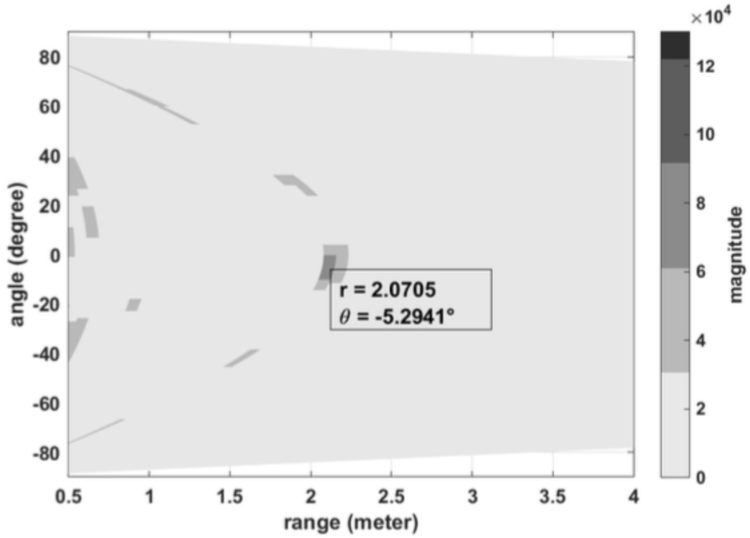

Fig. 2: AoA estimation for curb at 2 meters with AL.

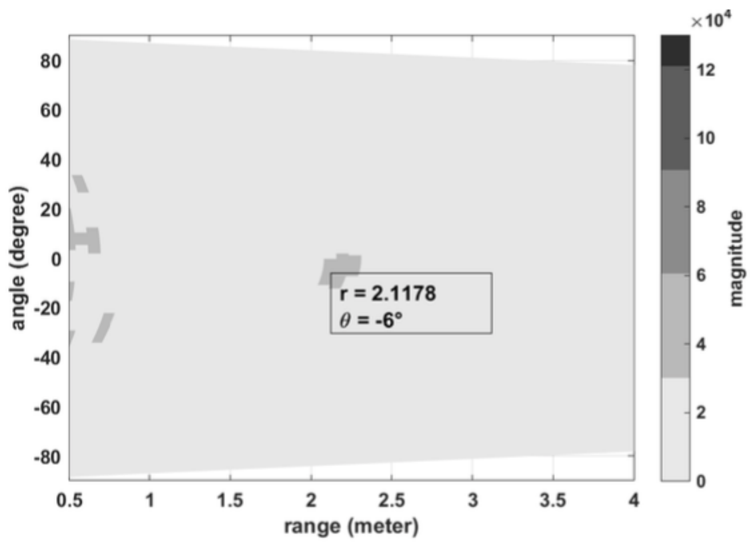

Fig. 3: AoA estimation for curb at 2 meters.

Table 1: Results of curb height evaluation using the AOA estimation method for curb with and without AL foil.

Range [m]	**Evaluation results for curb height 0.11 m**			
	Curb+AL, [m]	**Errors, [m]**	**Curb, [m]**	**Errors, [m]**
2	0.11713	0.00713	0.11475	0.00475
2.5	0.14420	0.03420	0.06253	-0.04747
3	0.11700	0.00700	0.04550	-0.06450
3.5	0.11473	0.00473	0.08183	-0.02817
4	0.15968	0.04968	0.14791	0.03791

3. Multipath propagation model

The height of the object can be calculated applying the method based on the geometry of multipath propagation model, which is shown in Fig. 4. Since one of the purposes of the work is to compare the performance of MIMO radar with one antenna radar, in our analysis only one Rx antenna input of 4 Rx antennas is taken for evaluation.

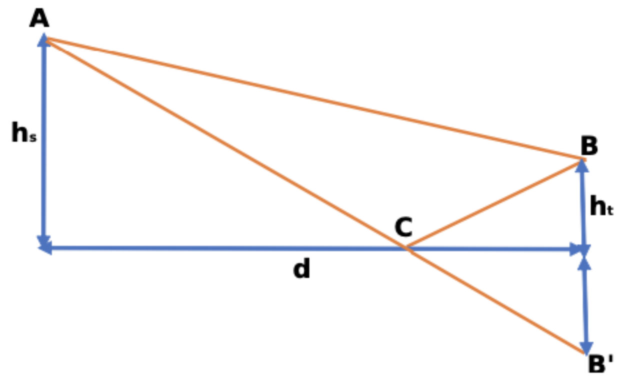

Fig. 4: A multipath propagation model. Propagation over a plane reflecting surface.

The signal radiates from the radar antenna (point A) and propagates directly to the target (B) or by reflecting from the surface (C) to the target. The magnitude of the echo signal depends on the magnitude and phase of the signal propagating via the direct and via indirect paths.

This model for height calculation was firstly mentioned in year 1962 [9]. At that time the calculation is made for aircraft elevation detection, using the earth reflection signal, by assuming it is to be a flat and reflecting surface. The radar is placed on the h_s height. The main difference is in application: the target is an aircraft and considered to be on a very far distance away and on a much higher height from the radar. So, assumptions in calculations of height of the target as an aircraft in far distance might be not applicable for automotive applications.

A method for calculation of height of the target as an airplane is firstly proposed in [10]. Where the target height can be calculated using the following equation:

$$h_t = (ACB^2 - AB^2)/4h_s \tag{1}$$

where h_s is a sensor height from the ground. For automotive application estimation of the object height by evaluation of the multipath propagated radar wave is mentioned first in [11]. The authors applied a Taylor expansion in calculations, assuming the $(h_s - h_t << d)$:

$$h_t = \Delta r d/2h_s \tag{2}$$

where $\Delta r = ACB - AB$. This algorithm made it possible to calculate the heights of low targets (h_t = 0.29 m) with a mean error of 0.03 m. This algorithm was applied in another work [12], where the radar was placed at 0.6 m above the ground and the curb height (h_t = 0.11 m) was found with max 0.08 m mean error in 4 meters distance.

In this work the method for low object height calculation is presented, which is based on the previous work. But the Taylor expansion is omitted in calculation, since for low objects and short distances the assumption as $(h_s - h_t << d)$ is not appropriate and it will lead to more errors. From Fig. 4:

$$ACB = \sqrt{(h_s + h_t)^2 + d^2} \tag{3}$$
$$AB = \sqrt{(h_s - h_t)^2 + d^2} \tag{4}$$

In order to eliminate the square root, the difference of two paths is squared:

$$\Delta r^2 = (ACB - AB)^2 \tag{5}$$

By applying another simplification, the final equation is calculated:

$$h_t = \Delta r^2 / 4h_s \tag{6}$$

where it is assumed, that in multiplication part in case of the low targets $(h_s + h_t)^2 + d^2$ can be replaced with $(h_s - h_t)^2 + d^2$.

The Fig. 5 and Fig. 6 show the income echo signals at Rx1 antenna for different distances. In Fig. 5 at range of 2.5 m the signal reflected from the curb has the main peak at 2.5 m. A second peak can be seen at the range of 2.8 m for the curb with AL and at the range of 2.88 m for the curb without AL, which correspond to the calculated curb heights of 0.0497 m and 0.0785 m, respectively. In Fig. 6 at a distance of 3.5 m the second peak for the curb with AL and without showed almost the same peaks and the height is calculated as 0.1211 m for curb without AL, 0.1157 m for curb with AL.

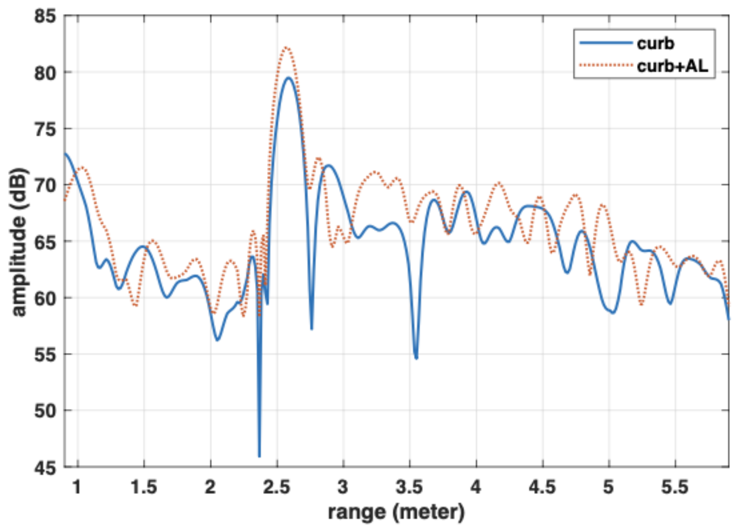

Fig. 5: Multipath based height estimation for curb at 2.5 meters with and without AL.

Table 2: Results of curb height evaluation using the multipath propagated echo signal estimation method for curb with and without AL.

Range [m]	**Evaluation results for curb height 0.11 m**			
	Curb+AL, [m]	**Errors, [m]**	**Curb, [m]**	**Errors, [m]**
2	0.07857	-0.03143	0.07406	-0.03594
2.5	0.06944	-0.04056	0.08785	-0.02215
3	0.06676	-0.04324	0.07273	-0.03727
3.5	0.10703	-0.00297	0.09512	-0.01488
4	0.06755	-0.04245	0.06594	-0.04406

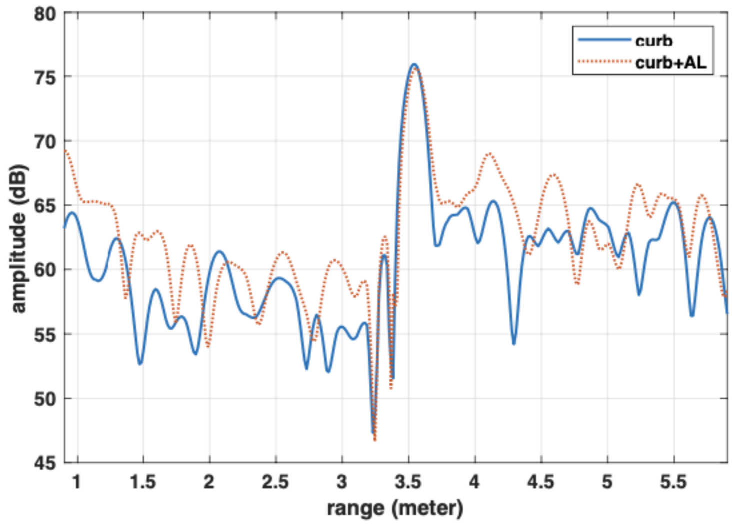

Fig. 6: Multipath based height estimation for curb at 3.5 meters with and without AL.

Several measurements are done, assuming that the curb will be in distances up to 4 m in parking scenario, and the radar will be installed at around 0.3 m above the ground. The average of 10 measurements for each distance is calculated and used for evaluation. From Table 2 it can be seen, that the results for curb with and without AL are almost the same and show the absolute errors up to 0.04 m.

4. Performance analysis of multipath propagation-based curb height estimation method for different sensor heights

Usually, the appropriate position of the radar is estimated in order to get the optimal performance. This section evaluates the introduced method for different radar heights. For this purpose, 100 measurements for each combination of different sensor heights and distances are done and the average MSE is calculated. The measurement setup is shown in Fig. 7 and the results are included in Table 3.

Table 3: Results of multipath propagation-based method of curb height estimation for different sensor heights.

Range [m]	**MSE for h_t = 0.11 m and different h_s**		
	h_s = 0.33m, [m2]	**h_s = 0.43m, [m2]**	**h_s = 0.56m, [m2]**
2	0.0227	0.0226	0.0184
2.5	0.0196	0.0238	0.0136
3	0.0257	0.0225	0.0134
3.5	0.0257	0.0170	0.0172
4	0.0168	0.0225	0.0195
Average MSE, [m2]	0.0221	0.02168	0.01642

Fig. 7: Multipath based height estimation for curb at 2 m and 0.33 m sensor height.

The results of MSE evaluation proved, that the applied method shows a promising performance. The method can be applied for sensor heights around 0.56 m above the ground with average MSE of 0.016 m^2.

In order to be able to compare with the previous method, the mean error (ME), which is used for their method evaluation, is calculated (depicted in Fig. 8). The evaluation results demonstrated that the average ME for the curb height estimation in case h_s = 0.56 m is equal to 0.0074 m, which is 3.4 times better than the previous method proposed in [12].

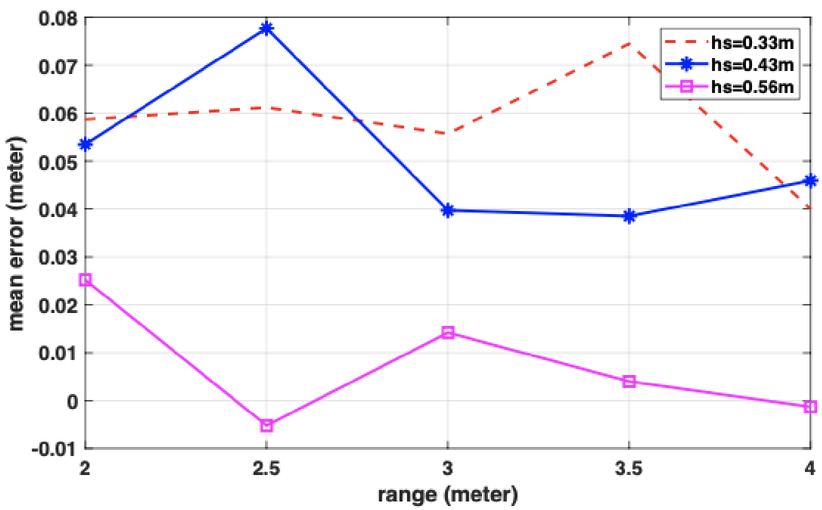

Fig. 8: Mean error of the estimated height for different radar heights from the multipath signal-based height finding algorithm.

4. Conclusion

In this paper an updated method of the target height calculation with automotive radar is presented. This method uses an equation, which is derived based on the geometry of the multipath propagation of the radar echo signal. The paper introduces a new approach to simplify the final equation computations, which can be applied to the lower height target detection. It is proved in terms of MSE, that the assumptions in computations applicable for aircraft detection, will lead to the loss of precision in the lower altitude target detections. With a new equation it is demonstrated up to 3.4 times better results for the curb height calculation in comparison with the former techniques. This method, which uses only one RX antenna, produced better results in comparison with method with several antennas, so that it can be considered as a cost-effective method too. Experiments with AL foil showed, that besides that the scattering from the curbstone surface might be not from the top edge of the curb, the object elevation can be estimated with low errors. The evaluation of an updated method for different sensor heights demonstrated, that the radar positioning at appropriate level shall be estimated as well. The future work will be dedicated to investigate the performance of the technique for different object altitudes and distances, to find the boundaries, at which the method is useful with low errors. If the boundaries are large, it can be applied not only in parking assistance applications, but also in collision avoiding systems.

Acknowledgements

The authors would like to thank the ECSEL Joint Undertaking, which funded the PRYSTINE project under the grant agreement number 783190 and the agencies for financial assistance including funding by the German Federal Ministry for Education and Research (BMBF) (funding code 16ESE0426).

References

[1] Texas Instruments, Data Sheet, Automated parking made possible with TI mmWave radar and ultrasonic sensors, May 2019.
[2] Robert J. Mailloux, Phased Array Antenna Handbook, Second Edition, Artech House Antennas and Propagation Library, 2005.
[3] A. Musralina, R. Kodari, M. Harter, Investigation of the Angle Dependency of Self-Calibration in Multiple-Input-Multiple-Output Radars, February 2021.
[4] M. Meyer, G. Kuschk, Deep Learning Based 3D Object Detection for Automotive Radar and Camera, November 2019
[5] L. Wang, T. Chen, C. Anklam, B. Goldluecke, High Dimensional Frustum PointNet for 3D Object Detection from Camera, LiDAR, and Radar, January 2021.
[6] S. Shishanov, A.Bystrov, E. Hoare, A. Stove, M. Gashinova, M. Cherniakov, T. Tran, N. Clarke, Height-Finding for Automotive THz Radars, IEEE Transaction on intelligent transportation systems, vol. 20, No. 3, March 2019.
[7] S. Brisken, J. Gütlein-Holzer, F. Höhne, Elevation Estimation with a High-Resolution Automotive Radar, September 2019.
[8] F. Diewald, J. Klappstein, F. Sarholz, J. Dickmann, K. Dietmayer, Radar-interference-based bridge identification for collision avoidance systems, July 2011.
[9] Merrill I. Skolnik, Introduction to radar systems, Published by McGraw Hill, NY (1962), International edition in 1981.
[10] Multipath Height Finding Method, United States Patent US7265710B2, 1978.
[11] A. Laribi, M. Hahn, J. Dickmann, C. Waldschmidt, A Novel Target-Height Estimation Approach Using Radar-Wave Multipath Propagation for Automotive Applications, September 2017.
[12] A. Laribi, M. Hahn, J. Dickmann, C. Waldschmidt, Vertical digital beamforming versus multipath height finding, May 2017.
[13] Texas Instruments, Data Sheet, AWR1443 Single-Chip77- and 79-GHz FMCW Radar Sensor, October 2018.