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Downscaling method of target geometries with minimum distortions on statistical features of radar cross sections for 77-GHz automotive radars

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Abstract

This article proposes a downscaling method of radar targets using the Kolmogorov-Smirnov (K-S) test to reduce the computational load of the radar cross section (RCS) simulation for 77-GHz automotive radars. The proposed method is employed to various target geometries, whose shapes are determined by the geometrical factor (GF), and their sizes are adjusted using a linear scale factor (SF). For each target geometry, the cumulative distribution function (CDF) is calculated by using the RCSs that are obtained from various observation angles and frequency points. Then, the K-S test is applied for the CDF to investigate a proper scaling factor that maintains the K-S test value of less than 0.1. The proposed method is also extended to a commercial vehicle to further verify the feasibility, and the results show that the geometries of hexahedrons and the vehicle can be downscaled by the factors of 0.6 and 0.8, respectively, without a significant distortion on the statistical features.

KEYWORDS

frequency-modulated continuous-wave radar, Kolmogorov-Smirnov test, radar cross section, scale factor

1 | INTRODUCTION

The radar cross section (RCS),[1,2] a backscatter cross section, is a measure of the detection area of a target by a radar and is defined as $4\pi r^2$ times the scattered power density divided by the incident power density, where r is the distance between the target and the receiver. These RCSs vary in accordance with the frequency used, the angle of the incident wave, polarizations, target materials, geometries, and absolute and relative (with respect to a wavelength) sizes of the targets. This variation makes unique features in RCS distributions, and particularly cumulative distribution functions (CDFs) of RCSs[3] are important and often used for the target recognition because the statistical characteristic of CDFs provides critical target information, such as types of the targets. Recently, an electromagnetic (EM) simulation method has been more widely used to obtain CDFs for various targets due to its low cost and the significant improvement in computational power within recent decades. However, obtaining the CDFs of an electrically large target still requires significant simulation time with a large amount of computational resources, especially at high frequencies of 77 GHz for automotive radar applications.

In this article, we propose a downscaling method of radar targets using the Kolmogorov-Smirnov (K-S) test to reduce the simulation time and computational resources of RCS simulations for 77-GHz automotive radars. The proposed method is applied to various target geometries that are created by varying a geometrical factor (GF), and the GF is

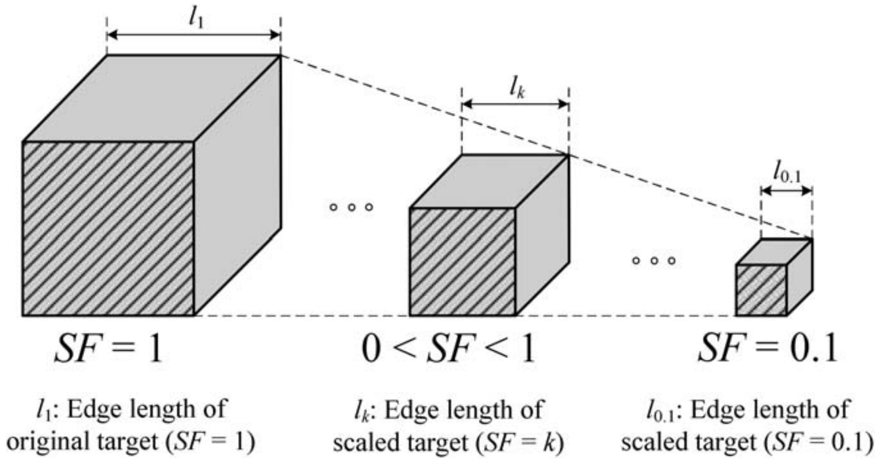

FIGURE 1 Original and downscaled target cubes. SF varies from 1 to 0.1 by a step of −0.1

defined as the ratio of the length between the upper and lower edges in hexahedrons. The target geometries are then imported as piece-wise mesh triangles into the EM simulation, and their RCSs are calculated by varying the angle of incident waves and observation frequency points to compute the CDF distribution of each target geometry. This process is repeated by varying the scale of each target geometry using a linear scale factor (SF), which is defined as the ratio of the downscaled edge length to the original edge length. To prevent a significant distortion of statistical features in the CDF distributions, the K-S test[4–6] is applied to evaluate similarities among statistical CDFs, which is often employed as a decision criterion for target recognition using RCSs[7,8] or scattering cross sections.[9] The feasibility of the proposed method is evaluated for a cube (GF = 1) with a SF from 0.1 to 1, and the proper SF is determined for a K-S test value of less than 0.1. Other geometries with GF values of 0.2 and 0.5 are also examined, and our investigation is extended to a commercial vehicle to demonstrate the suitability in a more practical application. The results show that a significant reduction in the simulation time and computational resources can be achieved without serious distortions of statistical features by determining proper SFs of 0.6 and 0.8 for hexahedrons and the commercial vehicle, respectively.

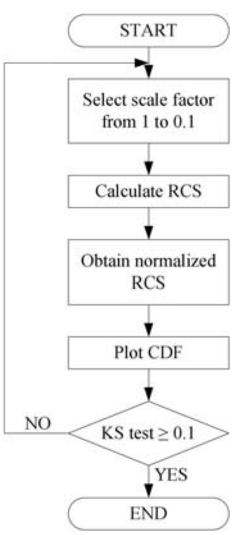

FIGURE 2 Flowchart for obtaining a valid SF

2 | K-S TESTS FOR VARIOUS TARGET GEOMETRIES

Figure 1 shows the target geometry, using a cube as an example, to obtain CDFs of RCSs for a scaled model. The original target is described on the left with an edge length of l_1, while l_k is the edge length of the downscaled structure. To investigate the validities of the downscaled model in the CDFs, the edge length of the original geometry is gradually reduced by a step of −0.1 using the linear SF that is defined as follows:

$$\text{scale factor (SF)} = \frac{l_k}{l_1}. \tag{1}$$

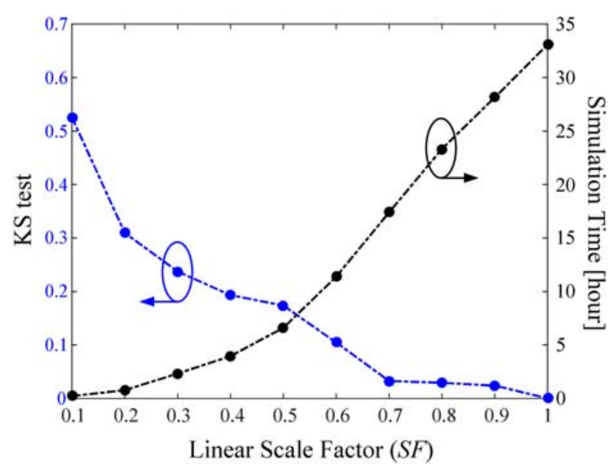

FIGURE 3 K-S tests and simulation times as a function of the SF. The K-S tests agree when SF > 0.7, and the simulation time of SF = 0.7 is reduced to 52.6% compared to SF = 1. [Color figure can be viewed at wileyonlinelibrary.com]

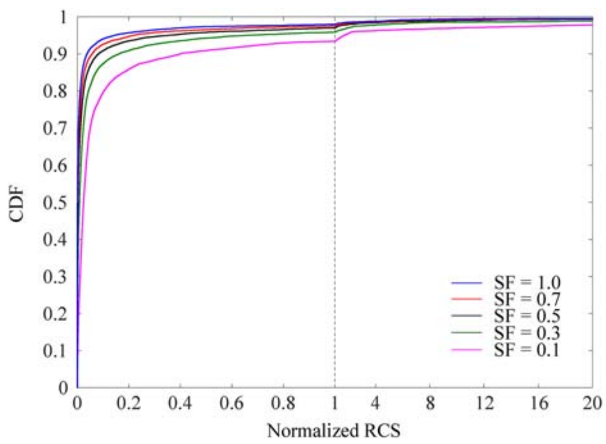

FIGURE 4 CDFs for various SFs. Note that two different scales, [0, 1] and [1, 20] are used to emphasize the CDFs with low RCSs. [Color figure can be viewed at wileyonlinelibrary.com]

Figure 2 shows the flowchart for obtaining appropriate SFs for downscaled models. In this approach, to achieve CDFs of RCSs for the downscaled models, the total number of 3240 RCSs are observed by varying the direction and the frequency of incident waves. The incident directions are varied from $\varphi = 0°$ to $\varphi = 359°$ by a step of 1° at each elevation angle of $\theta_{EL} = 0°$, 1°, and 2°. Observed frequency points are 76.4, 76.5, and 76.6 GHz. We then normalize the CDFs with respect to the mean RCS for each model, and the results are fitted using the Kaplan-Meier (K-M) estimate.[10] The obtained K-M estimates of the CDFs are then used to calculate the K-S test, which reveals how close the CDFs is to the reference distribution, and it can be defined as follows:

$$\text{K-S test} = \sup_x |F_o(x) - F_{SF}(x)|, \tag{2}$$

where $F_o(x)$ is the cumulative K-M distribution function of the original target (SF = 1). $F_{SF}(x)$ is a cumulative K-M distribution function of a downscaled target, and $\sup_x$ is the supremum of the set of distances. By checking K-S tests, the similarity of the statistical features in terms of CDFs for RCSs can be observed.

TABLE 1 K-S tests and simulation times of the target in Figure 1

SF	K-S test	Simulation time (h)
1.0	0	33.09
0.9	0.024	28.15
0.8	0.029	23.33
0.7	0.033	17.40
0.6	0.105	11.40
0.5	0.174	6.60
0.4	0.193	3.96
0.3	0.237	2.33
0.2	0.310	0.78
0.1	0.526	0.22

Figure 3 shows the K-S tests and simulation times as a function of the SF from 1 to 0.1 by a step of −0.1 for the cube in Figure 1 with $l_1 = 0.5$ m. A commercial full-wave EM simulator (FEKO EM Software and Systems[11]) and an Intel Core *i*7-3770 processor are used to solve the RCSs for 10 SF cases. As expected, the simulation time is reduced, and the K-S test increases as the SF decreases from 1 to 0.1. The simulation time decreases considerably when SF = 0.7, while the K-S test remains less than 0.1, which can be a good advantage of using the downscaled model. At SF = 0.7, the simulation time is 17.4 hours with a K-S test of 0.033, while the simulation time is 33.09 hours when SF = 1. However, the K-S test of greater than 0.1 is observed when the SF = 0.6, despite the reduced time of 11.40 hours. In an extremely reduced SF case of SF = 0.1, the K-S test

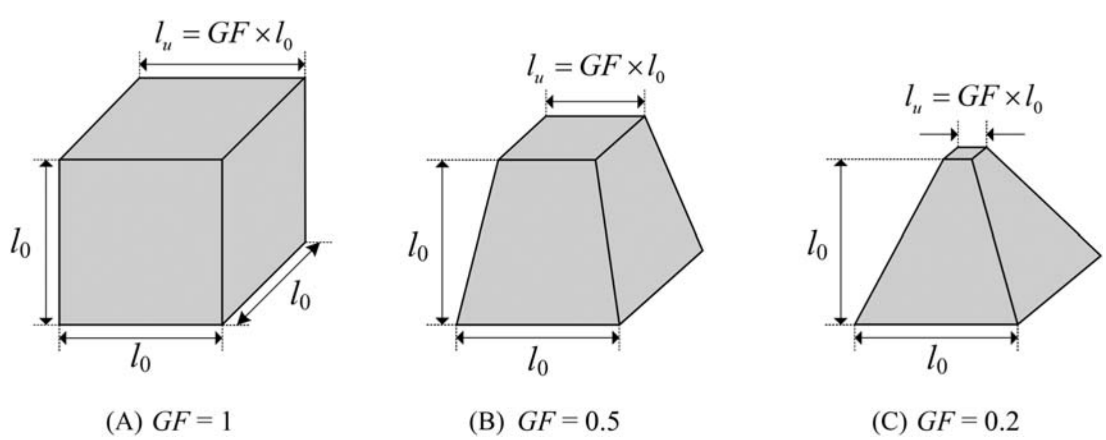

FIGURE 5 The target geometries for a cube and two trapezoidal hexahedrons are described. The baselines and heights are retained as l_0, while l_u is determined by the GF

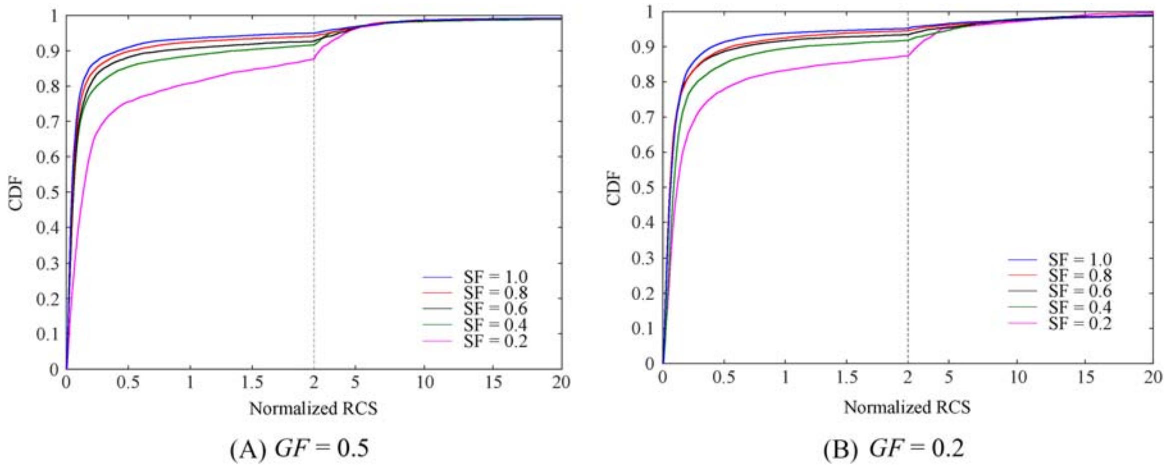

FIGURE 6 CDFs with GF = 0.5 and GF = 0.2 are plotted for selected SFs, respectively. Note that two different scales are used to emphasize the CDFs with low RCSs. [Color figure can be viewed at wileyonlinelibrary.com]

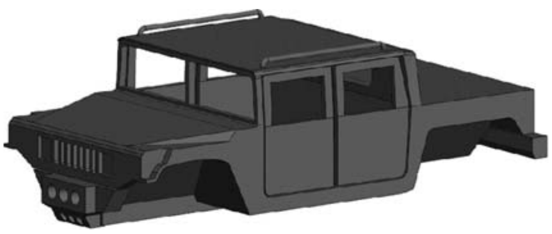

FIGURE 7 The commercial vehicle used for the RCS test. The dimensions of the vehicle are roughly $0.5 \times 1.2 \times 0.5\ m^3$

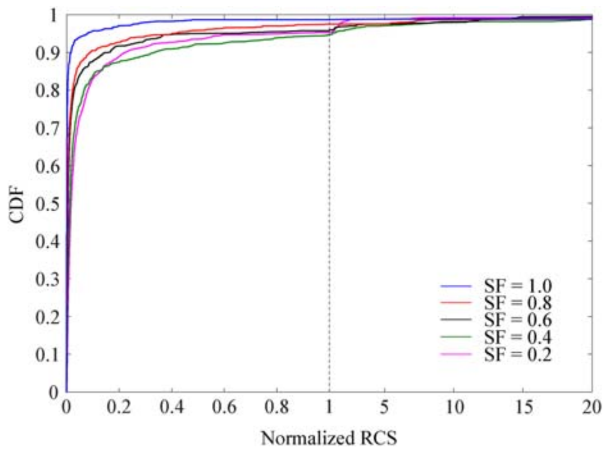

FIGURE 8 CDFs of various SFs for the vehicle. Note that, the normalized RCS also has two different scales. [Color figure can be viewed at wileyonlinelibrary.com]

increases more than 0.5, even when the simulation time is reduced to 0.22 hours, which indicates that the CDF result for such a case is not applicable. Therefore, in the case of the cube as described in Figure 1, the CDF results with SF§ 0.7 are agreeable, with a significantly reduced simulation time and a low K-S test. The K-S tests and simulation times of all SF cases are listed in Table 1. Figure 4 shows the CDFs versus the normalized RCSs for the selected SFs. Note that the normalized RCSs from 0 to 1 and from 1 to 20 are shown with different scales to emphasize the CDF with low RCS values.

Figure 5 illustrates the trial geometries used to examine the CDFs of the RCSs. Figure 5A shows the same geometry as Figure 1. Figure 5B,C shows trapezoidal hexahedrons with the same baseline length and height of l_0, while l_u is now determined by varying the GF as 1, 0.5, and 0.2. Table

TABLE 2 K-S tests and simulation times according to SF and GF

SF	GF=0.5 K-S test	GF=0.5 Simulation time (h)	GF = 0.2 K-S test	GF = 0.2 Simulation time (h)
1.0	0	48	0	43
0.8	0.0226	30	0.0232	28
0.6	0.0934	16	0.0269	16
0.4	0.1060	4	0.1412	3.9
0.2	0.3543	0.9	0.2142	0.8

TABLE 3 K-S tests and simulation times for the geometry in Figure 7

SF	K-S test	Simulation time (h)
1.0	0	17.5
0.8	0.137	12
0.6	0.202	5.0
0.4	0.320	2.3
0.2	0.330	0.53

2 indicates that the K-S tests are less than 0.1 with SF = 1.0, 0.8, and 0.6 for both the GF values. The simulation time with SF = 0.6 is reduced to less than a half of that with SF = 1.0. Therefore, the downscaled targets with SF = 0.6 are proper candidates for obtaining CDFs of these two trapezoidal hexahedrons with GF = 0.5 and GF = 0.2. Figure 6 depicts the CDFs versus the normalized RCSs for these structures. Note that two different scales are used to emphasize the CDFs with low RCSs. The two plots are similar but show a slight deviation when the normalized RCSs are greater than 2, because the RCSs with GF = 0.5 exhibit more spots with large reflections, due to steeper sides, compared to RCSs with GF = 0.2.

Finally, we apply the procedure for RCS analysis to a more complex and realistic target. Figure 7 illustrates a commercial vehicle, and only conducting parts are considered by neglecting nonconducting parts, such as the tires, carpeted seats, and glass windows, because the conducting body affects the CDFs more than nonconducting parts from an EM scattering standpoint. The reduced vehicle model with dimensions of $0.5 \times 1.2 \times 0.5$ m^3 is used for the convenience of modeling and simulation. K-S tests and simulation times for five SFs are listed in Table 3. The CDFs versus normalized RCSs are shown in Figure 8. In these cases, SF = 0.8 is agreeable with a K-S test of 0.137. Since the shape of the vehicle is more complicated with multiple windows, the K-S tests are greater than the K-S tests of the hexahedrons. The simulation time for the vehicle is reduced to 35.6% compared to that of SF = 1.

3 | CONCLUSION

We obtained CDFs and their K-S tests of the RCSs for a cube, trapezoidal hexahedrons, and a practical target such as commercial vehicles. In the cases of the cube and trapezoidal hexahedrons, the SFs of 0.6 and 0.7 were the proper downscaled factors, while the SF of 0.8 was a better downscaled factor for the commercial vehicle with a significantly reduced simulation time. These results indicate that CDFs with low K-S tests for RCSs can be obtained using the proposed procedure that finds proper SFs for various target geometries.

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Fractal broken-cross with Jerusalem load absorber for multiband application with polarization independence

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