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A Modeling Process of Equivalent Terrains for Reduced Simulation Complexity in Radar Scene Matching Applications

Gangil Byun[1] · Kyu-Young Hwang[2] · Hyeon-Gyu Park[2] · Sunwoo Kim[3] · Hosung Choo[4,*]

Abstract

This study proposes a modeling process of equivalent terrains to reduce the computational load and time of a full-wave electromagnetic (EM) simulation. To verify the suitability of the proposed process, an original terrain model with a size of 3 m × 3 m is equivalently quantized based on the minimum range resolution of a radar, and the radar image of the quantized model is compared with that of the original model. The results confirm that the simulation time can be reduced from 407 hours to 162 hours without a significant distortion of the radar images, and an average estimation error of the quantized model (20.4 mm) is similar to that of the original model (20.3 mm).

Key Words: Antenna Beamforming, Antenna Characteristics, EM Simulation Complexity, Radar Scene Matching.

I. INTRODUCTION

A radar scene matching technique has been widely adopted in various aeronautic applications to navigate current positions by mapping a pre-stored digital elevation map (DEM) with a real-time terrain image produced by a radar [1, 2]. As the radar transmits electromagnetic (EM) waves to measure the elevation profile under its flight path, the accuracy of this technique is easily affected by the antenna characteristics of the radar and EM properties of the terrain [3, 4]. However, previous studies are limited to using the ray tracing method without any in-depth consideration of antenna characteristics, such as the half-power beam width (HPBW), side-lobe level, and polarization [5]. Although some papers present the effect of terrain properties using EM simulations, the huge electrical size of terrains has been obstructed to perform a full-wave EM analysis because of the tremendous computational load and time [6].

In this study, we propose a modeling process of equivalent terrains that significantly reduces the computational load and time for a full-wave EM simulation. The proposed process is employed for a sample geometry with a size of 3 m × 3 m, and the terrain is equivalently quantized based on the minimum range resolution of the radar. The quantized model is then imported as piecewise mesh triangles into the EM simulation, and the antenna characteristics are taken into account by including the far-field radiation pattern of a transmit antenna as

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[1]Research Institute of Science and Technology, Hongik University, Seoul, Korea.
[2]Agency for Defense Development, Daejeon, Korea.
[3]Department of Electronics and Computer Engineering, Hanyang University, Seoul, Korea.
[4]School of Electronic and Electrical Engineering, Hongik University, Seoul, Korea
[*]Corresponding Author: Hosung Choo (e-mail: hschoo@hongik.ac.kr)

a point source [7]. The elevation profile is computed by taking the inverse Fourier transform of the reflected complex waves in the observation frequency band. The suitability of the proposed process is evaluated by comparing the similarity between the radar images of the original and those of the quantized terrain models. The results demonstrate that the process efficiently reduces the simulation load and time without a significant distortion of the radar images.

II. Proposed Modeling Process

Fig. 1 shows the flowchart of the proposed modeling process for equivalent terrains to obtain radar images using a full-wave EM simulation. The process begins with the import of the original terrains through DEM data, and the elevation information is quantized by the minimum range resolution ΔR of a scene matching radar [8], which is inversely proportional to the frequency bandwidth. For example, the radar with a frequency bandwidth of 150 MHz has a resolution of $\Delta R = 1$ m, and the resolution of $\Delta R \leq 0.1$ m can be achieved when the bandwidth is broader than 1,500 MHz. The definition of ΔR is expressed as

$$\Delta R = \frac{c}{2 \cdot BW} = \frac{c}{2 \cdot (f_{\max} - f_{\min})}, \tag{1}$$

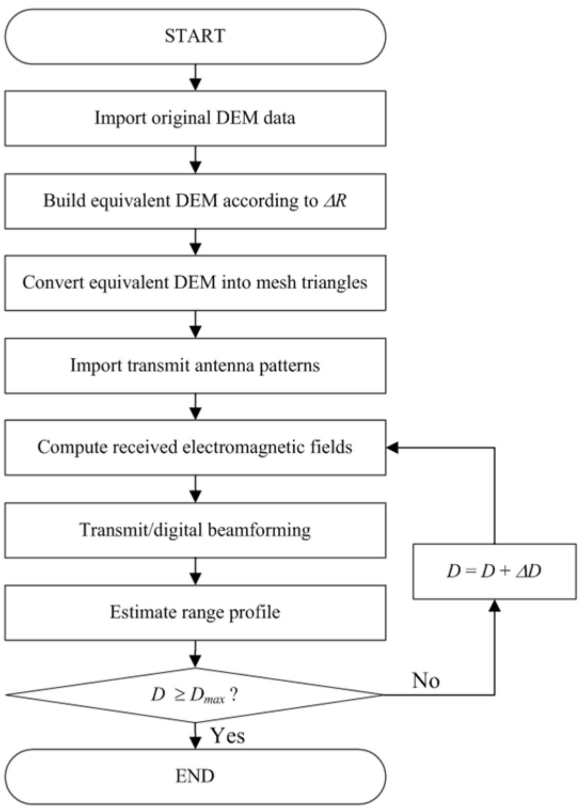


Fig. 1. Proposed process of the quantized terrain and radar images.

where c is the speed of light, and BW is the frequency bandwidth defined by the difference between the maximum frequency (f_{max}) and the minimum frequency (f_{min}). This quantization process transforms the original DEM into a multi-step geometry with a height difference between steps that is equal to the minimum range resolution ΔR. This quantized terrain model is included in the EM simulation as piecewise mesh triangles, and the radiation pattern of the transmit antenna is imported as a point source to compute the range profiles. For transmit beamforming, the point source direction is steered from −15° to 15° at an interval of 0.5°, and the estimated range profiles are accumulated to obtain elevation information at each radar position. After completing the rotation, the radar position is moved by an interval of ΔD, and this estimation process is repeated to scan the entire geometry for a 2D image.

To verify its suitability, the proposed process is applied to the sample geometry presented in Fig. 2(a). This terrain is scanned by using a scene matching radar operating in the Ku band (12 GHz ≤ *frequency* ≤ 18 GHz), and thus the terrain can be considered an electrically huge geometry with an edge length of greater than 120λ (λ= 25 mm at 12 GHz). To minimize the

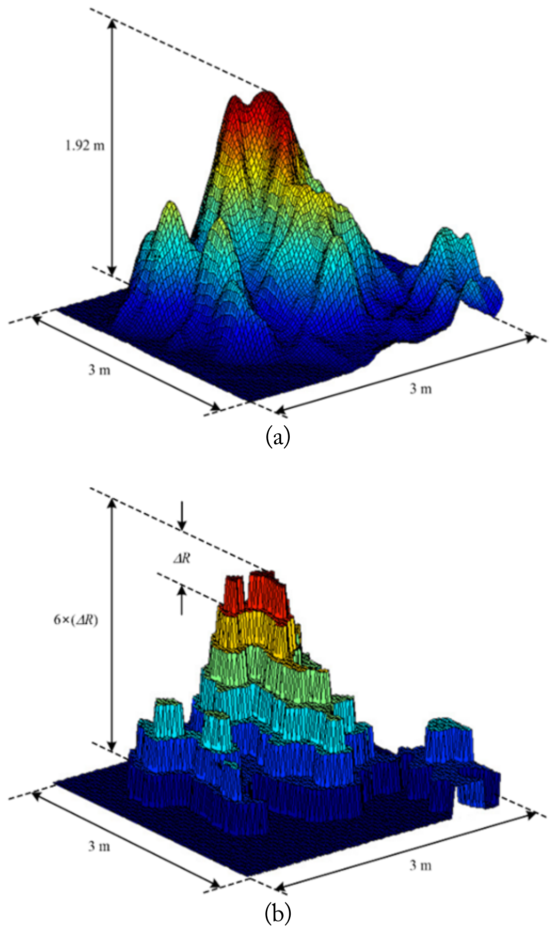


Fig. 2. The 3D view of the digital elevation model. (a) Original terrain model and (b) quantized terrain model.

computational load of the full-wave EM simulation, this terrain is quantized by applying the proposed process and is discretized as a six-step geometry with an equal height difference ΔR, as illustrated in Fig. 2(b).

Both terrains are imaged using an antenna having a HPBW of 0.1° with a side-lobe level of 24.8 dB, and its radiation pattern at each steering angle is pre-stored as a point source. The pattern with an HPBW of 0.1° is obtained from a uniform dipole array with a 1,000 × 1,000 configuration with an inter-element spacing of 0.75λ, and the steering angle of the array is adjusted by varying the phase difference among array elements. The terrains are assumed to be covered by a perfect electric conductor, and the surface roughness of the terrain is neglected. In addition, EM fields reflected by the terrains are computed using the physical optics method, and the radar is fixed at a height of 5.6 m. Then, we take the inverse Fourier transform of the reflected fields to obtain a time–domain signal, as presented in Fig. 3. This signal is normalized by the absolute peak value at around 14.5 ns. Some peaks exceeding a threshold level of 0.02 are taken into account to calculate their mean and median time delays, denoted as τ_{mean} and τ_{median}, respectively. Note that the threshold level is empirically determined by considering the system configuration, such as antenna characteristics, frequency bandwidth, maximum steering angle, and scanning altitude of the radar, for accurate results. We also consider the delays of the maximum amplitude (τ_{max}), which are used to estimate the distance between the antenna and the terrain for range profile estimations at each steering angle.

III. Verification of the Proposed Process

Fig. 4 shows a 3D radar image for the quantized terrain model estimated by τ_{median}. The maximum point is observed at a distance of 0.69 m with a steering angle of 6.9°, and it is similar

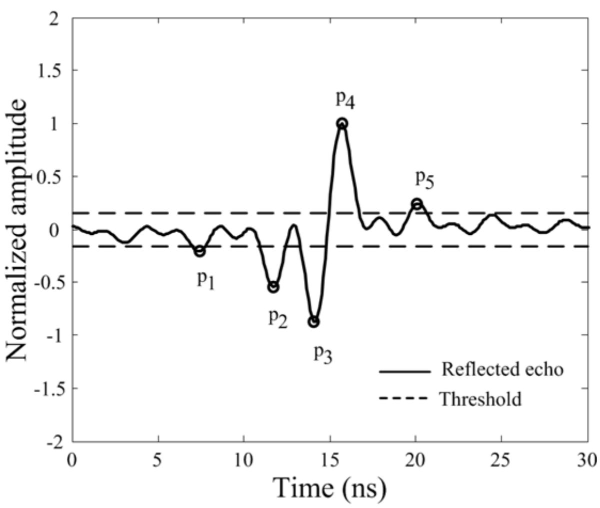


Fig. 3. Example of a reflected time–domain signal.

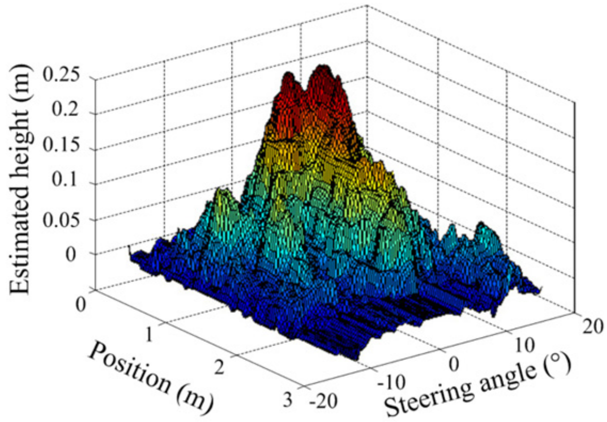


Fig. 4. A 3D radar image obtained from the quantized terrain model.

to the geometrical peak of the original terrain (0.72 m at 7.8°). In addition, the step edges are smoothed because of wave scattering effects, and this action becomes more significant with a broader HPBW [9–11].

Fig. 5(a) and (b) show the comparison of the radar images obtained for the original and quantized terrain models, which

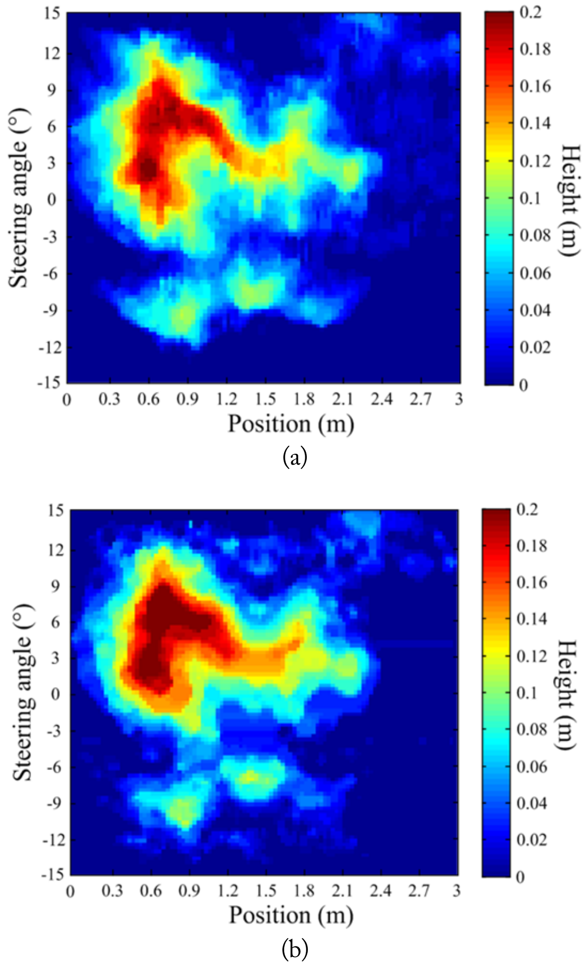
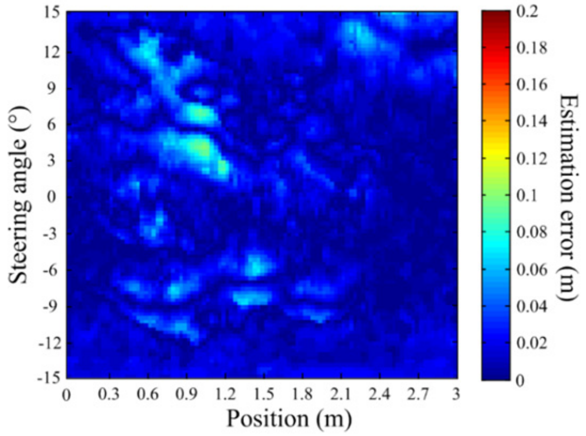
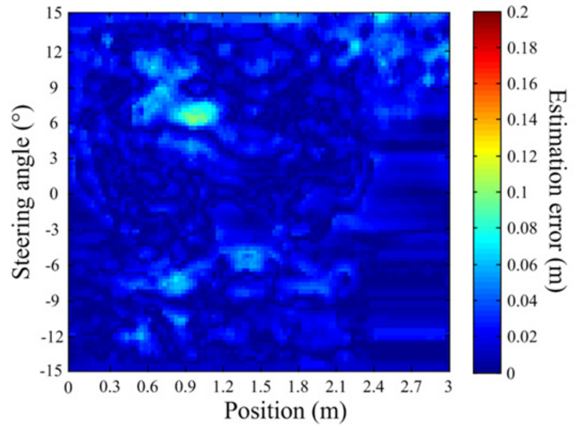


Fig. 5. Comparison of radar images estimated by τ_{median}. (a) A 2D image using the original terrain model and (b) a 2D image using the quantized terrain model.



(a)



(b)

Fig. 6. Comparison of the height differences for τ_{median}. (a) Error distributions for the original terrain model and (b) error distributions for the quantized terrain model.

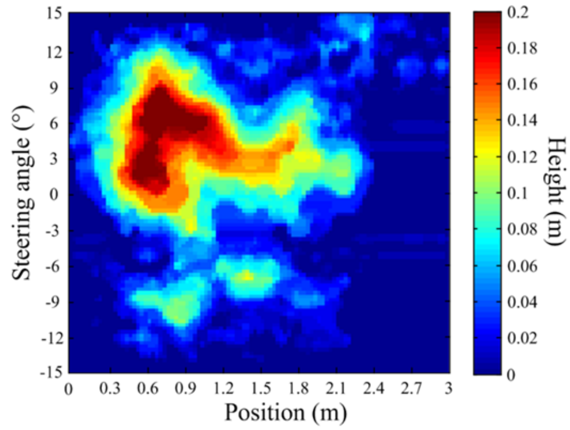
are estimated by τ_{median}, and their estimation error maps are illustrated in Fig. 6(a) and (b). The estimation error is defined as the root mean square (RMS) difference between the real value (h_{real}) and the estimated heights ($h_{est.}$) obtained from all steering angles and distance, as shown in (2).

$$RMSE = \sqrt{\frac{1}{N_d N_\phi}\sum_{n=1}^{N_\phi}\sum_{m=1}^{N_d}\left|h_{real}(m,n) - h_{est.}(m,n)\right|^2}, \tag{2}$$

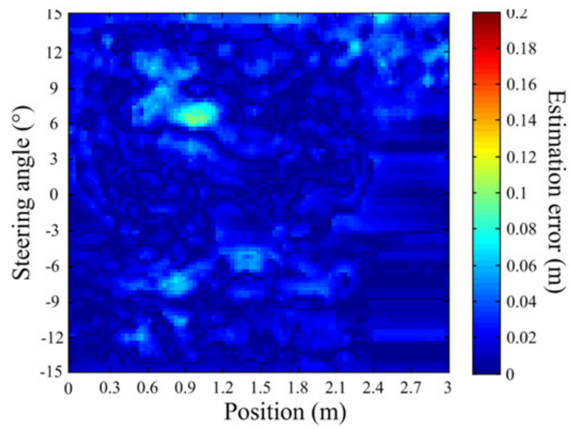
where N_ϕ is the total number of observation angles, and N_d is the number of radar positions in the image. As the total traveling distance of the transmitted wave varies geometrically for different steering angles, we compensate for the value of h_{est} for the geometrical difference of the traveling distance by multiplying "1/cos(θ_s)" for the steering angle θ_s. The two models exhibit similar error distributions with an average estimation error value of 20.3 mm for the original geometry and 20.4 mm for the quantized model. The estimation error in the range of the radar position from 0.5 m to 1 m for the steering angle of 6°–12° increases because of the wave blockage effect caused by the geometrical peak located at 0.72 m and 7.8°. The radar image of the original terrain model is expressed as discrete steps with a few range bins because of the minimum range resolution of the radar. These results demonstrate that the equivalent terrain model can produce similar radar images with drastically reduced computational load and time.

Fig. 7(a) and (b) show a radar image estimated by τ_{mean} and its error map, respectively. Fig. 8(a) and (b) illustrate a radar image and its error distributions estimated by τ_{max}, respectively. The step edges are apparently sharp when the image is obtained from τ_{max}, but the average error significantly increases from 20.1 mm (τ_{mean}) to 27.8 mm (τ_{max}). This error value is significantly increased in a large steering angle because of two main reasons: the power of the back-scattered field is reduced [12], and the radar resolution is degraded by the increased HPBW of the transmit antenna array [13].

Table 1 shows the comparison of the numbers of mesh triangles and simulation times between the original and quantized terrain models. The original model is composed of



(a)



(b)

Fig. 7. Simulation results of the quantized terrain estimated by τ_{mean}. (a) A 2D radar image and (b) 2D error distributions.

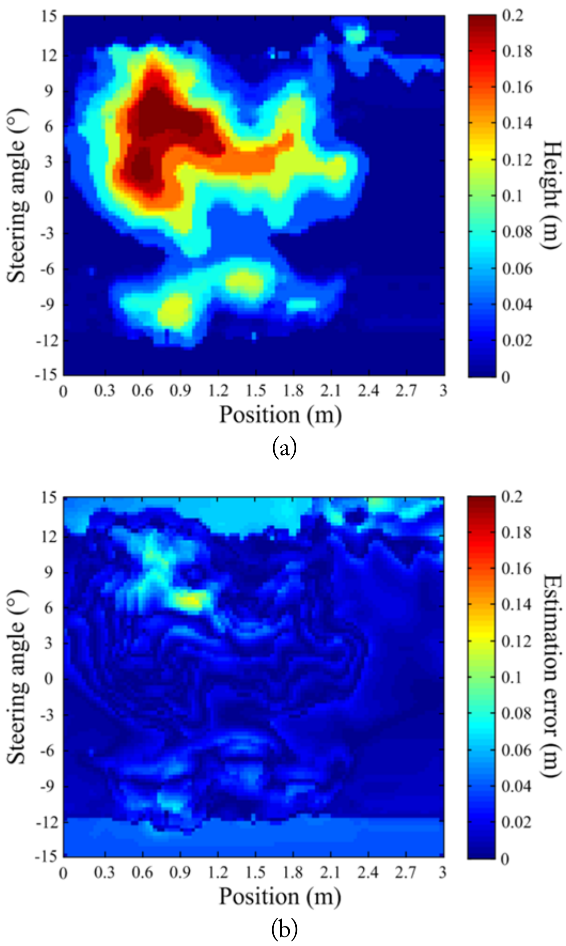


Fig. 8. Simulation results of the quantized terrain estimated by τ_{max}. (a) A 2D radar image and (b) 2D error distributions.

Table 1. Comparison of the simulation load and time between the original and equivalent terrain models

Geometry	Number of mesh triangles	Simulation time (hr)
Original terrain	109,251	407
Equivalent terrain	68,850	162

109,251 mesh triangles and requires 407 hours of simulation with an Intel Core i7-3820 quad-core processor and 64 GB of RAM. By applying the proposed process, the number of mesh triangles is decreased to 68,850 with a reduced simulation time of 162 hours, which is more than half of the original model.

IV. Conclusion

We investigated the modelling process of equivalent terrains to significantly reduce the computational load and time of a full-wave EM simulation. The original model was quantized by considering the range resolution of the Ku-band radar, and the actual antenna characteristics were included as a point source excitation. The elevation profiles were estimated by the mean and median time delays, and the delay of the maximum signal amplitude was considered to evaluate the similarity of the radar images between the original and quantized terrain models. The results confirmed that the process efficiently reduces the simulation load and time with an average estimation error of 20.1 mm.

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Gangil Byun

received his B.S. and M.S. degrees in electronic and electrical engineering from Hongik University, Seoul, Korea in 2010 and 2012, respectively, and his Ph.D. degree in electronics and computer engineering from Hanyang University, Seoul, Korea, in 2015. He is currently a research professor in the Research Institute of Science and Technology at Hongik University. Dr. Byun's principal areas of research are in circularly polarized antenna design, vehicular and aeronautic antenna design, global positioning system antenna design, antenna and array configuration optimization, and array antenna design for various adaptive beamforming applications, such as direction of arrival estimation, interference mitigation, and radar.

Kyu-Young Hwang

received his B.S., M.S., and Ph.D. degrees in electrical engineering from Pohang University of Science and Technology, Korea, in 1999, 2001, and 2007, respectively. He is currently a senior researcher in the Agency for Defense Development. His research interests are radar image processing and adaptive signal processing algorithm for radar systems.

Hyeon-Gyu Park

received his B.S., M.S., and Ph.D. degrees in electrical engineering from Pohang University of Science and Technology, Pohang, Korea, in 2006, 2008, and 2013, respectively. He is currently a senior researcher in the Agency for Defense Development. His research interest is computational electromagnetics for radar systems.

Sunwoo Kim

received his B.S. in electrical engineering from Hanyang University, Seoul, Korea, in 1999, and his M.S. and the Ph.D. degrees in electrical and computer engineering from the University of California, Santa Barbara, in 2002 and 2005, respectively. Since 2005, he has been with the Department of Electronics Engineering, Hanyang University, Seoul, Korea, and is currently an associate professor. His research interests include wireless communications, wireless localization, and signal processing, with current emphasis on location-aware communications.

Hosung Choo

received his B.S. degree in radio science and engineering from Hanyang University in Seoul in 1998 and his M.S. and Ph.D. degrees in electrical and computer engineering from the University of Texas in Austin in 2000 and 2003, respectively. In September 2003, he joined the School of Electronic and Electrical Engineering, Hongik University, Seoul, Korea, where he is currently a professor. His principal area of research is the use of optimization algorithm in developing antennas and microwave absorbers. His studies include the design of small antennas for wireless communications, reader and tag antennas for RFID, and on-glass and conformal antennas for vehicles and aircraft.