3D Representation of Radar Coverage in Complex Environment

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Summary
3D representation of Radar electromagnetic information affected by terrain, ocean and weather is an unavoidable problem in the future digital battlefield. Based on APM(Advanced Propagation Model), in-plane propagation loss was calculated by the virtual of digitalized virtual battlefield. Then 2D in-plane coverage of given Radar was deduced. At last multiple such 2D coverage were combined together to construct the 3D Radar coverage. Our experiment of embedding a typical Radar into digital battlefield showed that the 3D Radar coverage affected by complex environment was vividly and dynamically visualized in time and parameters of Radar and target could be adjusted interactively, which could provide excellent decision supporting and plan aiding for users.

Key words:
Radar Coverage; virtual battlefield; 3D Visualization;

1. Introduction

As Virtual Reality (VR) technology is widely used in daily drill and operation commands, combat games such as America's Army are walking up to actual combat drill. The article of "Virtual Reality Prepares Soldiers for Real War" published by The Washington Post on Feb 14, 2006 said that American soldiers regarded actual combats as computer game[1]. It can be said that VR not only have transformed the way the United States military fights wars, as well as soldiers' ways of killing. The technique of representing real terrain, physiognomy, bilateral situation and force location can now satisfy these basic requirements[2-5]. But for the invisible electromagnetic environment, it is not only laid on the performance of equipments themselves, but greatly on the environment around them. So it is extremely difficult to represent 3D electromagnetic environment efficiently and accurately. 2D Radar coverage diagrams drawn by hand or aimed by computers is the traditional manner of representing Radar electromagnetic information after obtaining the related electromagnetic information datum[6]. There are some evident shortages: ①2D curve cannot intuitively represent 3D Radar electromagnetic information; ②Radar coverage diagrams cannot change as target parameters change; ③ Radar coverage diagrams cannot represent the effects of jam coming from different directions or distances. The communication planners currently draw the locations of antennas on map only by hand and utilize coverage diagram and text information to represent the whole coverage. That needs much experience on radio equipments, weather, terrain and other environment factors. So the traditional representation methods can't satisfy the modern martial requirements. Future digital battlefield environment has to integrally consider the influences of complex environment so as to give user an exact 3D Radar Coverage, make user more clear about the current electromagnetic situation and make communication planners more realize the communication problems. The rigorous prediction of radar coverage in complex environment entails our solving the "vector wave equation", which is derived from Maxwell's electromagnetic field equations. Such a solution is challenging for two primary reasons. First, the slopes of the irregular terrain couple the three components of the vector field in an intricate fashion. Second, the inhomogeneity of the atmosphere complicates the nature of the field equations. These complications rule out analytical closed form solutions, leaving numerical simulations as the only resort. The methods applied to solve these problems are generally categorized as integral equation methods and differential equation methods. Integral equation methods result in extremely large, full matrices that need to be inverted in order to determine the unknown fields. In addition, rigorous treatment of a general, inhomogeneous troposphere via an integral equation method is extremely difficult[7]. Consequently, this method is not the choice for treating long-distance radar coverage problems. The differential equation method, on the other hand, accounts for atmospheric inhomogeneity (ducting) in a straightforward fashion and results in sparse matrix systems that can be efficiently inverted numerically[8, 9]. It has to resort to the exact vector differential wave equation and this leads to the vector Parabolic Equation (VPE) method [10-14]。SPACE AND NAVAL WARFARE SYSTEMS CENTER integrated four models named Advanced Propagation Model (APM) to calculate propagation loss in full space[15, 16]. They only paid attention to antennas and propagation, and seldom researched how to represent the 3D Radar Coverage. Kostic etc have predicted and visualized Radar Coverage in 3D Geographic Information System. They only model the Radar electromagnetic wave by geometric optics approach and represent the virtual 3D coverage by drawing overlays at different height. Their

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result is not only inaccurate but also not intuitional. Taking full advantage of the digital terrain environment, this paper uses APM to get the propagation loss in 3D space. Then the 3D coverage for a given target was calculated and presented in 3D environment. Users can interactively change parameters of Radar or environment to get different effects to serve the selection of Radar position, operation commands and daily drill.

2. Calculation of In-plane Propagation Loss

As Radar transmits an EM signal and then receives an echo of the target, the whole loss can be considered as three parts: system loss of Radar, path propagation loss and target reflection loss. In this paper, the system loss was always considered as a constant, which is determined by Radar itself. And the target reflection loss depends on the target's Radar Cross-Section (RCS). But the path loss is much complicated which depends not only on Radar itself but more on environment. But luckily, APM gives us a very good model which can process this complicated case.

2.1 Propagation Factor and Loss Definirion

In all radiowave propagation models, the basic quantity computed is the propagation factor F. The propagation factor is defined as(1):

$$F = \frac{E}{E_0} \quad (1)$$

where E is the field strength at a point, including antenna pattern effects but normalized to unity gain antennas, and E_0 is the field strength that would occur at that point under free space conditions if loss-free isotropic antennas were used for both the transmitter and receiver[13]. Once F is computed, propagation loss in dB is determined by taking the difference between the free space loss and F (in dB). In equation form(2):

$$L = 20\log\left(\frac{4\pi r}{\lambda}\right) - 20\log F \quad (2)$$

The first term in (2) is the free space loss, where r is the range and λ is the wavelength.

From (2) it should he apparent that F contains all environmental affects on the emitted EM wave. This includes effects from the atmosphere and a variable reflecting surface, such as rough ocean or land. Then by(2), the propagation loss value of all the grid nodes (range versus height locations) in one profile can be get.

2.2 Advanced Propagation Model

APM contains four basic submodels: flat earth (FE), ray optics (RO), extended optics (XO), and Parabolic Equation(PE), in which PE is undoubtedly more capable than the other three in computing loss due to varying refractivity and terrain along the propagation path. It is the primary model for which the other three submodels are built around. Therefore, all parameter contains and initializations are performed for the PE algorithm first, keeping the region over which it is applied to a minimum for the most efficiency. The other three models are then used to compute loss in regions where the PE algorithm is not applied. For more details please refer to literature [15]. By APM we can calculate propagation loss values on each range versus height location as EM energy propagates through a laterally heterogeneous atmospheric medium where the index of refraction is allowed to vary both vertically and horizontally, also accounting for terrain effects along the path of propagation.

3 Get 2D In-plane Coverage From Loss Value

For a given target, the Radar can detect it only when the total loss value is less than a threshold which is related to one RCS of a target and Radar's performance. Given that the loss value at everywhere is known, Radar's whole coverage is all the places where the total loss value is less than the threshold. First we have to determine this threshold for a given target. Considering environment factors the Radar equation [6] is:

$$P_r = \frac{P_t G_t G_r \lambda^2 \sigma}{(4\pi)^3 R^4 l_s l_\alpha} F^4 \quad (3),$$

in which P_t is the power of transmitter, P_r is the power of receiver, G_t is gain of transmitter's antenna, G_r is gain of receiver's antenna, λ is wave length, σ is the target's RCS, F is pattern propagation factor from transmitter to target, R is the range from transmitter to target, l_s is system loss of Radar, l_α is factor of atmosphere absorption. For the simplification we assume that $G_t = G_r = G$, and (3) can be transformed to:

$$P_r = \frac{P_t G^2}{l_s} \frac{4\pi\sigma}{\lambda^2} a^4 \quad (4),$$ in which $a = \frac{\lambda}{4\pi R} \frac{F}{l_\alpha^{1/4}}$.

According to [17], the total loss value L(dB) can be calculated as $L = -20 \log a$ (5).

From (3), (4) and (5), we can get:

$$L = 5\log\left(\frac{P_t G^2}{l_s}\right) + 5\log\left(\frac{4\pi\sigma}{\lambda^2}\right) - 5\log P_r \quad (6)$$

From (6), we can see that when P_t, l_s, and σ are fixed, the relation between L and P_r is determined. For the given probability of false alarm and probability of detection, Radar detection factor D_0 can be determined, and the minimum detectable signal $S_{i\min}$ can be determined by:

$$S_{i\min} = kT_s B_n F_0 D_0 \quad (7),$$

In which k is Boltzmann constant, T_s is noise temperature of receiver, B_n is predetection noise bandwidth of receiver filter and F_0 is receiver noise figure. The threshold of

minimum receivable power P_r is directly determined by $S_{i\min}$.
Then by (6), for the given probability of false alarm and detection, and target's RCS, we can get the loss value threshold $L_{\max}$ when P_r reaches its minimum. Then by comparing the loss value of one location and this threshold $L_{\max}$, we can know whether Radar can detect the target on this location or not. If it is larger than this threshold, Radar cannot detect it, otherwise Radar can detect it. After all the locations are compared, the whole Radar coverage is known.

4 3D Representation of Radar Coverage

4.1 Overview

Section 2 and 3 gives us a method how to get the loss value and coverage in one plane, which does not consider the 3D propagation in environment. To get the 3D coverage, a straight idea is to calculate the loss value in 3D space, but that will lead to solve 3D vector wave equation, which is an impossible task for concurrent computer, especially when calculation area is large. Because the 2D assumption will persist for years to come, even with foreseeable advances in processor speed, it is important to quantify and understand the errors it entails. So as shows, we divide the whole space into many planes (profiles) along the azimuth direction. Then for each profile we divide it into $m \times n$ grids and calculate the total loss on each grid node by (2). Then according the deduction of section 3, 2D in-plane coverage can be get. After all the profiles are processed, combine all these profiles together, we will get an approximation of the 3D Radar Coverage. It is evident that this approach does not capture out-of-plane scattering and diffraction effects; however, it does model the forward scatter and diffraction caused by the in-plane terrain variations. For the accuracy comparison between the result calculated in one plane and calculated all in 3D way, literature [18] shows the close agreement in a simple urban propagation environment composed of a flat terrain with four pairs of buildings and a simple terrain environment. This accuracy is adequate for our use of representing the coverage in 3D digital environment, especially in virtual battle field at strategic level. Moreover if computation capabilities allow, the profiles can be added adaptively for more detailed information.

4.2 Construction of 3D Radar Coverage

Fig.2 illustrates a profile at azimuth α, in which the loss value at every grid node has been calculated. The horizontal axis is in range direction R, vertical axis is in height direction H, and grid node represents the loss value $L(\alpha, R, H)$, the small red circle is the Radar location.
To determine a 2D coverage in one profile we compare the loss value $L(\alpha, R, H)$ on each grid node and the threshold $L_{\max}$. The node where its loss value larger than $L_{\max}$ is not in the coverage, or else is in. For simplification, here we only represent the outmost boundary of the 2D coverage, as depicted in red line in Fig.2. To get this outmost contour, we put forward a search-approach algorithm which is described as follow:

(1) For the profile at azimuth A, as showed in Fig.2, search the loss value $L(A, R, H)$ at every height along range direction, initially set R=0 and H =0, then switch to (2);

(2) Compare $L(A, R, H)$ and $L_{\max}$, if $L(A, R, H) > L_{\max}$, and $L(A, R+1, H) \leqslant L_{\max}$, one point on left contour must exist between nod (A, R, H) and $(A, R+1, H)$. By linearly interpolation can get the point's coordinates $(A, R+(L_{\max} - L(A, R, H))/(L(A, R+1, H) - L(A, R, H)), H)$, record it into the point series of left contour C_l (depicted in green) and switch to (4); or else switch to (3);

(3) If $L(A, R, H) > L_{\max}$, and $L(A, R+1, H) > L_{\max}$, move a step forward, set R=R+1, if R reaches the far most range, set R=0, H=H+1, and switch to (2);

(4) If $H<H_{\max}$, Set H=H+1, and R=0, switch to (2); or else switch to (5);

(5) Set $R = R_{\max}$, search the loss value $L(A, R, H)$ at height H from right to left, if $L(A, R, H) > L_{\max}$, and $L(A, R-1, H) \leqslant L_{\max}$, one point on right contour must exist between nod (A, R, H) and $(A, R-1, H)$. By linearly interpolation can get the point's coordinates $(A, R-(L_{\max} - L(A, R, H))/(L(A, R, H)-L(A, R-1, H)), H)$, record it into the point series of right contour C_r (depicted in red) and switch to (7); or else switch to (6);

(6) If $L(A, R+1, H) > L_{\max}$, and $L(A, R, H) > L_{\max}$, move a step backward, set R=R-1, if R<0, set R=$R_{\max}$ and switch to (5);

(7) If $H<H_{\max}$, Set H=H+1, switch to (5); or else end the algorithm.

In this algorithm, by search every node in the profile, we recorded two point series which make up of the whole contour composed of C_l and C_r. Connecting all these points in C_l and C_r orderly will make the 2D outmost contour of the coverage, as the green and red curve showed in Fig.2.

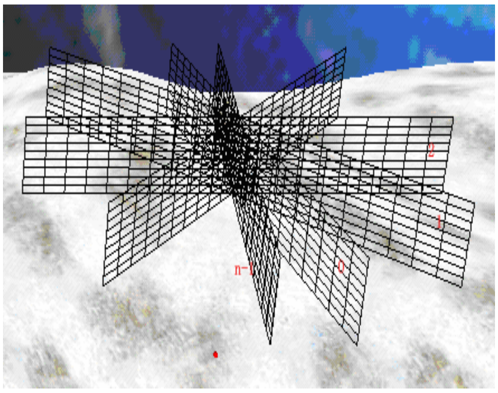

Fig.1 Construction of 3D data field

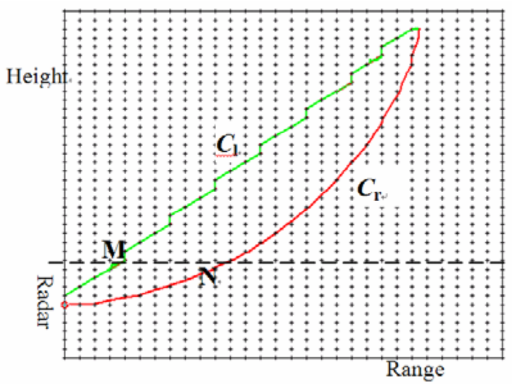

Fig.2 2D coverage of an in-plane profile

After all the 2D contour curves are obtained, corresponding points are connected to form the 3D Radar Coverage. The connection process is a process of triangulation which constructs the triangle model of the coverage. As the aforementioned search-approach algorithm shows, each point in C_r will not cross a point in C_l, in Fig.2 the point M and N is an example. So when connecting, we can do for left and right contour separately, as shown in Fig.2 the C_l and C_r. The triangulation is mainly to find the corresponding point. When two C_l (or C_r)of neighbor contours have the same number of points, connecting them form low to high can finish this triangulation process. Or else we have to do some extra work, first order the points in each C_l (or C_r) according to their height, the lowest one is given the number 0, the point which is just above the lowest one is given the number 1, and so on. Then connect the points which have same order number in their own contour from low to high until one of them have no point to be connected. All the unconnected points in another contour are connected to the top point of its neighbor. Thus all the points are processed and the triangle model of the coverage is get.

To represent the triangle model in 3D virtual battlefield, we have to process the lighting problem for vivid look. The normal method is to compute normal of each point in 3D model. Here we simply take the vector from Radar to the point as normal of this point.

5 Experiment Results and Discussion

In our experiment, the Radar's parameters are shown in Table 1, atmosphere absolute humidity above the earth surface was $10g/m^3$, temperature of the earth surface was 25^oC, and the refraction index was shown in Table 2. We represented the 3D coverage of this Radar into a virtual battlefield whose height map size was 256×256 and sample interval was 1km, the height of each terrain point was generated randomly. The terrain type was all selected to medium dry ground, and the target's RCS was 30 m^2. For the cases of random terrain, full Smooth terrain, with and without lighting processing, the results are shown in Figure 3-8. The program was run on two different PC and the computation time was much different, in which PC1's configure was P4 2.0A CPU/256M RAM/GForce5200 64M Graphic card and PC2's configure was PM760 2.0CPU/512M/64M ATI Radeon X300 Graphic card.

From the result we found the most time was consumed on the computation of APM. When the loss data was get, the time of constructing model was relative very little and could be ignored. The time of random terrain case was double of the time of full Smooth terrain case. This was mainly due to that PE method was the center of APM, which consumed a great deal of time. When terrain was simple, the time consumed was decreased. Time consumed on PC2 was almost half of PC1. This difference gave us a conclusion that the efficiency depended mainly on the performance of CPU and size of RAM. So the performance of computer was very important for our experiment. When the number of profiles increased, the time of APM computation increased linearly, that was to say, the time consumed for one profile was almost a constant. But when the number of profiles increased, the time of constructing model increased little and didn't obey this rule. This was much due to the simplicity and great efficiency of our model construction method. It was apparent that the size of the last model was not large. Although it depended on the number of profiles, this was a little case for concurrent graphic hardware.

As compared to the result of Kostic, our result was more vivid and more immersing. The 3D coverage could be viewed from all the angle of view. And the parameters of target or Radar could be interactively adjusted, by which many different effects could be viewes.

Table 1 parameters of Radar

frequency	***polarization***	***Antenna height***	***elevation***	***gain***	***Beam width***
1KMHz	horizontal	20m	0^o	60 dbi	5^o
pattern	***power***	***Pulse length***	***Pulse frequency***	***System loss***	***False alarm probability***
Sin(x)/x	2K KW	10	300 Hz	3 dB	$1.0e^{-6}$

Table 2 refraction index

Profile	***Height (m)***	***Refraction index (0km, M unit)***	***Profile (m)***	***Refraction index (0km, M unit)***
1	0.	330.	0.	330.
2	100.	342.5	600.	405.
3	230.	312.5	730.	375.
4	2000.	517.8	2000.	522.3

Table 3 computation time

Number of profile	***Terrain***	***APM computation time (ms)***		***Model Construction time (ms)***	
		PC1	***PC2***	***PC1***	***PC2***
18	random	5656	2758	0	0
18	plain	3109	1509	0	0
180	random	30074	10004	9	4
180	plain	10224	5764	9	4

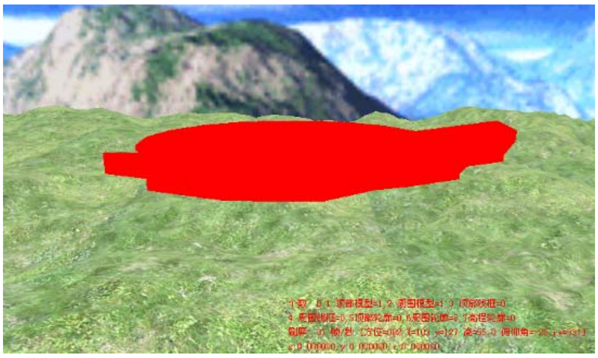

Fig.3 Random terrain without lighting

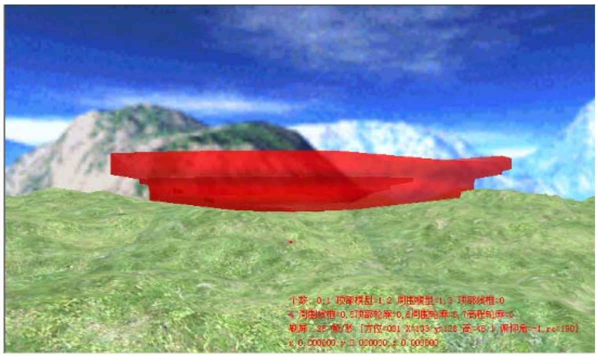

Fig.4 Random terrain with lighting and view forward

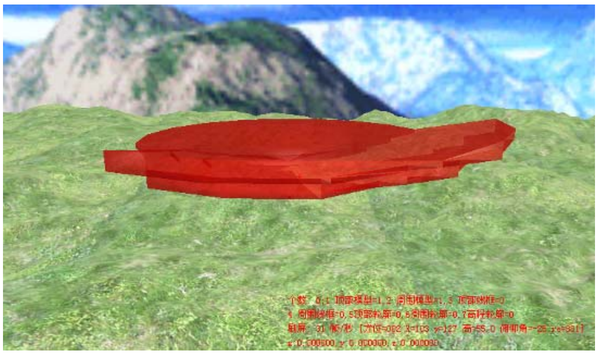

Fig.5 Random terrain with lighting and view downward

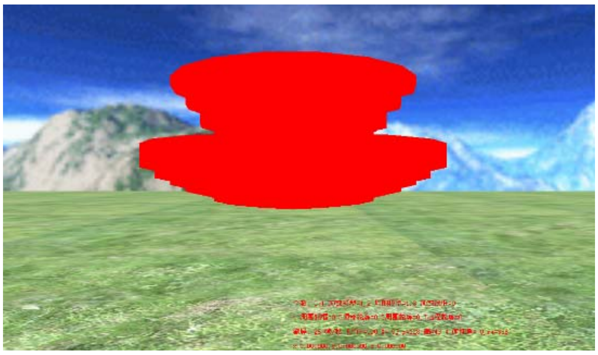

Fig.6 Smooth terrain without lighting

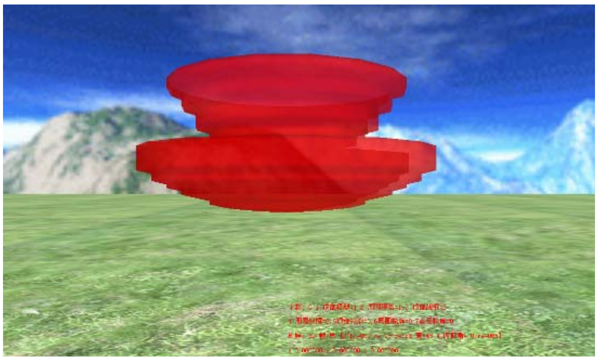

Fig.7 Smooth terrain with lighting and view forward

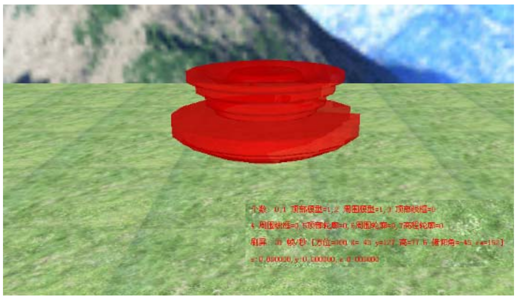

Fig.8 Smooth terrain with lighting and view downward

6 Conclusions

Based on digitalized virtual battlefield, APM were used to compute in-plane propagation loss, from which the 2D coverage contour was captured. All the 2D contours were combined together to form the last 3D Radar Coverage. Typical Radar was taken into our experiment, in which the terrain was generated randomly and atmosphere was standard. From the experiment result, we could see that Radar electromagnetic situation affected by complex environment could be clearly and intuitively viewed by this mean. Commanders can also use it for decision-making plan-aiding and sense-supporting. Also we could see that the efficiency of APM was key factor for our method. So our next step is to enhance it by the virtue of relationship between two neighbor profiles, especially when profiles' number is large. Because of the numerous and complex real environment, Radar Coverage is influenced by terrain, atmosphere, weather, jamming, and other electromagnetic devices. Only the terrain, sea surface and atmosphere influence were considered in this paper. Many more complex cases were not considered, such as wildfire case[19], if all the cases can be modeled, the predicted result would be more accurate. We have only advanced a half step on the way of representing Radar Coverage accurately. Next we set out to do some work on jamming so as to represent a more accurate Radar Coverage. At the same time more representing manners are also our aspiration.

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