APPROACH TO SIMULATION OF RADAR SIGNALS REFLECTED FROM OBJECTS OF COMPLEX SPATIAL CONFIGURATION

The paper presents an approach to modeling the secondary emission field, based on the Huygens-Fresnel method. Various methods for simulating the secondary radiation field are briefly reviewed, and their key characteristics are given. Features of the software implementation of the algorithm for synthesizing signals reflected from objects of a complex spatial configuration and obtaining on their basis radar range portraits are considered. The description of the modeling process is divided into stages, which makes it possible to trace the structural and logical connection between the methods and actions performed in the course of the modeling of the secondary radiation field. The key feature of this approach is the use of depth maps (Z-buffer) to determine the visible areas of the irradiated object. Also, some methods of improving the performance of computations are described, which is especially important where it is required to obtain a large number of radar range portraits.

Keywords: secondary radiation, mathematical modeling, Huygens-Fresnel principle, 3D-models, Z-buffer, radar detection, radar range portraits.

Introduction

The development of methods for the most complete information reception using radar signals and interferences is one of the key directions in modern radio-location. Radar detection (RD) is a part of this direction.

The information on detection is relevant both for the needs of the air traffic control system and for the air defense system, especially during the heightened tensions in the global political situation or under the conditions of battle actions.

The best quality factors of radar detection are achieved using wide-band and ultra-wideband sounding signals. In this case, separate items of the radar target (RT) can be distinguished, and the radar range portrait (RRP) of this RT can be obtained; the RRP is the function of the secondary radiation amplitude at the reception point depending on the range [1]. The RRP parameters depend on the following factors: the geometric form of the illuminated object, the electric properties of the object and the propagation medium for electromagnetic waves (EMWs), the aspect angle of the object, and the parameters of the sounding signal. Hereafter, the alphabet for classes and types of radar targets (RTs) is generated on the base of some RRP set.

In practice, the reception of an RRP by natural experiments is a resource-intensive task. In addition, the availability of an RRP from a real RT is provided not often. The realization of experiments using mathematical modeling is one way for the solution of this problem. It should be highlighted that mathematical modeling does not avoid the necessity for the realization of natural experiments and tests, but it is one of those steps that allow reducing the financial and time expenditures at the initial stage of development of RD devices and systems.

The state of the art for modern computing systems allows providing mathematical modeling even using relatively inexpensive equipment.

However, the availability of proper computing facilities alone is not the guarantee for the successful mathematical experiment. The availability of the required software is the second essential component. Whereby, poorly debugged or too resource-intensive algorithms realized in the software will render null all the capabilities of computing facilities.

Based on the above, one can make a conclusion that the following requirements are imposed on the RRP modeling software:

1. The availability of a large number of RRPs received with the specified accuracy; these RRPs are received for different target aspect angles within short time frames using relatively small computing capacities. This requirement is particularly relevant if RRPs are planned for the training of neural network classifiers where the training set can be numbered into hundreds of thousands and millions of portraits.
2. The data uploading capability at all modeling stages that simplifies significantly the verification of generated models.
3. The capability of source code editing for the updating and evolution of software as well as the porting of code into other programming languages and development environments.

In this regard, the tasks of the development of proper efficient algorithms for RRP synthesis, the software implementation of these algorithms, their verification, and further use are critical.

The modeling methods for the secondary electromagnetic field

Two main groups of modeling methods for secondary radar field signals reflected from complex objects exist [2]:

1. Precise methods.
   These methods allow obtaining a rigorous solution of any diffraction task for electromagnetic waves. They come down to determining the solutions for Maxwell equations and for corresponding wave equations at specified boundary conditions. The solutions for partial model problems using precise methods are known for bodies with simple geometric forms. The disadvantage of precise modeling methods is the computational complexity of the secondary radiation field for objects with a complex spatial configuration, and radar targets (RTs) refer to such objects.

2. Approximate methods.
   This group of secondary radiation field modeling methods includes the following: the geometrical optics method, the physical optics method, the method of the geometrical theory of diffraction, the method of the physical theory of diffraction. In practice, the methods of this group appear as more preferable for secondary radiation field modeling, because they allow receiving sufficiently precise models satisfying the needs of RD systems modeling subjected to the constraints of computing resources.

Whereas, the tasks for secondary radiation fields computation can be split into three groups:

1. Small-size targets (in comparison to the wavelength).
2. Targets with sizes comparable to the wavelength.
3. Targets with sizes larger than the wavelength.

One of the requirements for the program to be compiled was the generation of secondary field models for sounding signal frequencies at C and X bands (4–12 GHz), which corresponded to 0.025–0.075 m (2.5–7.5 cm) wavelengths. The electromagnetic radiation wavelength at such frequency band was much less than RT linear dimensions which were used for modeling. In this regard, when the modeling tasks of the secondary radiation field for objects with a complex spatial configuration were solved, the physical optics method and the Huygens-Fresnel method as its special case were used for solving the diffraction scattering problems of electromagnetic fields.

The Huygens-Fresnel principle states that each point interacting with the electromagnetic field is the source of the secondary electromagnetic field with a spherical shape. The perturbation at any spatial point is the result of coherent secondary interference with regard to the phases and amplitudes of waves [3].

The schematic interpretation of the Huygens-Fresnel principle is presented in Fig. 1. Let \( S \) be the wave surface, and \( P \) – the point of observation. The perturbation at the point caused by the electromagnetic wave reflection from the square \( dS \) can be expressed in the following way:

\[
dE = k(\varphi) \frac{a_0 dS}{r} \cos(\omega t - kr + \alpha_0),
\]

where \( k(\varphi) \) is the function of the dependence of the \( dE \) amplitude on the angle between the normal line to the \( dS \) square and the direction to the \( P \) point; \( a_0 \) is the oscillation amplitude at the \( dS \) surface; \( \omega \) is the circular frequency; \( k = \frac{2\pi}{\lambda} \) is the wave number.

The resultant field at the point \( P \):

\[
E = \int_{S} k(\varphi) \frac{a_0}{r} \cos(\omega t - kr + \alpha_0) dS
\]

(1)

The character of secondary radiation depends on the following factors:

- the geometric form of the RT;
- the electrical characteristics of the RT;
- the movement and relative motion of reflecting object elements;
- the correlation between the object linear dimensions and the wavelength;
- the modulation law and wave polarization.

Fig. 1. The schematic interpretation of the Huygens-Fresnel principle.
The features of synthesis algorithm implementation for signals reflected from the objects with a complex spatial configuration

The following suppositions were provided during the modeling:

1. The relative dielectric constant and the relative permeability of the propagation medium for electromagnetic waves are equal to \( \varepsilon = 1 \) and \( \mu = 1 \), respectively.
2. The surface of the RT is assumed to be perfectly conducting.
3. The object is assumed to be immobile for the sound period.
4. The dimensions of the allowable volume by the spatial angular coordinates are larger than the linear geometrical dimensions of the object.

The MATLAB development environment was selected for the software implementation of the algorithm described below; this was due to the fact that MATLAB was the most adapted to working with a data array in comparison with such program languages as C++, Java, etc.

The modeling process is split into two stages: preparation and main, respectively.

The preparation stage

The 3D model of the RT is generated during the preparation stage; then this model is imported into MATLAB. Then, a «point cloud» is generated using the imported model.

The generation of a 3D model of the RT

The starting point for the modeling process is the 3D model generation using the 3D graphics editor (e.g., Autodesk 3ds Max®, etc.). The so-called «bevel» models are used for the description of the object geometry in the three-dimensional space. A bevel is a triangle described in the three-dimensional space using the coordinates of three points:

\[
F_i = \begin{bmatrix}
 x_{i,1} & y_{i,1} & z_{i,1} \\
 x_{i,2} & y_{i,2} & z_{i,2} \\
 x_{i,3} & y_{i,3} & z_{i,3} \\
\end{bmatrix}
\]

(2)

Such description allows defining univalently the plane where the bevel is located, and describing simultaneously the bevel boundaries using the equation of the plane going through the three points \( P_i(x_{i,1}, y_{i,1}, z_{i,1}) \), \( P_2(x_{2,1}, y_{2,1}, z_{2,1}) \), \( P_3(x_{3,1}, y_{3,1}, z_{3,1}) \) [4]:

\[
\begin{bmatrix}
 x-x_{1} \\
 y-y_{1} \\
 z-z_{1} \\
 x_{2}-x_{1} \\
 y_{2}-y_{1} \\
 z_{2}-z_{1} \\
 x_{3}-x_{1} \\
 y_{3}-y_{1} \\
 z_{3}-z_{1} \\
\end{bmatrix} = 0
\]

(3)

In addition, the unit vector is «tied» to each bevel; the normal line of the vector \( \vec{h}_F(x, y, z) \), characterizes the bevel orientation in the space (Fig. 2).

The export of the 3D model into the file with ASCII coding

When the model has been generated using the 3D editor, it should be exported into the STL (Stereo Lithography) or ASE (ASCII Scene Export) formats. Fig. 3 shows an example of a bevel airplane model. These data formats represent the text files with ASCII coding (ASCII files). The reasonability of such transformation is caused by the fact that further computations would be implemented in the MATLAB environment which can interact only with the character mode files by default of all the candidates to 3D model export file formats.

The conversion of the generated 3D model from the ASCII into the MATLAB variable environments.

The 3D model point cloud synthesis

The RRP modeling precision is proportional to the number of elementary reflectors in the point cloud. The high precision of modeling along with the rational use of computing resources is provided with the interval between the adjacent point cloud elements \( d \leq \frac{\lambda}{2} \) (i.e. \(< 0.5\) of the irreducible Fresnel bandwidth). Proceeding
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from this condition, each bevel of the 3D model is completed equidistantly by the elementary reflectors (Fig. 4a). Hereafter, all the computations are implemented with the point cloud (Figs. 4b, 5).

**The calculation of the bevel area**

\[ S_F = \sqrt{p_F(p_F - a)(p_F - b)(p_F - c)} \]

where \( p = \frac{1}{2}(a + b + c) \) is the bevel half-perimeter;

\[ a = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2}, \]

\[ b = \sqrt{(x_3 - x_2)^2 + (y_3 - y_2)^2 + (z_3 - z_2)^2}, \]

\[ c = \sqrt{(x_3 - x_1)^2 + (y_3 - y_1)^2 + (z_3 - z_1)^2} \]

are the bevel lateral lengths.

The data of the «point cloud» of the bevels area are stored into the separate variable. The calculation of the area is required for the further calculation of the conditioned effective scattering surface (ESS) for point cloud elements. Further, at the main stage, the computations are implemented for the already synthesized «point cloud».

**The main stage**

**The spatial orientation of the point cloud**

The position of the radar station (RS) serves as the supporting point which requires the determination of the model view. The coordinates of this point are determined at the start of the main stage of modeling and remain as the constant \( P_{RS} = \text{const} \) during the secondary radiation field computation for all required aspect angles.

![Fig. 4. The transformation of the bevel model into the point cloud: a – completing of the bevel by points; b – the sphere presented as the point cloud](image)

![Fig. 5. The presentation of the 3D model of an airplane as a point cloud](image)
The need for 3D model spatial orientation at the azimuth and site angle planes arises because the RRP should be computed for different aspect angles $\beta$ ($XOY$) and the angle of sight $\varepsilon$ ($XOZ$). The orientation comes to the turn of all point cloud elements to the specified angles at the $XOY$ and $XOZ$ planes (Fig. 6):

\[
r_{XOY} = \sqrt{x^2 + y^2} = \text{const}
\]
\[
\Delta \alpha = \alpha_2 - \alpha_1,
\]
\[
x_1 = d \cos(\varepsilon_1) \quad x_2 = d \cos(\varepsilon_1 + \Delta \varepsilon),
\]
\[
y_1 = d \sin(\varepsilon_2) \quad y_2 = d \sin(\varepsilon_1 + \Delta \varepsilon),
\]
\[
r_{XOZ} = \sqrt{x^2 + z^2} = \text{const}
\]
\[
\Delta \beta = \beta_2 - \beta_1,
\]
\[
x_1 = d \cos(\beta_1) \quad x_2 = d \cos(\beta_1 + \Delta \beta),
\]
\[
z_1 = d \sin(\beta_2) \quad z_2 = d \sin(\beta_1 + \Delta \beta).
\]

The interception of bevels oriented «from the observer»
The sufficient condition for determination of bevel spatial orientation using the binary criterion («from the observer» or «to the observer») is the following condition:

\[
\psi = \arccos \frac{\vec{n}(x)R_{PC}(x)+\vec{n}(y)P_{PC}(y)+\vec{n}(z)P_{PC}(z)}{\sqrt{(\vec{n}(x)R_{PC}(x)+\vec{n}(y)P_{PC}(y)+\vec{n}(z)P_{PC}(z))^2}} \geq \frac{\pi}{2} \quad (8)
\]

Therefore, if the $\psi$ angle between the bevel normal line and the vector directed to the point with the coordinates $P_{RS}$ is greater than or equal to 90°, the bevel is considered as «from the observer» oriented.

Z-buffering of the point cloud
The Z-buffer [5] is used for the «deletion» of 3D model point cloud areas running into the shadow. The depth map is computed for each aspect angle; this map contains the points optically visible for this aspect angle from the entire point cloud. The Z-buffering function rebounds the $Z_{m,n}$ matrix (Fig. 7), where $m$, $n$ is the matrix dimension depending on the computation discreteness for the depth map.

The resultant secondary field vector computation at the $P_{RS}$ point
In accordance with Huygens-Fresnel principle, the RT secondary field amplitude at the $P_{RS}$ point is

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig6.png}
\caption{The spatial orientation of the i-th element of the point cloud}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig7.png}
\caption{The graphic representation for the depth map of the Z-buffer}
\end{figure}
calculated as the sum (the integral in the discrete representation is substituted to the sum) of reflections from all point cloud elements taking into account their amplitudes and phases (Fig. 8):

\[
U_{\text{HPM}_i}(t) = \sigma_i \Re \left( \exp\left(-j2\pi f_0 + \frac{4\pi r_i}{\lambda}\right) \right)
\]

then each iteration can be used for the calculation of the phase factor only.

**The matched processing of received signal and its amplitude detection**

The vector of the received signal is subjected to the matched processing procedure (Fig. 10) for the provision of the optimal time resolution; this procedure is the result of received signal convolution with the impulse response of the matched filter [6]:

\[
U_{\text{cos}}(t) = U_{\text{HPM}}(t) h(t),
\]

where \( h(t) \) is the impulse response of the matched filter.

Fig. 8. The explanation for the field superposition vector computation at the \( P_{RS} \) point

![Field superposition vector computation](image)

Fig. 9. The model of the signal at the input of the radar receiver at the PRS point. The extension of the reflected signal (X-axis) is measured in meters; the amplitude (Y-axis) is measured in volts

![Signal model](image)

Fig. 10. The signal at the matched filter output. The extension of the portrait (X-axis) is measured in meters, and the amplitude (Y-axis) is measured in volts

![Signal at matched filter output](image)
The synthesized signal is subjected to the amplitude detection after the matched filtering. The signal envelope (Fig. 11) is the radar range portrait (RRP).

**Conclusion**

The use of the Z-buffer allows determining rapidly the visible areas of the illuminated object; this is particularly relevant for secondary radiation field modeling using the physical optics methods, when the areas running into the shadow region can be neglected. However, this method is unacceptable for the generation of secondary field models in the Rayleigh and resonance regions, when the radiation wavelength is smaller than the linear dimensions of the object due to the effect of inflowing of the electromagnetic field over the visible parts of the object.

It should be noted that the described approach to the modeling does not consider the features of object electric properties; this does not allow receiving valid RRPs of objects including the elements in their structure which are manufactured using composite and radar absorbent materials.

The software algorithm based on the described above approach to the modeling of the secondary radiation field allows generating RRPs for their further use in the modeling of systems and devices for radar detection. The feature of the developed software operation is the RRP computing speed, which is particularly relevant during the generation of portraits for the «training» of neural network classifiers for RT classes and types. So, the computation of 25 thousand portraits for 10 RT types using the computing cluster of 10 computers based on the Intel Core i3 processor (CPU) has taken about 8 hours; this has been provided on condition of the initialization of two data processing flows on the CPU. The further speeding of RT secondary field modeling is possible through the use of information arrays for the computation; this is provided using graphics processing units (GPUs) along with the computation on the CPU.

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