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MODELING OF WAVE DISTRIBUTION IN LAYERED INHOMOGENEOUS ENVIRONMENT CONTAINING A FLUX OF DISCRETE INHOMOGENEITIES

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The algorithm of modeling wave distribution in layered random environment containing a stream of discrete inhomogeneities has been developed and realized. Dependences of dispersed and absorbed signal energies on the parameters describing inhomogeneous structure of random layered environment and inhomogeneity flux were investigated. Numerical calculations of angular spectrum of dispersed signal were carried out. Frequency spectrum of a signal passed through the flux of discrete inhomogeneities was analyzed.

Introduction

There is quite a number of physical problems demanding accurate calculation of the problems of radiation transport theory subject to multiple scattering. Solving a number of applied problems of radio physics, optics and acoustics modeling the process of wave distribution in layered discrete media including a flux of discrete inhomogeneities is of interest. Questions of electromagnetic waves distribution in random inhomogeneous discrete media at multiple scattering approximation are the least developed theoretically.

In papers [1–3] the methods of studying the equation systems made for solving the problem of reflectance and absorptances defining for an arbitrary number of layers are examined. This resulted in obtaining general schemes in the form of which the solutions may be presented. However, these solutions have very bulky form and if a number of layers exceeds 3 they are almost useless for analyzing the influence of one or another layer on absorptance or refraction coefficient.

For example, L.M. Brekhovskih [3] suggests proceeding from Maxwell equations provided homogeneous isotropic medium for revealing general ratios when studying reflection and refraction of electromagnetic waves. He examines the analytical solution of the problem of wave reflection and passing for a random layer number. The solution of assigned task is acceptable for two, three layers but increasing the number of layers the formula bulkiness and respectively computational complexity multiply growths.

The aim of the given work is to develop numerical model of the process of signal multiple interaction with random discrete inhomogeneities of layered medium and flux.

List of symbolic notations

- N, V are the profiles of concentration and velocity of discrete inhomogeneities flux;
- $\vec{e}_s$ is the unit isotropic vector of discrete inhomogeneity reradiation;
- $\vec{e}_v$ is the velocity vector of discrete inhomogeneities flux;
- $\vec{e}_i$ is the distribution vector of discrete inhomogeneity flux;
- D is the length of particle free propagation in inhomogeneous flux;
- x is the random number uniformly distributed in the range from 0 to 1;
- l is the average length of wave free distribution in the medium;
- f_0 is the carrier frequency of incident wave;
- Fi is the angle of particle outlet from the media;
- S is the quantity of particles.

1. Solution technique

In the given paper the problem of electromagnetic wave distribution in discrete random layered medium is solved by the Monte-Carlo method [4–10]. The numerical model of wave distribution in layered discrete medium including the flux of discrete inhomogeneities is developed.

Signal source with isotropic directional pattern is supposed to be on the surface of layered medium including inhomogeneous scatterer flux. The length of incident wave is supposed to be less than layer size and flux characteristic dimensions. Scattering occurs incoherently at statistically independent discrete inhomogeneities. Irradiator of electromagnetic signal is represented as particle source with proper radiation pattern. The original particle coordinates are specified in the point of irradiator location. The mode of wave interaction with discrete inhomogeneities is determined according to the specified scattering and absorption coefficients.

In the case of fulfillment of dispersion condition the direction of wave distribution changes according to the specified indicatrix of discrete inhomogeneity reradiation. The solution of the problem of wave distribution in random discrete medium comes to defining the function of particle distribution in coordinate space.

The wave radiated by the source is modeled by particles uniformly distributed in wave front space and oriented along the direction of signal $\vec{e}_i$ distribution. Moving discrete inhomogeneities are assigned statistically independent scatterers.

Profiles of concentration N and velocity V of discrete flux inhomogeneities are shown in Fig. 1 and problem geometry is in Fig. 2.

Determining free propagation length of particle D in non-uniform flux the ratios are used [4]:

$$D = -l \cdot \ln x. \quad (1)$$

The wave is supposed to be distributed along axis-X (Fig. 1). The interaction type of the wave with the medium is determined according to the sections of absorption and scattering. In the case of fulfillment of wave scattering condition the direction of particle distribution changes according to the specified indicatrix of reradiation. The indicatrix represents vector scattering pattern [3]. All calculations are carried out in dimensionless quantities.

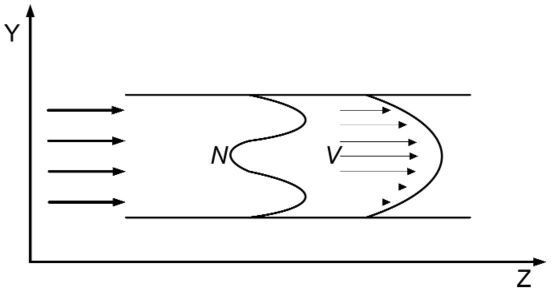

Fig. 1. *Profiles of velocity and discrete inhomogeneities concentration*

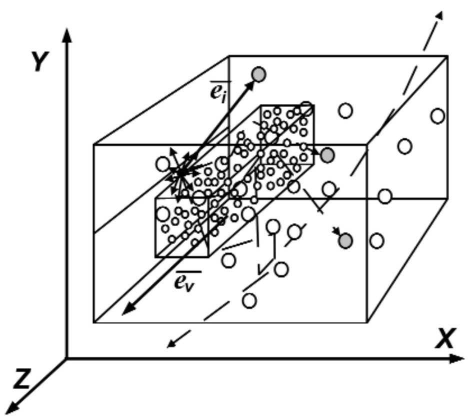

Fig. 2. *Problem geometry, $\vec{e}_i$ is the vector of propagation and $\vec{e}_v$ is the vector of velocity of discrete inhomogeneity flux*

The velocity of discrete inhomogeneity flux is determined by the formula

$$V(X) = V_0 \exp(-\mu_v (X - X_0)^2), \quad (2)$$

V_0 is the velocity of discrete inhomogeneity flux along axis Z, X_0 is the specified value of coordinate X.

The profile of flux concentration is determined by the expression

$$N(X) = N_0 \exp(-\mu_c \rho), \quad (3)$$

where: N_0 is the concentration of turbulent flux along the axis of the flux

$$\rho = (X - X_1)^2; \qquad 0 \le X_1 \le X_m / 2;$$

$$\rho = (X - X_2)^2; \qquad X_m / 2 \le X_2 \le X_m, \quad (4)$$

where X_m is the size of flux along axis-X.

The length of particle free path in the flux is determined as

$$\lambda(Z) = D / N(Z). \quad (5)$$

To specify frequency spectrum of incident wave the function is applied [5]

$$f_0 = \vartheta \sqrt{-2\ln(x_1)} \cos(2\pi x_2) + A, \quad (6)$$

where x_1, x_2 are the random numbers uniformly distributed in the range from 0 to 1, A determines the position of spectrum centre, ϑ is the width of frequency spectrum.

Owing to discrete inhomogeneity transfer in the flux the Doppler shift of frequency scattered signal occurs [7, 9]

$$f^* = (\vec{e}_s - \vec{e}_i)\vec{e}_v \varphi(V) + f_0, \quad (7)$$

where $\varphi(V)$ is the function characterizing profile inhomogeneity of flux velocity.

To model a unit isotropic vector of reradiation the following algorithm is used [6]:

$$y_1 = 1 - 2x_1,$$
$$y_2 = \gamma_2 U,$$
$$y_3 = \gamma_3 U,$$
$$\gamma_2 = 1 - 2x_2,$$
$$\gamma_3 = 1 - 2x_3,$$
$$U = \sqrt{(1-\gamma_1)^2 / \gamma_2^2 + \gamma_3^2} \quad (8)$$

at

$$\gamma_2^2 + \gamma_3^2 \le 1. \quad (9)$$

Unit vector of flux velocity determines moving direction of discrete inhomogeneity, according to the statement of the problem it is directed along axis Z.

The coordinates of scatterer $\boldsymbol{r}$, with which the wave interacts, are determined from the expression [7]:

$$\vec{r} = \vec{r}_o + D \cdot \vec{e}_i. \quad (10)$$

Modeling random paths of particles propagation in nonhomogenious medium the resultant array of a quantity of absorbed and dissipated energy in the medium is accumulated in cells [7, 9]. Doppler frequency shift acquired by the wave as a result of multiple interaction with discrete inhomogeneities is computed and accumulated. In the case of particle spillover the medium the storage of its propagation direction occurs in PC.

2. Electromagnetic wave propagation in layered environment containing the flux of discrete inhomogeneities

Let us consider at the beginning the results of comparative calculations carried out using the algorithm described above and with the help of algorithm descried in the article [11] and package MCNP. Geometry and statements of problem from the work [11] were used for comparison. Monochromatic source of roentgen radiation with photon energy 100 keV, iron plate 5×5×1 cm were used in calculations. The results of calculations both of direct and scattered radiation given in Fig. 3, 4 coincide within the bounds of calculation statistical error.

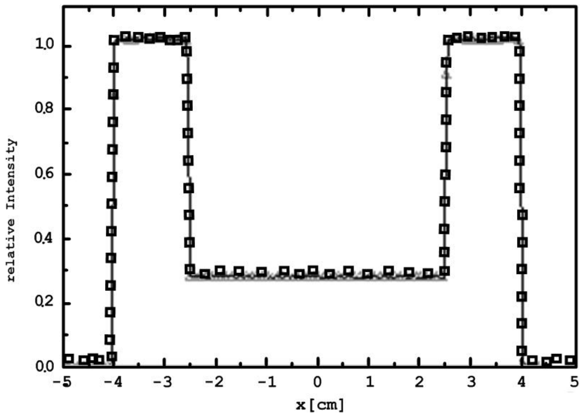

Fig. 3. The results of direct radiation calculations

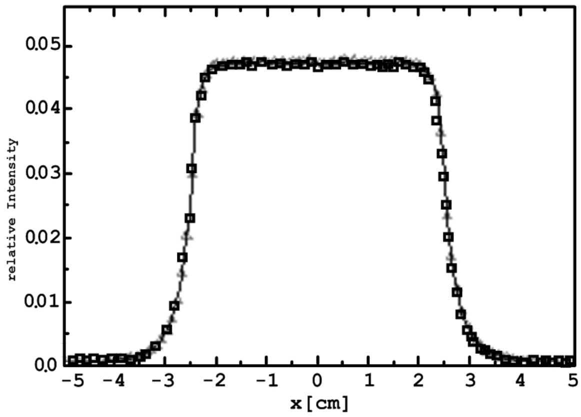

Fig. 4. The results of scattered radiation calculations

In the given Figures the graphs of relative intensity of recorded radiation from the coordinate along central section of plate image on detector surface are given. The results obtained using the technique [11] are displayed by full line, triangles – MCNP, and squares – the considered algorithm. It should be mentioned that the algorithm considered in the given article stores the propagation of scattered and absorbed signal dependence over the whole volume of the modeled medium but not only in the plane of detector plate.

Thus, the comparison of the results of the carried out calculations with the data obtained by the other techniques [11] showed proper work of the proposed algorithm. Now let us pass to the main problem solution.

It is supposed that particle interaction with the flux of discrete inhomogeneities occurs according to isotropic scattering indicatrix. All the results are presented in relative units and normalized to the maximum for each Figure. Medium is characterized by the presence of parallel-plate layers and flux in the form of parallelepiped.

The source of electromagnetic signal with isotropic radiation indicatrix placed on the medium surface with coordinates X=0, Y=50, Z=50 is considered in the first experiment. Initial data describing average length of free propagation and wave absorbtance in the medium are presented in Fig. 5 and 6. Profiles of velocity and concentration of discrete inhomogeneities in the flux are shown in Fig. 7, 8.

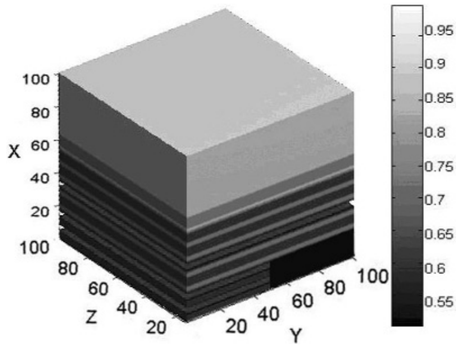

Fig. 5. Wave absorptance in the medium

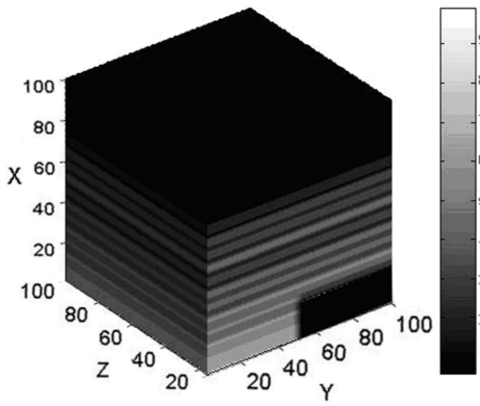

Fig. 6. Average length of wave free propagation in the medium

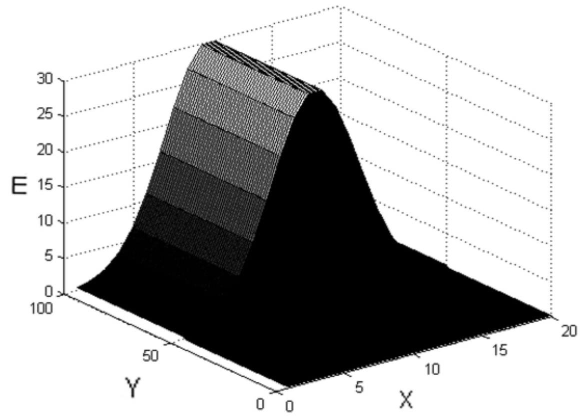

Fig. 7. Profile of discrete inhomogeneities velocity in the flux

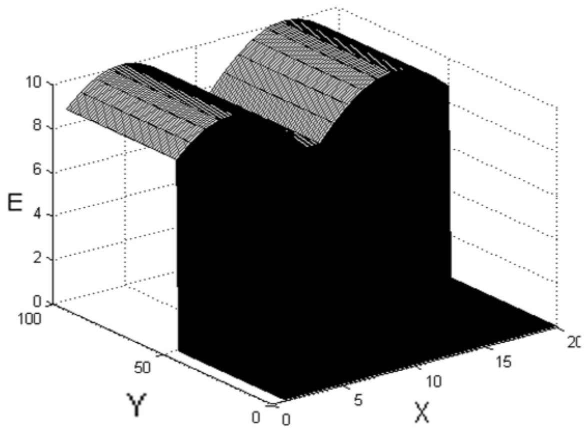

Fig. 8. Profile of discrete inhomogeneities concentration in the flux

Frequency spectrum of incident signal is presented in Figure 9. As it is seen from the Figure the frequency spectrum has the form of gaussoid with maximal value by the frequency 7, 4 and minimal by the frequency 2, 57. Frequency characteristic of the signal escaped from the flux is presented in Fig. 10.

The results of calculation of the absorbed signal energy and energy of the signal scattered in the medium correspondingly are presented in Figures 11, 12.

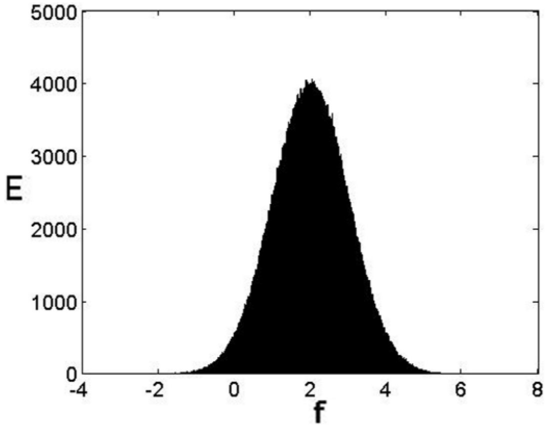

Fig. 9. *Spectrum of incident signal*

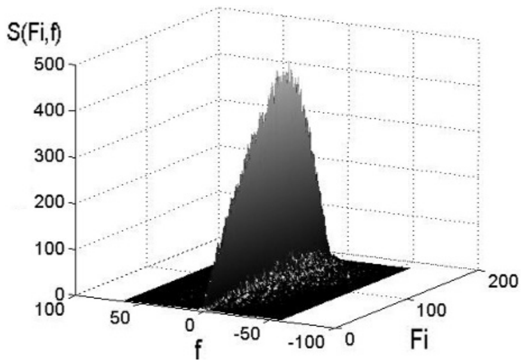

Fig. 10. *Frequency and angular spectrum of the signal escaped from the flux*

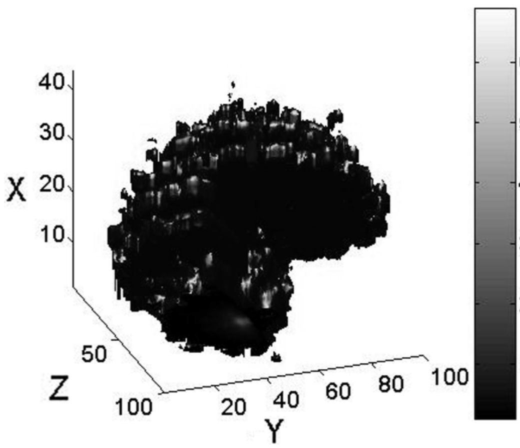

Fig. 11. *Distribution of the absorbed signal energy in the medium*

The coordinates of radiator position are changed by X=10, Y=80, Z=50 in the next experiment. The rest initial parameters of the model remain unchanged and correspond to the initial parameters of the previous experiment (Fig. 5–9). Thus, the source of radiation is transferred inside the flux. It is necessary for checking work correctness of the algorithm with the flux. Having placed the source of radiation in the flux we get rid of particles with small quantity of interactions in the flux which have a very low frequency shift.

Frequency and angular spectrum of the signal escaped the flux is shown in Fig. 13. Fig. 14 demonstrates propagation of scattered signal energy in the medium.

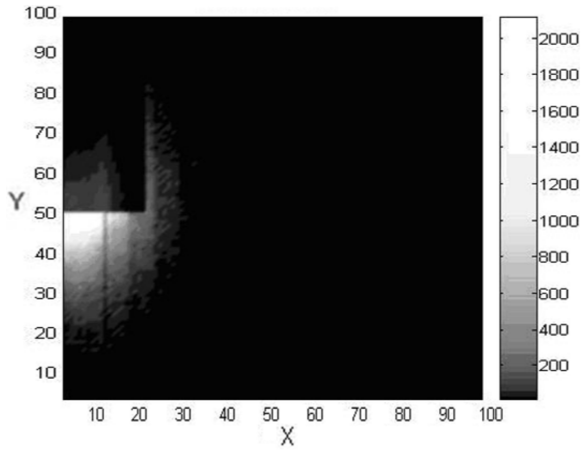

Fig. 12. *Distribution of the scattered signal energy in the medium*

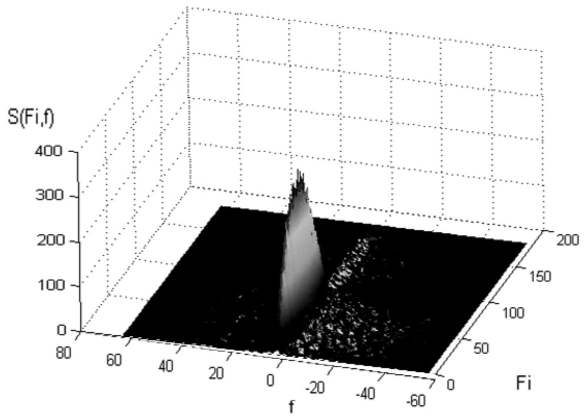

Fig. 13. *Frequency and angular spectrum of the signal escaped the flux*

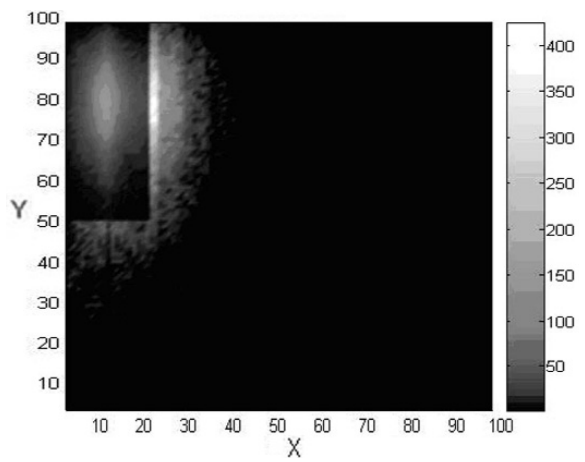

Fig. 14. *Propagation of scattered signal energy in the medium*

3. Analysis of numerical simulation results

Absence of absorbed signal in the flux, Fig. 11 may be explained by the fact that there is a very low coefficient of absorption in the flux in comparison with the medium, in which we can be sure looking at Fig. 5. But the result (Fig. 11) is significantly influenced by the length of free range of a particle in the medium. The length of free range in the flux is insignificant (in comparison with the medium, Fig. 6) owing to which particles do not practically penetrate inside the flux but interact only on the surface of the flux. Layers are also seen in this Figure as they have comparatively high absorbtance. In Fig. 11 and 12 particles getting in object shadow region is clearly observed. Such result is explained by the fact that beams are propagated chaotically in the medium and therefore they may be equiprobabally reradiated in any direction including shadow region.

Paying attention to frequency characteristics of the signal escaped the flux (Fig. 10) it is seen that frequency spectrum form is held. But in this case maximal value of frequency is 62,9 and minimal is 58,6. Such change of spectrum width is explained by significant velocity of the flux (Fig. 7) and high concentration of scatterers in the flux (Fig. 8). We can also observe that energy maximum is not practically shifted by frequency. It is explained by the fact that the majority of particles having interacted with the flux underwent only single or double scattering and accumulated insignificant frequency shift. As the source is on the boundary of the flux and medium then only certain particles with high energy penetrate the flux and interact in it and the rest of them even though interacting with the flux then only on its surface.

Having transferred the source inside the flux in the second experiment it was suggested to obtain the spectrum with considerably wider range of frequencies and insignificant influence of particles with low amount of interactions in comparison with the previous experiment. Frequency and angular spectrum of the signal escaped the flux obtained as a result of modeling is presented in Fig. 13. The analysis of the obtained result shows significant decreasing the influence of particles with low amount of interaction on frequency spectrum of the signal escaped the flux. Profile of flux concentration is presented in Fig. 1. According to this fact the profile of discrete inhomogeneity concentrations is unsteady in simulated flux, Fig. 8. Energy distribution observed in Fig. 14 is explained by inhomogeneous concentration of discrete inhomogeneities in the flux, Fig. 8. Such result is stipulated by lower concentration of discrete inhomogeneities inside the flux in comparison with concentration at approaching to the flux edges. The analysis of the results of program operation on the basis of the developed algorithm allows making conclusion about its proper work.

Conclusion

The algorithm of modeling multiple interaction of electromagnet wave with random three-dimensional discrete medium including the flux of discrete inhomogeneities was developed. The developed algorithm was tested for the task of roentgen radiation scattering and the results of carried out calculations were compared with the data obtained by other methods. The problem of three-dimensional visualization of model input and output parameters was solved. Frequency spectrum of the signal passed through the flux was analyzed. The correctness of algorithm operation at simulating electromagnet signal propagation in the flux was checked. The results of the carried out numerical experiments demonstrate electromagnet signal reflection from the object. Particles getting in object shadow region was clearly observed in one of carried out experiments. In future the algorithm is supposed to be improved for decreasing time of calculation and comparing the results of calculations with the experimental data.

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