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DEVELOPING A TECHNOLOGY FOR MODELING RADAR PORTRAITS OF COMPLEX-SHAPE OBJECTS FOR INTELLIGENT RECOGNITION SYSTEMS

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The object of this study is the modeling of radar portraits (RPs) for intelligent recognition systems based on the use of faceted 3D models. In order to solve the problems of target identification in homing systems of high-precision missile weapons, a technology is needed that could make it possible to efficiently and quickly generate RPs of military objects of complex shape in the required quantity.

The research results are based on a combination of separate component technologies, in particular: the devised technology of using faceted 3D models – their construction and further processing with invisible surfaces excluded from it for an arbitrary viewing angle. The basic part of the work is the development of an algorithm and technological procedures for the formation of a spatial tracing grid for the current observation angle. A feature of the proposed technology is the application of a facet selection algorithm using an array of tracing facets and the application of the Huygens-Fresnel principle to recognize objects of complex shape.

The RP database of military objects of complex shape was built. The results of modeling faceted RP's, in particular the armored boat "Gyurza-M", are given.

The results of the experimental study showed the ability to recognize the type of military object of complex shape at the level of 80–90 %, which makes the use of this technology appropriate for recognizing military objects of complex shape.

The achieved high-speed and quality characteristics of RP generation of military objects of a complex shape makes it possible to assume that the main prospective field of practical application is the identification and visual interpretation of targets in homing systems of high-precision missile weapons

Keywords: radar signal, radar portraits of targets, intelligent recognition, facet models, noises

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1. Introduction

Recently, the importance of radar reconnaissance has increased, in particular, the recognition of military objects of complex shape, such as combat aircraft, ships, etc. During war, the cost of economic, time, and technical resources also increases, and their availability becomes more limited.

Scientific research on intelligent radar recognition is important and aimed at practical results. Namely, to increase the speed and quality of identification of complex military targets without significantly increasing the requirements for computing power.

The most effective means for intelligent radar recognition of military objects of complex shape is the use of their radar portraits (RPs). The information necessary for recognition is mostly obtained from reflected radar signals, on the basis of which the classification of targets by type is carried out.

However, obtaining the required number of RPs through natural experiments requires significant economic and time costs. It should also be noted that sometimes there is no possibility to obtain RPs from real radar targets at all.

Therefore, the generation of RPs of military objects of complex shape requires a technology that simulates the reflection of radar signals from targets. This technology must take into account the dependence on many factors, such as the geometric shape of the irradiated object, the electrical properties of the object and the medium of propagation of electromagnetic waves, the angle of the object, the parameters of probing signals, etc.

This approach will make it possible to efficiently and fairly quickly generate RPs of military objects of complex shape in the amount necessary to solve the problems of identification and visual interpretation of targets in homing systems of high-precision missile weapons.

Scientific research aimed at the development of technology with minimal requirements for computing resources and computing time will allow taking into account the following features of the goals. The use of such technology will increase the effectiveness of the existing radar systems and allow the development of new small-sized target identification systems. Solving the problem of identification of RPs from objects made of composite and radio-absorbing materials, modeling of arbitrary sounding signals, Doppler frequency shifts will open the way to the introduction of homing systems of a new level and the transition to the figurative interpretation of targets based on machine learning methods.

Therefore, studies on the development of RP modeling technology for systems of intelligent recognition of military objects of complex shape, using faceted models, are relevant.

2. Literature review and problem statement

Modern research in the relevant field reveals that the recognition and identification of targets based on their images depends on the ability to highlight the characteristic features of the object of observation on the image.

Thus, in [1], the radar cross-section (RCS) is considered as one of the most significant parameters for the inconspicuous design of the ship. A Radar Cross Section Analysis (RACSAN) program based on the Kirchhoff approximation in the high frequency range was developed to predict the ship's RCS.

Work [2] reports the results of forecasting the radar cross section (RCS) of complex targets that have a shadowing effect. The paper considers the problem of shadow effects during the calculation of electromagnetic scattering by a complex target using iterative physical optics (IPO). It offers a comparison between a classical physical optics (PO) approach and a physical approach based on shadow emission with a PO approximation to consider shadowing effects in a generalized IPO. The simulation results illustrate the importance of considering physical shading for both the transmitter and the receiver.

A method of iterative physical optics was investigated in [3]. The method is based on iterative refinement of first-order physical optics. Unlike other high-frequency asymptotic methods, no ray tracing is required, and spurious diffraction effects from the unphysical shadow boundary are avoided.

Although it is shown in the literature [1–3] that the values of the effective scattering area (EPR) and its spatial features are mostly used as features for radar signals, however, this approach does not make it possible to significantly increase the number of informative features for obtaining accurate and detailed assessments of radar images military objects of complex shape. And this, in turn, does not make it possible to reliably recognize and identify radar targets.

The research results showed that the problem of increasing the number of information signs can be overcome. But the issues related to the use of their radar portraits remained unresolved.

Thus, work [4] shows an option to overcome the relevant difficulties; today the most informative existing means for radar recognition of military objects of complex shape is the use of their radar portraits (RPs). It is from the RPs of reflected radar signals that information necessary for recognition is acquired, on the basis of which a list of classes and types of radar targets is compiled. But the question of the variability of the marine environment remained unresolved in the cited work.

This very issue is addressed in [5]. In the work, a smooth estimate of the radar range profile (RP) contaminated by the contribution of unpredictable variability of the marine environment is obtained. The authors simulated visibility of the target, which may change during the time interval. A general prediction strategy was devised by dividing the time interval into separate short-term segments and averaging over a set of observations.

But a new unsolved issue is emerging, namely, the rapid growth of computational requirements related to target identification.

It should be remembered that the list of military objects of complex shape can include a rather large range. These can be any static or mobile objects, such as flying objects (planes, missiles, UAVs), sea objects (ships, boats, submarines), land objects (tanks, cars, various buildings), etc.

Therefore, solving the problem of obtaining the necessary number of RPs for a significant number of military objects of a complex shape through full-scale experiments requires significant expenditure of economic, time, and technical resources. In addition, in practice, it is not always possible to obtain RPs from real radar targets.

To overcome these problems, it is possible to try to find a solution by developing a more successful than existing algorithm aimed at reducing the surfaces to be analyzed. In [6], an algorithm for removing invisible surfaces from a hierarchical Z-buffer is proposed. The Z-buffer is divided into 4 parts so that in each part the farthest value of z is recorded. The allocation process is repeated up to the pixels. The z-pyramid makes it possible to quickly rule out triangles by comparing the minimum z-value of a triangle and the maximum z-value of an area. During software implementation, the pyramid is expensively updated when new objects are added, which reduces the efficiency of working with large scenes.

And in work [7] it is proposed to store objects using a tree-like data structure for the representation of static architectural scenes and their decomposition along axes. The resulting hierarchy corresponds to the structure of rooms in the building. Visibility information is stored in the corresponding R-tree. Visibility is determined by the method of spatial indexing, which combines potentially visible objects. However, drawing a graph requires a lot of computing resources and the work of the method focuses on static scenes.

It is suggested to use coverage masks for visibility determination. An array of polygons is fed to the input in order of distance from the camera (front-to-back). A recursive division of the image into a quad tree occurs until the visibility of the polygons can be determined for each quadrant. But for the effective implementation of this approach, specialized hardware is required.

Another attempt to solve the given problem is considered in [8], in which it is proposed to use hierarchical coverage masks for rejecting invisible objects. First, potentially blocking visibility objects are rasterized, then the hierarchy is traversed, and visibility checks are performed. The algorithm makes it possible to make an approximate determination of visibility when the visibility threshold is less than one. The main disadvantage of the algorithm is the complex process of selecting objects that block visibility.

The works below show ways to overcome the complexity of the process of selecting objects that block visibility.

In [9], a new approach to the evaluation of the simulation of scattered fields from arbitrary metal objects is considered. Its main idea is to combine the ray tracing algorithm with the principles of physical optics and the physical theory of diffraction. The ray tracing algorithm stochastically launches discrete rays and uses ray density normalization. A PO/PTD formula is required to perform simulations on finite objects. But this asymptotic approach to the scattering properties of large objects is too complex for exact methods.

Concepts of rays, ray tracing algorithms and modeling of radio wave propagation using ray tracing methods are described in [10]. But the research is limited to fundamental concepts and the development of ray tracing algorithms. The work envisages propagation modeling as an intelligent, accurate real-time system in which ray tracing will play a major role.

In [11], the use of the Angular Z-Buffer (AZB) algorithm to accelerate ray tracing is considered. While the basic idea behind this approach is certainly sound, there is a flaw in the implementation method presented by the AZB developers. It is shown that there is a loss of accuracy in the distribution of the electric field predicted by the original.

Paper [12] presents the future prospects of radio wave propagation modeling, with an emphasis on the deterministic propagation model.

All those works describe ray tracing procedures, but the description of the procedures is provided only theoretically, without practical application.

Our review of the literature [9–12] allows us to make an assumption that in order to eliminate the shortcomings of existing methods for removing the shaded facets of the target model and to increase the speed, it is advisable to conduct a study on the digital methods for mathematical modeling of the secondary radiation of real objects using computer technology. The main advantage of modeling is the possibility of obtaining a large number of radar portraits of the reflected signal with a given accuracy for various angles of objects in a short time when using relatively small computing power.

Technology that provides modeling of signals reflected from radar targets, taking into account their dependence on many factors, should be aimed at solving these tasks. The main ones are the geometric shape of the irradiated object, the electrical properties of the object and the medium of propagation of electromagnetic waves, the perspective of the object, the parameters of sounding signals, etc.

Thus, the listed methods are either technically resource-intensive or require full-scale (physical) experiments, which are often time-consuming and difficult to access. Another problem with the methods is the difficulty of obtaining enough radar data for modeling. Modeling technology should make it possible to acquire a sufficient number of radar portraits of the reflected signal, with a given accuracy, for different angles of targets in a short time, using relatively small computing power. Otherwise, the creation of methods and algorithms for the identification and visual interpretation of targets is appropriate if it is based on machine learning methods (neural network classifiers), where the training sample can be calculated by hundreds of thousands of portraits.

3. The aim and objectives of the study

The purpose of our study is to devise a technology for modeling radar portraits for systems of intelligent recognition of military objects of complex shape, using faceted models. This will increase the effectiveness of existing radar systems and allow the development of new small target identification systems.

To achieve the goal, the following tasks were set:

– to choose a way of representing the surface of complex radar objects within the framework of modeling technology of spatial 3D models;

– to devise a procedure for processing facet model data and excluding surfaces that are invisible from the current perspective;

– to devise a procedure for forming a spatial grid of radar beam tracing for the current angle of radar observation;

– to devise a procedure for determining the coordinates of elementary reflectors and their visibility for the current angle of radar surveillance of targets.

– to choose the best method of accurate calculation of objects for elementary reflected radar signals when building radar portraits.

4. The study materials and methods

The object of our study is the modeling of radar portraits using faceted models.

The main hypothesis of the study assumes that there is a way to reduce the requirements for computing power when applying target identification algorithms based on machine learning methods.

In general, such theoretical and methodological research tools as the theory of analysis, methods of linear algebra, mathematical modeling and computer experiment were used in the study; methods of visualizing information, methods of confidently performing recognition. Methods of classification and visual interpretation of complex-shaped radar sea targets by known means of identification, such as correlation and spectral methods of statistical analysis, were applied. Additionally, such tools as Wasserstein metrics, peak harmonic analysis, Euclidean distance algorithms, neural networks, Maxwell's equations in integral and differential form, asymptotic calculation methods, principles of using the Huygens-Fresnel principle, etc. As well as methods and algorithms that we have developed.

The design of 3D models was carried out with the help of software "3D Studio Max" [13] according to overall characteristics available in the public domain, as well as according to photos available on the network [14]. Modeling for the study was performed on a 1:1 scale according to real existing models. When modeling in the 3DS Max environment, the models were implemented in ".max" format with metric settings. That made it possible to build each object immediately with reference to the real size and not to perform the procedure of scaling the model after the end of construction. Accordingly, the dimensions of the used models, in particular the Gyurza-M artillery boat, correspond to the dimensions of actual existing models (length 23 m, width 4.8 m, units of measurement of coordinate axes in meters). Changing the scale of the model will distort the generated reflected radar signal.

The initial development and testing of the system were performed in the MATLAB programming environment. The software for simulating radar signals reflected from targets was implemented in the C++ programming language.

5. Research results related to simulating radar portraits using faceted models

5. 1. Construction of target portraits based on spatial 3D models of reflected radar signals

The RP modeling technology for intelligent recognition systems of military objects of complex shape is based on the use of faceted 3D models [15, 16]. They are formed on the basis of the mathematical description of the surface of complex radar objects by elementary triangular sections, which are called facets. The main advantage of the faceted representation of the surface of complex radar objects is the absence of restrictions on the geometry of 3D models of any object of complex shape, as well as the possibility of setting the electromagnetic parameters of the reflection of radar signals for each facet separately. The construction of 3D models can be based on measurements, drawings, or scale models using automated design systems. 3D model files are converted to the ".obj" format, which makes it possible to describe the model in a numerical format and contains 3D geometry, in particular the positions of vertices, information about the number of faces, normals, the number and placement of polygons. The ".obj" file format that describes the geometry of models, which was created at Wavefront Technologies, is an open file format that has been adopted by other 3D editor developers as a standard. It should be understood that any other standards of 3D editors can be used as the file format of 3D models [17, 18].

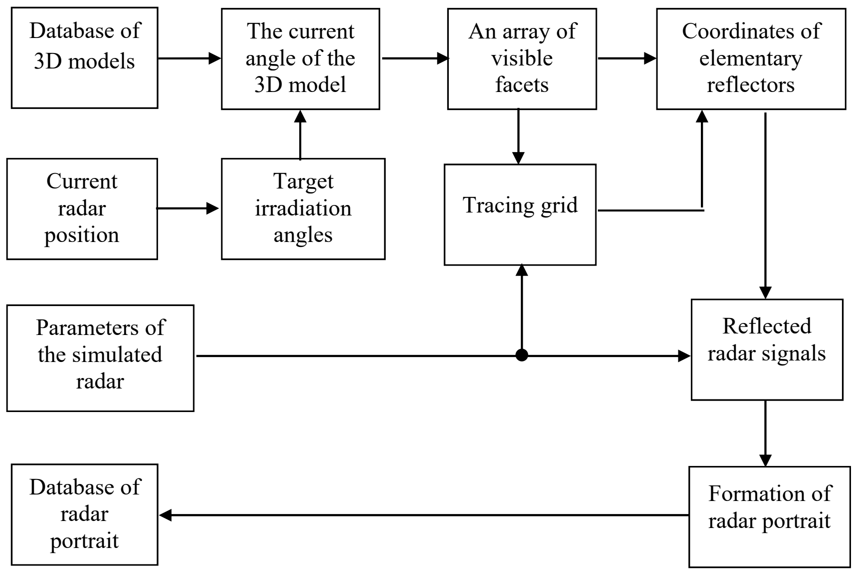


Fig. 1. Block diagram of the basic components in radar portrait modeling technology

For more accurate construction of radar portraits of the reflected signal from targets, it is necessary to take into account the properties of the materials from which the object is made before the signal is reflected. For this purpose, the file that describes the object model is accompanied by parameters that describe the signal reflection property of each surface.

When converting a complex-shaped object model file to an ".obj" format file, its so-called faceted model is built, which is formed by dividing the initial model into a final network of triangles. This simplification of the model makes it possible to simplify the calculations regarding the simulated formation of reflected radar signals from the model's surfaces.

In the work, 3D models for simulating the formation of reflected radar signals are built in the simplified ".obj" format. This format describes the geometry of an object by specifying the coordinates of all V vertices and F facets (triangles), which in turn are specified by lists of corresponding V vertices. The V vertices of F facets are set by default counterclockwise, making explicit specification of normals optional. Such faceted 3D models of complex-shaped radar objects make it possible to effectively simulate reflected radar signals and build radar portraits of modeled targets based on them.

5. 2. Procedure for processing facet model data and excluding surfaces that are invisible from the current perspective

Constructed files of faceted 3D models of radar objects in ".obj" format are preliminarily placed in the database (DB) of 3D models (module "DB of 3D models" in Fig. 1). Subsequently, they are used in the technology of modeling radar portraits.

The research involves a relational database with the following structure:

1. Tables with clearly defined attributes:

– radar target model (name, format);

– modeling parameters (target type, antenna height, distance of the radar antenna to the target, model orientation angle, model roll in degrees, radar antenna frequency, length of the electromagnetic pulse, pitch of the spatial grid of electromagnetic beam tracing, number of pulses, pulse width, angular size of the petal, horizontal/vertical deviation of the radar beam from the aiming center, noise level, etc.);

– simulation results (file name, distance, antenna height, orientation angle, etc.).

2. Relationships between the target model and the simulation parameters, as well as between the simulation parameters and the simulation results.

3. Data storage in files with a clearly defined structure that corresponds to the data storage format in relational databases.

When modeling a specific radar portrait, the corresponding 3D model file is extracted from the 3D model database. Data from this 3D model file are entered into the array of vertices V_0 and the array of facets F, which, in turn, describe the geometry of the corresponding radar object.

The array of vertices V_0 contains the coordinates of all points of the faceted 3D model of the target in the form:

$$V_0 = \begin{pmatrix} x_1 & y_1 & z_1 \\ x_2 & y_2 & z_2 \\ \dots & \dots & \dots \\ x_i & y_i & z_i \\ \dots & \dots & \dots \\ x_m & y_m & z_m \end{pmatrix}, \quad (1)$$

where i=[1, m] is the row number in the array of vertices V_0; m is the total number of vertices V in the faceted 3D model of the target; x_i, y_i, z_i are the coordinates of the ith vertex $v_i(x_i, y_i, z_i)$ from the array of vertices V_0.

That is, each i-th element of the array of vertices $V_0=(v_1, v_2,...,v_i,...,v_q)$ corresponds to a spatial point $v_i(x_i, y_i, z_i)$ with coordinates x_i, y_i, z_i in the $OXYZ$ coordinate system associated with the target .

Each j-th facet f_j of the array F is given by the set of three indices p_{j0}, p_{j1}, p_{j2} in the form:

$$F=\begin{pmatrix} p_{10} & p_{11} & p_{12} \\ p_{20} & p_{21} & p_{22} \\ \dots & \dots & \dots \\ p_{j0} & p_{j1} & p_{j2} \\ \dots & \dots & \dots \\ p_{q0} & p_{q1} & p_{q2} \end{pmatrix}, \quad (2)$$

where j=[1, q] is the row number in the facet array F; q is the total number of facets of the 3D target model; p_{j0}, p_{j1}, p_{j2} are indices indicating the coordinates of vertices v_{pj0}, v_{pj1}, v_{pj2} from the array of vertices V_0.

That is, each facet $f_j(p_{j0}, p_{j1}, p_{j2})$ from the array of facets $F=(f_1, f_2,...,f_j,...,f_q)$ is defined by three indices p_{j0}, p_{j1}, p_{j2}, which, in turn, indicate the point coordinates of the vertices $P_{j0}=v_{pj0}$, $P_{j1}=v_{pj1}$, $P_{j2}=v_{pj2}$ from the vertex array V_0. Thus, the points with coordinates P_{j0}, P_{j1}, P_{j2} directly describe the facet f_j in the $OXYZ$ coordinate system associated with the target.

In the simulation process, the corresponding current position of the radar relative to the target is also established. The measurements of it include the orientation of the target C, the range to the target D, and the height of the target A (the "Radar Current Position" module in Fig. 1). After that, the current irradiation angles of the modeled radar target are calculated, namely the angle of direction to the target, the angles of the current orientation and current elevation of the target (module "Target irradiation angles" in Fig. 1).

Next, to simulate the reflected radar signal from the 3D model from the current viewing angle of the radar, the array of vertices V0 coordinates of the points of the faceted 3D model of the target is rotated to the corresponding irradiation angles of the simulated radar target. Obtaining in this way an array of vertices V for the current angle of radar observation (module "Current angle of 3D model" in Fig. 1), i. e.:

$$V=R\cdot V_0, \quad (3)$$

where R is the rotation matrix for the irradiation angles of the simulated radar target for the current radar observation angle.

An example of the appearance of a faceted model of a radar object, namely a military aircraft, from the current viewing angle is shown in Fig. 2.

For adequate simulation formation of reflected radar signals from a faceted 3D model, it is necessary to exclude from this faceted model surfaces that are invisible from the current angle of radar observation. Checking the visibility of the surfaces of the faceted 3D model from the current angle of radar observation is carried out by the algorithm for selecting visible facets by the angle between the vectors normal to them and the direction of their radiation from the radar [13, 14, 18].

Based on the calculated array of vertices V for the current observation angle of the radar, the visibility of the surfaces of the faceted 3D model from the current observation angle is checked. The check is performed by the angles between the normal vectors to the surfaces of the faceted 3D model and the direction of their radiation from the radar.

To this end, at the first stage, the visible facet selection algorithm calculates the normal vectors n_j to each facet f_j from the facet array F. All calculated normal vectors n_j collectively form an array of normal vectors N:

$$N=\left(n_1,n_2,...n_j,...,n_q\right). \quad (4)$$

The basis for calculating the normal vectors n_j to any facet f_j are its vertices P_{j0}, P_{j1}, P_{j2} since they are set counterclockwise in the ".obj" target model. This determines the possibility of their use in the algorithm for determining the vectors of normals to the facets of the array F.

Fig. 3 shows the j-th facet f_j with the coordinates of the vertices: $P_{j0}(x_{pj0}, y_{pj0}, z_{pj0})$, $P_{j1}(x_{pj1}, y_{pj1}, z_{pj1})$, $P_{j2}(x_{pj2}, y_{pj2}, z_{pj2})$. The location point of the radar L_1 acts as a reference point for which the angle of the model must be determined.

To find the normal vector n_j to the j-th facet f_j, two vectors u_j and v_j are first determined.

$$u_j=P_{j1}-P_{j0}, \quad (5)$$

$$v_j=P_{j2}-P_{j0}. \quad (6)$$

Then the vector product vp_j is calculated:

$$vp_j=u_j-v_j. \quad (7)$$

and determine the normal vector n_j to the j-th facet f_j according to the ratio:

$$n_j=\frac{vp_j}{\left|vp_j\right|}. \quad (8)$$

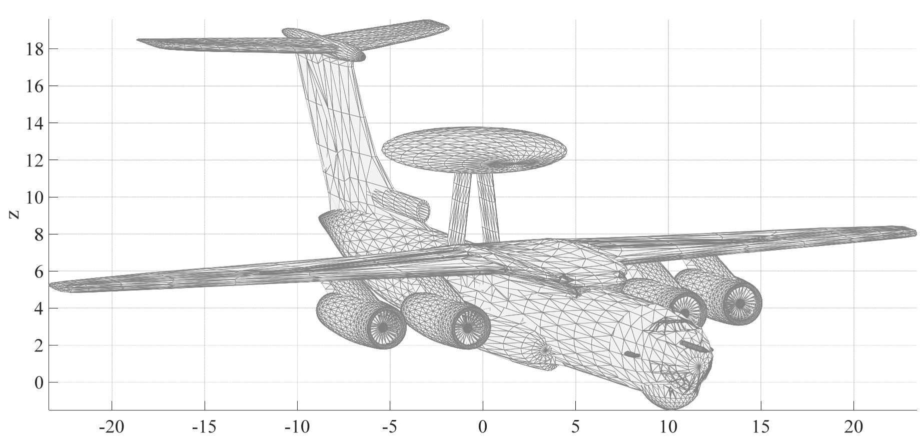


Fig. 2. A faceted 3D model of a military aircraft from the current radar observation angle

Also, for a sample of visible facets, the coordinates of its center cf_j in the target-related coordinate system $OXYZ$ are calculated for the j-th facet f_j according to the ratios:

$$cf_j = \begin{bmatrix} \dfrac{\left(x_{pj0}+x_{pj1}+x_{pj2}\right)}{3}, \\ \dfrac{\left(y_{pj0}+y_{pj1}+y_{pj2}\right)}{3}, \\ \dfrac{\left(z_{pj0}+z_{pj1}+z_{pj2}\right)}{3} \end{bmatrix}. \qquad (9)$$

From the faceted 3D model, it is necessary to exclude surfaces that are invisible from the current angle of observation of the radar. To this end, determine the unit vector dir_j of the j-th facet f_j, which is directed from the location point of the radar L_1 to the center of the j-th facet cf_j according to the ratio:

$$dir_j = \frac{L_1 - cf_j}{\left|L_1 - cf_j\right|}. \qquad (10)$$

Then, for the j-th facet f_j, the scalar product sp_j is calculated:

$$sp_j = n_j \cdot dir'_j. \qquad (11)$$

If for the j-th facet f_j the scalar product $sp_j>0$, then this facet f_j is visible. Such a facet is entered into the array of visible facets $F_V=(f_1, f_2,\ldots,f_j,\ldots,f_p)$, p is the total number of visible facets of the 3D model of the target (module "Array of visible facets" in Fig. 1). Otherwise, when the scalar product $sp_j\leq 0$, the facet f_j is invisible. Such a facet f_j is not included in the array of visible facets F_V and is not used in future calculations during simulation modeling of reflected radar signals.

An example of the operation of algorithms (1) to (11), developed for processing data of facet models and excluding surfaces from facet models that are invisible from the current angle of radar observation, is shown in Fig. 4. So, in Fig. 4, *a*, the model of the military river armored boat "Gyurza-M" from the current angle of radar observation is shown, downloaded from the corresponding file in ".obj" format. The same faceted model of the "Gyurza-M" boat, but with invisible surfaces excluded from it from an arbitrary viewing angle, is shown in Fig. 4, *b*.

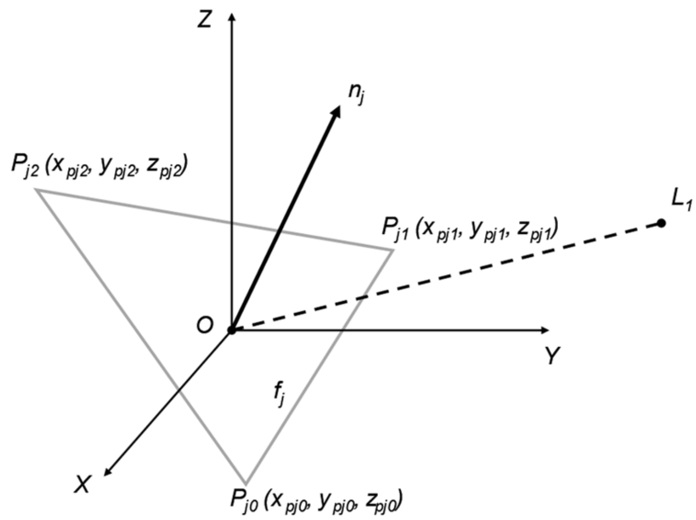
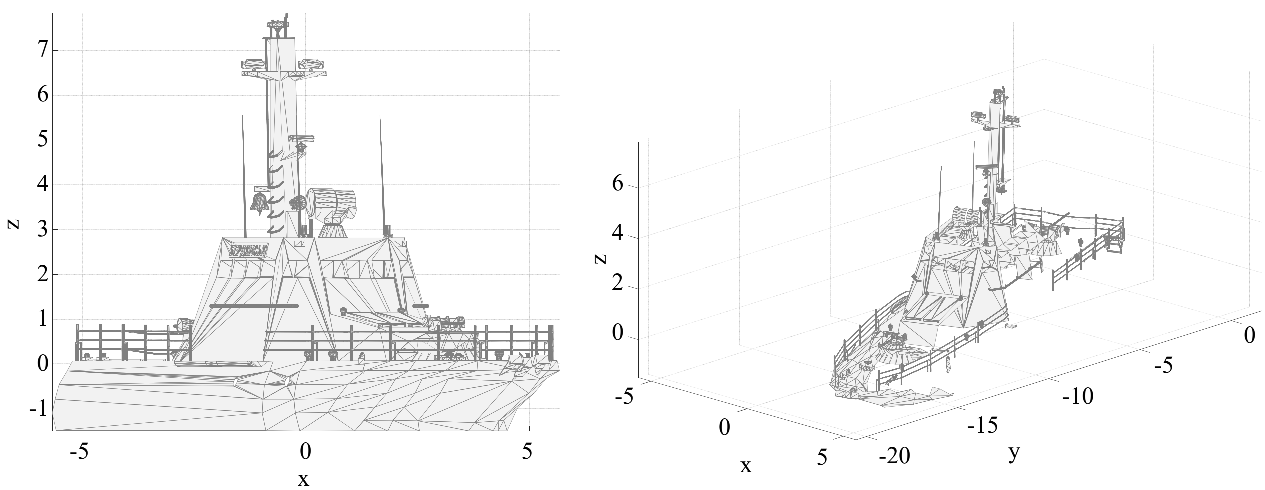


Fig. 3. Location of the facet and its normal vector in the *OXYZ* coordinate system associated with the target



a *b*

Fig. 4. Image of the faceted 3D model of the boat: *a* — from the current angle of radar observation; *b* — with excluded invisible surfaces for an arbitrary viewing angle

The simplified model remains available for identification and visual interpretation, but the number of elements (facets) is significantly reduced. This intermediate result approaches the stated goal of minimizing the number of necessary calculations and computing requirements.

5. 3. Procedure for forming a spatial grid of radar beam tracing for the current angle of radar observation

When observing a faceted 3D model of a target from the current radar angle, some surfaces of this model are shaded. This determines the need to exclude such surfaces from consideration for adequate simulated formation of reflected radar signals and construction of corresponding radar portraits of targets.

A shaded surface is a facet of the 3D model of the target, which is covered by another facet visible from the current radar observation angle.

Usually, to remove facets that fall into the shadow of other facets, algorithms for removing invisible surfaces based on visibility checks are used [19].

The first step of the technological procedure of ray tracing and construction of reflective surfaces of the 3D model is the formation of the tracing grid ("Tracing grid" module in Fig. 1).

The accuracy of RP modeling by applying the tracing procedure depends on the number of elementary reflectors into which the 3D model is divided by the tracing grid. For accurate modeling in combination with the rational use of computing resources, the step of the tracing grid is $d\leq\lambda/2$, where λ is the wavelength of the sounding signal in free space.

The *GKn* radar beam tracing grid (Fig. 5) is placed in the *GS* plane perpendicular to the line that runs from the location point of the radar L_1 to the point *O* of the center of the *OXYZ* coordinate system. The *GS* plane is placed at such a distance that all the vertices of the array *V* are outside the *GS* plane from the point *O* of the center of the *OXYZ* coordinate system and as close as possible to the plane of the tracing grid.

Further, during the construction of the tracing grid, the points of intersection with the *GS* plane of straight lines such as those that go from the location of the radar L_1 to each of the vertices of the array $V=(v_1, v_2,...,v_i,...,v_m)$ are calculated. All intersection points calculated in this way form the array $VG=(vg_1, vg_2,...,vg_i,...,vg_m)$, which is the mapping of the array *V* onto the plane of the tracing grid *GKn* in the *OgXgZg* coordinate system.

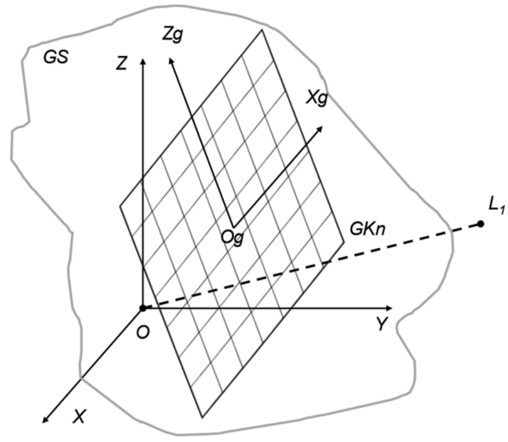


Fig. 5. Construction of a spatial grid of radar beam tracing

Take all points $vg_i(xg_i, yg_i, zg_i)$ from the array of intersection points $VG=(vg_1, vg_2,...vg_j,...vg_q)$. Among them, determine the maximum max*vgx* and minimum max*vgx* values of the coordinates of these points along the *OXg* axis, as well as the maximum max*vgz* and minimum min*vgz* values of the coordinates of these points along the *OZg* axis. The specified max*vgx* and min*vgx* values specify the size of the *GKn* tracing grid along the *OZg* axis.

Next, the L_2 nodes of the *GKn* tracing grid are determined, placing them in rows along the *OXg* axis and in rows along the *OZg* axis with a step of *OZg*, where λ is the wavelength of the sounding signal in free space.

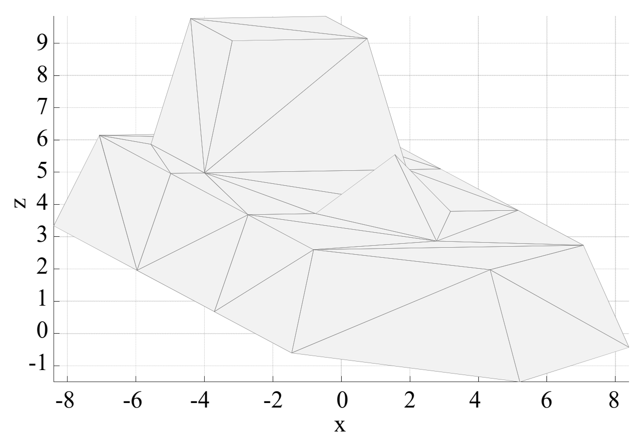
The tracing lattice *GKn* formed in this way has *Gst* nodes in a line and *Gln* rows according to the ratios:

$$G_{st}=\left[\frac{\max vgx-\min vgx}{stepgrid}\right], \tag{12}$$

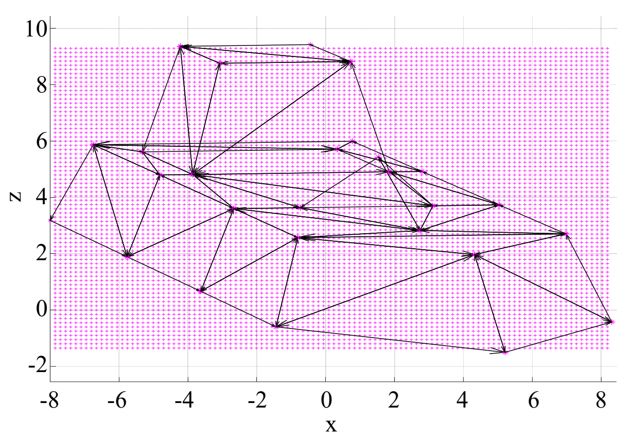
$$G_{st}=\left[\frac{\max vgz-\min vgz}{stepgrid}\right], \tag{13}$$

and in general it consists of *k* nodes $L_{2K}=(L_{21}, L_{22},...,L_{2h},...,L_{2k})$, where $k=Gst\cdot Gln$ is the total number of nodes of the tracing lattice *GKn*, $h=[1, k]$ is the node number of the tracing lattice *GKn*.

Fig. 6 shows an example of an image of a simplified faceted 3D model from the current radar observation angle (Fig. 6, *a*) and a projection of this model onto the *GS* plane with a *GKn* tracing grid applied (Fig. 6, *b*).



a



b

Fig. 6. Image of a simplified faceted 3D model: *a* – from the current angle of radar observation; *b* – projection of this model onto the *GS* plane with the *GKn* tracing grid applied

The sequence of performing procedures for working with arrays of points takes into account the wavelength of the probing signal, and this again simplifies future RP calculations and brings the research results closer to practical application.

5. 4. Procedure for determining the coordinates of elementary reflectors and their visibility for the current angle of radar surveillance of targets

Construction of reflective surfaces of 3D models using ray tracing makes it possible to investigate radar objects of any complexity. In addition, ray tracing is a way of creating reflective surfaces of 3D models, in which tracking the course of electromagnetic wave rays makes it possible to create an RP representation without additional analysis and searching for shaded surfaces of 3D models.

In the devised radar portrait modeling technology, an array of nodes L_{2K}=(L_{21}, L_{22},...,L_{2h},...,L_{2k}) of the *GKn* tracing grid is formed together with an array of vertices V=(v_1, v_2,...,v_i,...,v_m) for the current observation angle radar and the array of visible facets F_V=(f_1, f_2,...,f_j,...,f_p) serves as the basis for algorithms for calculating the coordinates of elementary reflectors (module "Coordinates of elementary reflectors" in Fig. 1).

For each *h*-th node L_{2K}=(L_{21}, L_{22}, ..., L_{2h}, ..., L_{2k}) of the tracing lattice *GKn*, the coordinates of the intersection point P_h of each *j*-th facet f_j from the array of visible facets F_V=(f_1, f_2, ..., f_j, ..., f_p) by a straight line starting from the location point of the radar L_1 through the *h*-th node of the tracking grid L_{2h}. If the existence of intersection points of the array facets F_V=(f_1, f_2, ..., f_j, ..., f_p) is determined for the *h*-th node, the distance $distP_h$ to the intersection point P_h is calculated for each of them.

From all the intersection points of the facets of the array of visible facets F_V=(f_1, f_2, ..., f_j, ..., f_p) found for the *h*-th node, the point P_h closest to the radar is chosen as a visible elementary reflector. The coordinates of this point are entered into the array of coordinates of elementary reflectors of the facet model P_K. At the same time, the index of the facet $indP_h$, to which the point P_h belongs, is entered into the array of indices of the facets of elementary reflectors *indexP*. There is a sequential passage of rays from the location point of the radar L_1 through the nodes L_{2K}=(L_{21}, L_{22}, ..., L_{2h}, ..., L_{2k}) of the *GKn* tracing grid to the points of intersection with the facets. An array of coordinates of elementary reflectors of the facet model P_K=(P_1, P_2, ..., P_h, ..., P_k) and an array of indexes of facets of elementary reflectors *indexP*=($indP_1$, $indP_2$, ..., $indP_h$, ..., $indP_k$) are formed.

The process of forming the coordinates of elementary reflectors of the facet model (P_K=P_1, P_2, ..., P_h, ..., P_k) is illustrated in Fig. 7, and consists in the fact that a beam is directed from the location point of the radar L_1, which passes through the node of the tracing grid L_{2p} and crosses facets 1 and 2 at points P_{f1} and P_{f2}, respectively.

In Fig. 7, of the two points P_{f1} and P_{f2}, the closest point to the radar, namely P_{f1}, is chosen as the visible elementary reflector. Likewise, another ray that passes from the radar location L_1 through the trace grid node L_{2s}, intersects facets 3 and 4 at points P_{f3} and P_{f4}, respectively. From these two points P_{f3} and P_{f4}, the closest point to the radar, namely P_{f4}, is also selected as the visible elementary reflector. This sequential passage of rays from the location of the radar L_1 through all nodes L_{2K}=(L_{21}, L_{22},...,L_{2h},...,L_{2k}) of the tracing grid forms an array of coordinates of elementary reflectors of the facet model P_K=(P_1, P_2,...,P_h,...,P_k), where *k* is the number of nodes of the *GKn* tracing grid.

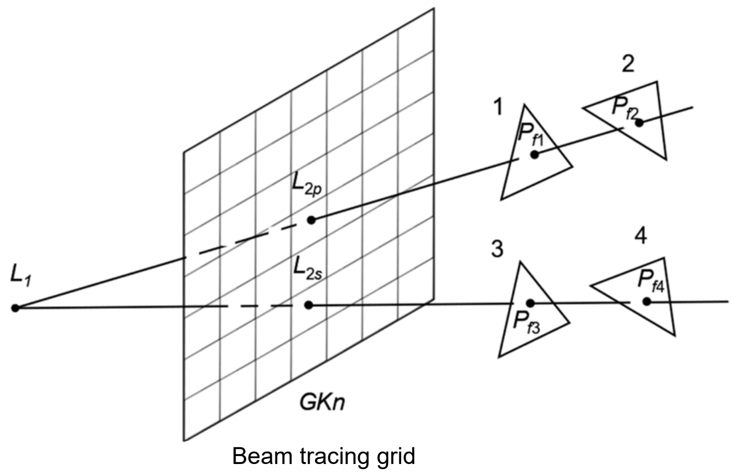


Fig. 7. Illustrating the principle of determining the coordinates of elementary reflectors

Thus the formed array of coordinates of elementary reflectors of the facet model P_K=(P_1, P_2,...,P_h,...,P_k) and array of indexes of facets of elementary reflectors *indexP*=($indP_1$, $indP_2$,...,$indP_h$,...,$indP_k$) describe the constructed as follows reflective surface of the 3D model of the target.

The array of elementary reflectors of the faceted model P_K=(P_1, P_2,...,P_h,...,P_k) is formed on the basis of a cyclical search procedure by the method of complete search. It should be understood that various means can be used to increase the speed of this process. So, for example, in order to reduce the time spent when performing a search by the method of a full search of the array of visible facets F_V=(f_1, f_2, ...,f_j, ..., f_p) it is possible to form a new array of tracing facets F_G=(f_1, f_2, ..., f_j, ..., f_p). This array is the projection of the array of visible facets F_V=(f_1, f_2,...,f_j,...,f_p) onto the plane of the tracing grid *GKn* in the *OgXgZg* coordinate system.

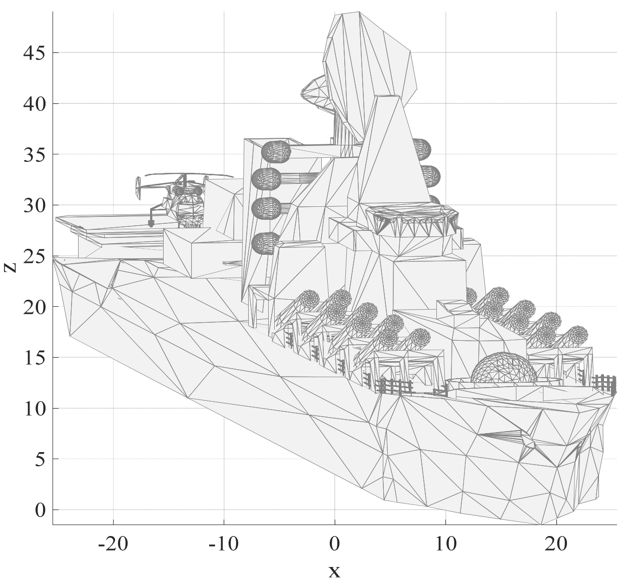
For each selected *j*-th facet f_j from the array of trace facets F_G=(f_1, f_2, ..., f_j, ..., f_p), the maximum $X\max f_j$ and minimum $X\min f_j$ values of the coordinates along the *OgXg* axis, as well as the maximum $Z\max f_j$ and minimum $Z\min f_j$ values of the coordinates along the *OgZg* axis are calculated.

For each *h*-th node L_{2h}(x_{L2h}, z_{L2h}) from the array of nodes L_{2K}=(L_{21}, L_{22}, ..., L_{2h}, ..., L_{2k}) of the tracing grid *GKn*, when searching for intersection points P_h, only those *j*-th facets f_j from the array of visible of facets F_V=(f_1, f_2, ..., f_j, ..., f_p), for which the conditions are fulfilled:

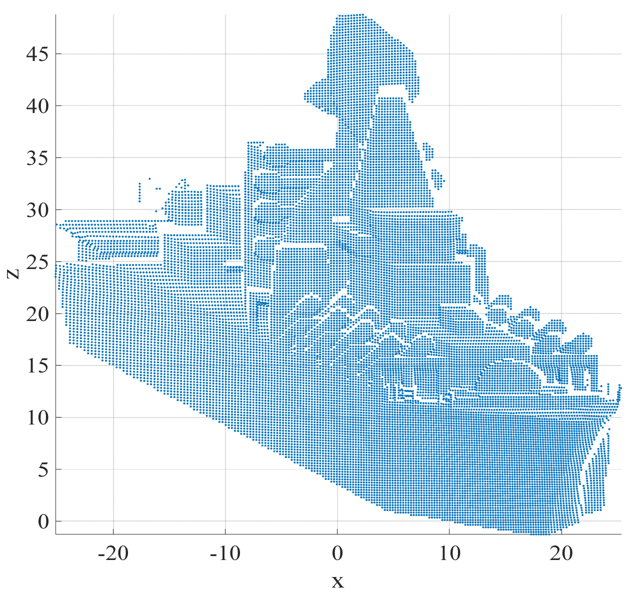
$$X_{L2h} < X_{\max f_i} \text{ and } X_{L2h} > X_{\min f_i} \text{ and } Z_{L2h} < Z_{\max f_i} \text{ and } Z_{L2h} > Z_{\min f_i}. \quad (14)$$

Facets for which conditions (14) are not fulfilled are not used when determining the array of coordinates of elementary reflectors of the facet model P_K=(P_1, P_2,...,P_h,...,P_k). The application of facet selection conditions (14) using the array of trace facets F_G=(f_1, f_2,...,f_j,...,f_p) makes it possible to reduce the time of the process of searching elementary reflectors of the facet model P_K by 8–12 times. The exact value of the calculation acceleration depends on the angle and complexity of the description of the facet model. This is a necessary condition for carrying out calculations regarding the construction of the reflective surface of the faceted 3D model by the method of complete sorting.

Fig. 8, *a* shows an example of an image of a faceted 3D model of a warship from the current angle of radar observation. And Fig. 8*b* gives an example of the formed reflective surface of the faceted 3D model from the current viewing angle based on the use of the array of coordinates of elementary reflectors of the faceted model $P_K=(P_1, P_2,...,P_h,...,P_k)$.



a



b

Fig. 8. Image of a warship from the current angle of radar observation: *a* — faceted 3D model; *b* — image of the reflective surface of the 3D model of the warship

Although the generated reflective surface of the faceted 3D model from the current observation angle can already be used to construct RPs, it is still difficult for accurate calculation methods.

5. 5. Superposition of elementary reflected radar signals when constructing radar portraits

Accurate methods for calculating radar objects are based on Maxwell's equations in integral or differential form. They include the method of moments, the method of finite elements, the method of finite differences in the time domain, the method of finite integrals and their hybrid modifications. Currently, the use of accurate methods of calculating radar objects is limited due to the need to use significant computing power in their implementation.

From the asymptotic methods of calculating the secondary radiation from radar objects of complex shape, one can distinguish the method of geometric optics, the method of physical optics, the geometric theory of diffraction, the physical theory of diffraction and their modifications [20, 21]. The most acceptable, in the sense of the required volume of calculations, from the asymptotic methods are the methods of geometric optics. In them, the behavior of the electromagnetic field at the interface of two media is described by the Snelius law, and the amplitude and phase of the reflected radiation is determined by the Huygens-Fresnel principle [22, 23].

It was on the basis of using the Huygens-Fresnel principle that the technology of modeling radar portraits was developed for systems of intelligent recognition of military objects of complex shape. The developed technology makes it possible to study the nature of secondary radiation of radar targets depending on many characteristics. In particular, depending on the geometric shape of RTs, the electrical characteristics of RTs, the movement of RTs, the ratio of the linear dimensions of RTs and the wavelength of irradiation, the laws of modulation of the irradiating wave, etc.

When simulating the secondary electromagnetic field to simulate the formation of reflected radar signals, first set the parameters of the simulated radar ("Parameters of the simulated radar" in Fig. 1). Set such parameters as the operating frequency of the radar, the length and time of the rise/fall of the electromagnetic pulse wave, the repetition period, and the type of modulation of the sounding radio pulses, the shape of the envelope of the sounding signal, the pattern of the antenna, etc. It is also important to take into account noise interference as it affects the quality of evaluation and recognition. To determine the noise level, preliminary high-frequency filtering of radar signals should be performed.

To determine the reflected radar signals (RL), a technology for modeling radar portraits has been developed. It uses the formed arrays of coordinates of elementary reflectors $P_K=(P_1, P_2,...,P_h,...,P_k)$ and the array of indices of facets of elementary reflectors $indexP=(indP_1, indP_2, ..., indP_h, ..., indP_k)$ together with the parameters of the modeled radar.

The amplitude of the reflected radar signals at the location of the radar L_1, according to the Huygens-Fresnel principle, is calculated as a superposition of elementary reflected radar signals of the secondary electromagnetic field. The calculation is carried out taking into account their amplitudes and phases from all elementary reflectors $P_K=(P_1, P_2,...,P_h,...,P_k)$, which describe the reflecting surface of the faceted 3D model (Fig. 9).

To this end, first determine the distance $distv_i$ from the location point of the radar L_1 to each i-th vertex of the array $V=(v_1, v_2, ..., v_i, ..., v_q)$:

$$distv_i = |L_1 - v_i|. \tag{15}$$

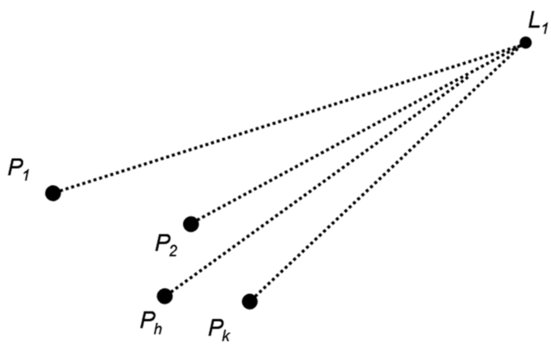


Fig. 9. Illustration of the principle of superposition of elementary reflected radar signals of the secondary electromagnetic field from elementary reflectors $P_K=(P_1, P_2, ..., P_h, ..., P_k)$ of the faceted 3D model

Among all the distances found, $distv_i$, find the distance that is the smallest and mark it as the minimum distance *distV*min to the nearest vertex *V*min to the radar.

In order to determine the amplitudes and phases from all elementary reflectors, cyclically for each *h*-th elementary reflector P_h from the array $P_K=(P_1, P_2, ..., P_h, ..., P_k)$, determine the distance $distP_h$ from the location point of the radar L_1 to the point of the elementary reflector P_h from array $P_K=(P_1, P_2, ..., P_h, ..., P_k)$:

$$distP_h = |L_1 - P_h|, \quad (16)$$

and also calculate the unit vector $dirVP_h$, which is directed from the location point of the radar L_1 to the point of the elementary reflector P_h from the array $P_K=(P_1, P_2,...,P_h,...,P_k)$:

$$dirVP_h = \frac{L_1 - P_h}{distP_h}. \quad (17)$$

Also, for each *h*-th elementary reflector P_h, a facet f_j is extracted according to the facet index $indP_h$ from the array of visible facets $F=(f_1, f_2,...,f_j,...,f_q)$, in which the elementary reflector P_h is located, and the normal vector n_j to this facet f_j is calculated.

Then, for the *h*-th elementary reflector P_h, the scalar product sp_i is calculated:

$$sp_h = n_i \cdot dirVP_h', \quad (18)$$

by which the reflection angle $angleP_h=arccos(sp_h)$ is calculated between the vector $dirVP_h$, which is directed from the location point of the radar L_1 to the point of the elemental reflector P_h, and the normal n_j to the facet f_j, in which the elemental reflector P_h is located.

Next, the distance shift $shiftD_h$ in meters and the time shift $shiftT_h$ in seconds are calculated for the *h*-th elementary reflector P_h relative to the peak *V*min closest to the radar:

$$shiftD_h = distP_h - distV_{\min}, \quad (19)$$

$$shiftT_h = 2 \cdot \frac{shiftD_h}{C}, \quad (20)$$

where *C* is the speed of light.

After that, the amplitudes and phases of all radar signals of the secondary electromagnetic field reflected from elementary reflectors $P_K=(P_1, P_2, ..., P_h, ..., P_k)$ of the surface of the faceted 3D model are determined. Then, based on the use of the superposition of reflected elementary radar signals from elementary reflectors $P_K=(P_1, P_2, ..., P_h, ..., P_k)$, a model of the reflected radar signal of the target is formed (module "Reflected radar signals" in Fig. 1).

The developed software for simulation of reflected radar signals consists of a library for modeling the reflected radio signal and a simulation application module. To implement parallel calculations, the OpenMP (Open Multi-Processing) library is used, which is designed for programming multithreaded applications on multiprocessor systems with shared memory in the C, C++ languages.

For a better understanding of the sequence of modeling the reflected signal, a simplified module diagram of the algorithm is shown below (Fig. 10).

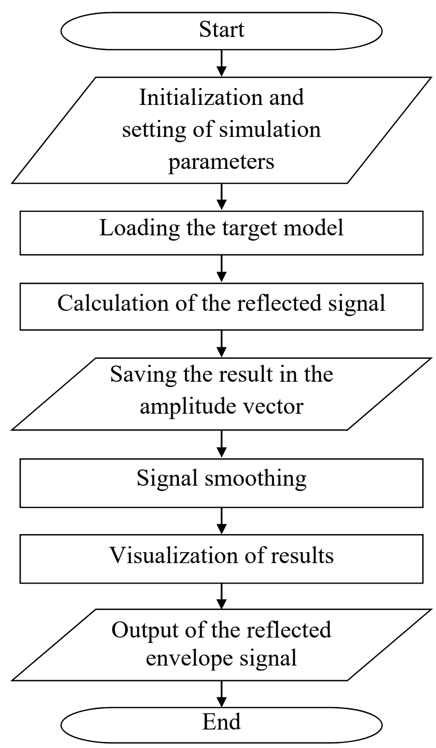


Fig. 10. Block diagram of the reflected signal modeling process

In the first step, the simulation parameters are initialized, then the 3D model of the target is loaded and its orientation relative to the radar is set. After that, the reflected signal is calculated (for example, using the reflected ray tracing method). In the next step, the signal is smoothed to obtain an envelope. At the last step, the simulation results are obtained and visualized.

Fig. 11 shows a simulation model of the reflected radar signal of the target, which was formed for a faceted 3D model of a warship from the current radar observation angle.

Next, radar portraits of targets are formed from simulated models of reflected radar signals by means of filtering and amplitude detection (module "Formation of RPs" in Fig. 1).

Fig. 12 shows a radar portrait of a faceted 3D model of a warship from the current observation angle, which is formed by the simulated model of the reflected radar signal shown in Fig. 11.

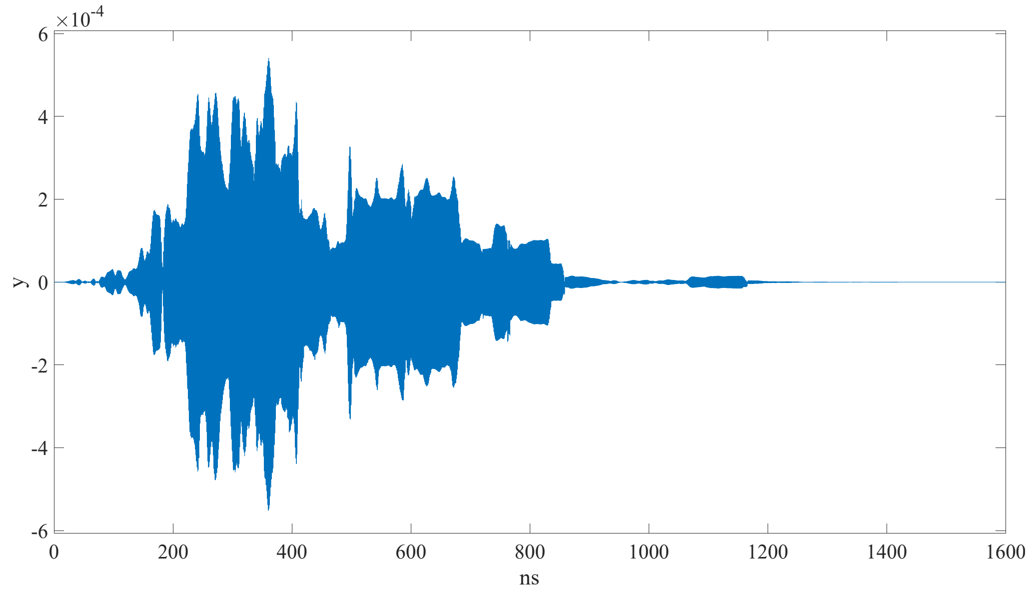


Fig. 11. Simulation model of the reflected radar signal of the 3D model of a warship from the current observation angle

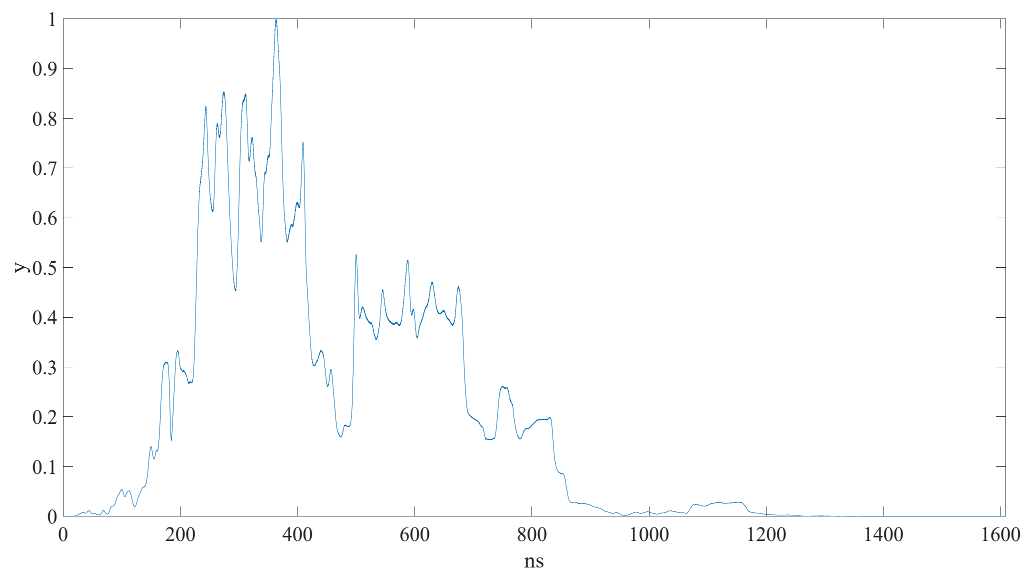


Fig. 12. Radar portrait of a faceted 3D model of a warship from the current observation angle

Data on the current position of the radar relative to the target and the type of the simulated radar target are used to create identification indexes, which are applied to place the generated radar portraits of targets in the radar portrait database (module "RP database" in Fig. 1) or (Fig. 1).

6. Discussion of results of radar portrait modeling using facet models

The result of our work is the developed technology for modeling radar portraits. It describes both the process of building faceted 3D models and simplifies their further processing with invisible surfaces excluded from them for an arbitrary viewing angle. You can see the simplification and fundamental difference between the image of the radar portrait of the faceted 3D model (Fig. 12) and the primary image of the boat model (Fig. 4, *a*).

The RP modeling technology for systems of intelligent recognition of military objects provides for the rapid development of models of objects of various classes of technology of arbitrary shape. That is why the use of faceted 3D models significantly simplifies calculations regarding the simulated formation of reflected radar signals from the model surfaces. To this end, 3D models for simulating the formation of reflected radar signals are built in the simplified ".obj" format. This format compactly describes the geometry of the object, which makes it possible to obtain a faceted model for an object of any complexity in terms of shape or detail. Such faceted 3D models of complex-shaped radar objects make it possible to effectively simulate reflected radar signals and build radar portraits of modeled targets based on them.

Constructed files of faceted 3D models are preliminarily placed in the relational database of 3D models with clearly defined attributes. This simplifies the modeling process and specifies the sequence of execution of the main procedures of the modeling technology, the components of which are shown in Fig. 1. The database formed by the technology makes it possible to store radar portraits of military objects of complex shape.

Checking the visibility of the surfaces of the faceted 3D model from the current angle of radar observation is carried out by the algorithm for selecting visible facets according to formulas (4) to (9), as shown in Fig. 3. Next, it is necessary to exclude from the faceted 3D model surfaces that are invisible from the current angle of radar observation, according to (10), (11). As a result, the simplified model remains available for identification and figurative interpretation, but the number of elements (facets) is significantly reduced. This intermediate result approaches the stated goal of minimizing the number of necessary calculations and computing requirements. Its illustration is given in Fig. 4, *b*.

The basis for solving the problem of shading was the use of an algorithm for forming a spatial tracing grid for a given perspective. This is due to the ray tracing procedure and the construction of reflective surfaces of the 3D model. To this end, a tracing grid is formed (module "Tracing grid" in Fig. 1). This approach makes it possible to choose the step of the tracing grid, and this, in turn, reduces the time of calculations.

In general, the release of computing resources for more rational use became possible thanks to the use of an array of trace facets and the application of the Huygens-Fresnel principle for the recognition of objects of complex shape. To this end, the tracing grid is formed according to the ratios: (12), (13), as shown in Fig. 5. According to the results in Fig. 6, it is possible to conclude that the sequence of procedures for working with arrays of points takes into account the wavelength of the probing signal. This is important for simplifying future RP calculations and brings research results closer to practical application.

Construction of reflective surfaces of 3D models using ray tracing makes it possible to investigate radar objects of any complexity. Another advantage is the creation of RP representation without additional analysis and search for shaded surfaces of 3D models. Accordingly, the process of forming the coordinates of elementary reflectors of the facet model is illustrated in Fig. 7. Thus, the formed arrays of coordinates of elementary reflectors of the facet model describe the constructed reflective surface of the 3D model of the target. This, again, makes it possible to reproduce the refined spatial characteristics of radar targets of complex shape.

To increase the speed of this process, the search for reflectors has been optimized. Formula (14) is used to reduce the time spent by the method of a complete search of the array of visible facets. Facets for which the conditions are not met are not used when defining the array of coordinates of elementary reflectors of the facet model. The application of such selection conditions makes it possible to reduce the time of the process of searching for elementary reflectors of the facet model by 8–12 times.

Fig. 8, *a* shows an example of an image of a faceted 3D model of a warship from the current angle of radar observation is given. And Fig. 8, *b* demonstrates an example of the formed reflective surface of a faceted 3D model from the current viewing angle. The results testify to the effectiveness of using faceted 3D models and the usefulness of the radar ray tracing procedure when forming the reflective surface of a faceted 3D model.

The use of the Huygens-Fresnel principle makes it possible to study the nature of the secondary radiation of RTs depending on the geometric shape of RTs, electrical characteristics, movement of RTs, linear dimensions, and many other characteristics. The use of accurate calculation methods using Maxwell's equations is limited due to the need to use significant computing power in their implementation.

Accordingly, when simulating the secondary electromagnetic field to model the formation of reflected radar signals, the parameters of the simulated radar are first set (module "Parameters of the simulated radar" in Fig. 1). The amplitude of reflected radar signals at the location of the radar, according to the Huygens-Fresnel principle, is calculated as a superposition of elementary reflected radar signals of the secondary electromagnetic field, which is shown in Fig. 9. At the same time, the model of the reflected radar signal of the target (module "Reflected radar signals" in Fig. 1) is formed through the superposition of reflected elementary radar signals according to formulas (15) to (20).

The effectiveness of the approach is evidenced by the result of modeling the radar portrait of the faceted 3D model of the warship in Fig. 12. It demonstrates the detailed features of radar images selected on the basis of models, which are necessary in the future for confident recognition, classification, and image interpretation of radar targets of complex shape by known means of identification. In particular, such as correlation, cluster and spectral methods of statistical analysis, Wasserstein metrics, peak and harmonic analysis, Euclidean distance algorithms, neural networks, etc.

It is important that the proposed solution does not require the construction of complex models to solve the problem. It does not require either the construction of a tree-like data structure that takes into account the RPs of the targets, or the use of a coverage mask [6, 7]. Thanks to the features of the proposed solutions, an advantage is provided in terms of speed and volumes of necessary calculations in general. In particular, it was proposed to use software for modeling radar signals reflected from these targets, implemented in the high-level C++ programming language. The use of the language depending on the strategy of parallelization of calculations gives an increase of several orders of magnitude in the speed of execution of RP calculations of sea targets of complex shape. This created an additional advantage compared to other studies (given in the literature review) that used the MATLAB environment.

The technology was tested through an experimental study. The practical use of RP databases modeled in accordance with the proposed invention in known identification methods made it possible to recognize the type of military object of complex shape at the level of 80–90 %. The speed of the proposed technology makes it possible to provide recognition on a real-time scale in the case of the availability of a developed database of targets.

For the development of new small-sized target identification systems, it is possible to apply the obtained solutions to the researched ones, which makes it possible to reduce the necessary calculations by several times at several stages. Accordingly, this reduces the mass-dimensional characteristics of computer tools and, importantly, their cost, if we are talking about use in the military domain for homing warheads.

The results of modeling radar portraits of faceted models remain adequate under the conditions of work with the standard listed military targets, such as an aircraft, tank, ship. For work with objects the size of a quadcopter, the calculation accuracy may deteriorate due to the reduction of the geometric dimensions of the facets.

Among the shortcomings of this study is the limited work with multi-layered radio-absorbing materials. The use of innovative materials with low radar reflectivity can make it impossible to ensure target recognition. Although the technology takes into account the material of the targets, in some scenarios the nature of the reflected radio waves imposes too strict limits on the recognition hardware and algorithms. In addition, the probability of detection and recognition of long objects decreases, in the design of which technologies of reducing the effective reflective scattering surface ("stealth") are used.

Other limitations of the proposed method are characterized by its working principle and parameters. According to them, the formation of facet models of targets and the corresponding duration of the reflected radar signals depend on the given characteristics of the targets. Namely, they depend only on the type and angle of target orientation; its size; range parameters; the height of the location of the homing head. In the case of radar recognition of surface sea ships, an adequate assessment of the listed parameters takes place only with singly located targets under static conditions. This paper reports the results of modeling the operation of the technology under the conditions of a stationary target and the case of radar observation of the target. Further research involves the study on the influence of the speed of rotation of the circular survey radar and the use of phased antenna arrays.

The further development of the research involves the study of the influence of the speed of a military object on the result of the formation of its RPs since it is currently known that the influence of a set of destabilizing factors that cause an increase in errors in the measurement of features, in order to ensure the required probability of correct recognition of objects, necessitates an increase in the target observation period . Among these factors that can cause distortion of the shape of the received RPs of the target are non-linear signal distortions in the transmission and reception paths; non-identity of the frequency characteristics of the reception-transmission paths of phased antenna arrays; influence of external obstacles; delay of the signal on the aperture of the antenna for transmission and reception and movement of the target at high speed, which causes changes in the RPs, both during linear movement and during constant maneuvering.

The further development of our research may consist in finalizing the work with RP libraries, developing technologies for their use, their addition, updating, and administration. Among the risks that pose additional challenges to the technology are the problems of ensuring the level of reliability of working with libraries when scaling them and organizing interaction with other systems.

7. Conclusions

1. A procedure for processing facet model data has been devised. A block diagram of the main components of the radar portrait modeling technology has been built. A simplified 3D model was obtained by performing a sequence of operations on working with arrays of vertices and facets to exclude surfaces that are invisible from the current perspective. Confirmation of the successful construction, as a result, is provided by the devised procedure for checking the corresponding file in the ".obj" format, which is an integral part of the algorithm.

For example, a faceted model of the "Gyurza-M" boat and its model with invisible surfaces excluded from it from an arbitrary viewing angle are demonstrated.

2. A procedure has been devised and appropriate technological procedures have been developed for the formation of a spatial tracing grid for the current observation angle. To determine the shaded facets, a ray tracing procedure was proposed in order to form a tracing grid. In contrast to known works, the proposed algorithm rationally uses computing resources, as in the determination of facets, but also in the calculation of the wavelengths of the probing signal in free space. That has made it possible to obtain a projection of the model with the applied tracing grid and further reduce the number of necessary calculations for constructing the RPs of the reflected signal.

3. A procedure for determining the coordinates of elementary reflectors and their visibility for the current perspective of radar surveillance of targets has been devised. It has been proven that the application of facet selection conditions using an array of tracing facets reduces the duration of the process of searching for elementary reflectors of the facet model by 8–12 times. This makes it possible to carry out calculations regarding the construction of the reflective surface of the faceted 3D model by the method of complete enumeration.

4. The best method, relative to the required volume of calculations, of the asymptotic methods – methods of geometric optics – was chosen. The most acceptable of them are those in which the behavior of the electromagnetic field at the interface between two media is described by the Snelius law, and the amplitude and phase of the reflected radiation is determined by the Huygens-Fresnel principle. On its basis, an optimal method of accurate calculation of objects for systems of intelligent recognition of military objects of complex shape has been devised.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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