Показано, що проведення математичного моделювання дозволяє створювати та досліджувати радіолокаційні портрети сучасних і перспективних літальних апаратів. Побудова та дослідження математичних моделей на базі сучасної інформаційно-обчислювальної техніки може реалізовувати методи розрахунку характеристик вторинного випромінювання літальних апаратів з потрібною точністю, що забезпечить практичну спрямованість. Обґрунтований метод розрахунку характеристик вторинного випромінювання літальних апаратів для аналізу радіолокаційного розсіяння моделі протитанкового штурмовика Су-25Т. Перевагою такого методу є врахування інтегральних уявлень класичної електродинаміки та короткохвильових асимптотик. Запропонована модель поверхні літака Су-25Т та розроблено метод математичного моделювання. Обґрунтовані основні характеристики радіолокаційного розсіяння літальних апаратів – ефективна поверхня розсіяння, "некогерентна" ефективна поверхня розсіяння, середні та медіанні значення ефективної поверхні розсіяння, закони розподілу амплітудного множника відбитого сигналу. Наведені результати розрахунку таких характеристик радіолокаційного розсіяння літака Су-25Т для різних частот опромінення сигналу зондування. Отримані результати пропонується використати при модернізації існуючих і проектуванні перспективних засобів радіолокації. Представлені результати є корисними для оцінювання можливостей різних конструктивних варіантів таких засобів щодо виявлення, супроводження та розпізнавання літальних апаратів аналогічного типу. Застосування отриманих результатів дозволить проводити оптимізацію конструкції модернізованих і перспективних літальних апаратів з метою зменшення радіолокаційної помітності. Запропонований метод є основою математичного моделювання радіолокаційних характеристик літальних апаратів різних типів при заданих просторових і часово-частотних параметрах сигналів зондування для розв'язання прикладних задач радіолокації

Ключові слова: аеродинамічна модель літального апарату, вторинне випромінювання, ефективна поверхня розсіяння

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CHARACTERISTICS OF RADIOLOCATION SCATTERING OF THE Su-25T ATTACK AIRCRAFT MODEL AT DIFFERENT WAVELENGTH RANGES

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1. Introduction

The availability of data on the characteristics of secondary radiation of an aircraft makes it possible to solve several practical tasks on radiolocation. On the one hand, to carry out a set of measures to form a positional area of subdivisions that provide intelligence and battle information for divisions and units of anti-aircraft missile troops. On the other hand, it is possible to acquire information that makes it possible to detect areas in the object's surface, which introduce dominant contribution to the reverse scattering of an object in general. That would provide an opportunity to assess the effectiveness of predicted measures to optimize the radiolocation characteristics both of an entire object and some of its sections.

There are two most common techniques to obtain radiolocation information about aerial objects: field (physical) experiments, and mathematical modeling of the secondary radiation of airborne objects.

Each of the proposed techniques is associated with certain difficulties. Thus, when carrying out the field (physical) experiments, enormous financial, organizational, and time costs are required. The main difficulties in mathematical modeling of the secondary radiation of air objects models relate to the accurate design of the model itself, correctness of its mathematical description, etc.

The modern level of development of computational tools makes it possible to realize sufficiently complex methods for mathematical modeling of the secondary radiation of airborne objects at the required accuracy for practical application.

Thus, it is a relevant scientific task to calculate the characteristics of scattering of modern aerial objects.

2. Literature review and problem statement

Construction of radiolocation profiles of aerial objects is carried out to improve the indicators for their detection and recognition, to simulate the aircraft of the required type. Simulation of aerial objects often involve false targets in the form of towed aircraft with the simplest design. The geometrical dimensions of such aircraft are much smaller than those of the objects that are protected, but signals from the false targets at the input to a receiver exceed the signals reflected from the protected object [1]. Paper [2] reports results of numerical modeling of radiolocation distant profiles of cruise missiles over the meter, centimeter, and decimeter wavelengths. The modeling employed numerical methods for calculating characteristics of the secondary radiation of airborne objects with a complex shape and different electric sizes. However, the paper focuses on the analysis of radiolocation distant profiles of cruise missiles at different angles, polarization, and the width of spectrum of the probing signal; a possibility to applying them as false targets is considered.

Studies [3–5] substantiated in detail the advantages and disadvantages of the application of integral equations for the calculation of characteristics for the secondary radiation of airborne objects. However, the reported results could be used for volumetric objects with a small curvature, such as cruise missiles or unmanned aerial vehicles [2, 6].

A method for calculating the effective scattering surface (ESS) of a triangular corner reflector of arbitrary shape and irradiation conditions was described in paper [7]. From a practical point of view, it could lead to difficulties related to determining the optimal geometric shape of reflectors and to adding the active systems for radiation or re-reflection of radar signals.

The need to conduct the study, results of which are reported in this work, is confirmed by the authors of papers [8–10]. Resolving the range of tasks related to an airborne object is possible through a rational combination of the flight-technical, those that demask, the operational, and other characteristics, in their totality based on a comprehensive approach to the formation of its appearance, including when irradiated with different radiolocation signals [10].

All this gives grounds to assert that it is a relevant task to undertake a research into the acquisition of characteristics for the scattering of airborne objects, based on the earlier constructed high-frequency calculation methods that would comprehensively account for the entire totality of prevailing factors.

3. The aim and objectives of the study

The aim of this study is to determine the radiolocation characteristics of Su-25T attack aircraft at different frequencies of irradiation. That would make it possible to optimize the structure of the modernized and promising aircraft in order to reduce their radiolocation visibility.

To accomplish the aim, the following tasks have been set:

– to design a model of the surface of the Su-25T anti-tank aircraft;

– to propose basic estimation ratios, which underlie the basis of the method for acquiring the radiolocation characteristics of an aircraft;

– to identify the features of irradiation influence (the centimeter, decimeter, meter ranges of wavelengths) on the analysis of radiolocation characteristics (radiolocation profile) of the Su-25T attack aircraft.

4. A method for the calculation of radiolocation characteristics of the Su-25T anti-tank aircraft

Su-25T is an anti-tank aircraft (AA), shown in Fig. 1, designed to destroy armored vehicles, fire weapons, vessels (to a destroyer ship inclusive), helicopters, transport aircraft, bridges, shelters, air defense complexes, and the living forces of enemy. It is operated during day and night, at a battlefield, and at a depth of up to 450 km beyond a frontline, in the range of heights from 30 to 5,000 m [11].

The Su-25T attack aircraft is a modification of the Su-25 attack aircraft, designed to directly support ground-based forces. Immediately after the testing was officially over, a special aviation squadron was formed, armed with Su-25, which was sent to Afghanistan. That is where the plane got its name "Grach". The Su-25T attack aircraft fought in Afghanistan for eight years; over that period, it showed its high reliability and efficiency.

Fig. 1. Su-25T anti-tank aircraft

"Grach" performed 60 thousand flights, while having only 23 aircraft destroyed. There were times when Su-25 returned to the aerodrome, with up to 150 holes. None of the aircraft was lost due to the explosion of fuel tanks or death of a pilot. In addition to Afghanistan, the Su-25T attack aircraft took part in the civil conflict in Angola. These aircraft took part in the Iran-Iraq war, though there is no information about their military application. These aircraft were involved in conflicts that took place in the former Soviet republics. These machines fought in Africa, and were used during the first and second Chechen war. Su-25 is in service in Iraq against militants from the ISIS organization [12].

4. 1. Description of the modelled object and the model of its surface

In its design, the aircraft Su-25T is a one-seat fully metallic monoplane, executed based on a regular scheme with a highly placed small swept wing; a stabilizer, adjustable for takeoff and landing; unregulated air intake; a three-support chassis with a nose wheel; with two free-thrust turbojet engines. Su-25T was developed based on an aerodynamical assembly of the two-seat training-combat aircraft Su-27UB, which is why structural identity in terms of airframe and aircraft systems from the aircraft Su-27UB is (85...90) %.

Selected specifications of Su-25T are as follows [11]:

– geometric and weight characteristics: wingspan is 14.52 m; length is 15.33 m; height is 5.20 m; mass is (9,500...19,500) kg;

– the type of engines – turbojet with afterburners P-195M;

– combat capabilities: maximum speed is 950 km/h; combat load is 4,400 kg; combat radius of action is (400...700); maximum combat altitude is 5,000 m; flight ceiling is 10 000 m.

In accordance with the design of Su-25T, in order to perform calculation of radiolocation characteristics (RLC) (specifically ESS), we built a model of its surface.

A model of the Su-25T AA surface is shown in Fig. 2.

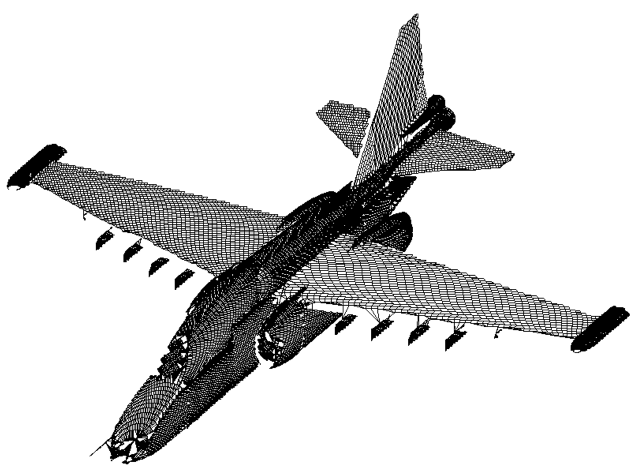

Fig. 2. A model of the Su-25T anti-tank aircraft surface

Simulation of the surface was conducted according to the procedure that is reported in [1–3]. This procedure implies the splitting of scattering surfaces, and elements of the object, into two groups: a smooth part of the surface and the boundary local scattering regions, and the antenna system, which is arranged under the bow dielectric streamer. The smooth part of the aircraft surface was approximated by regions of 63 triaxial ellipsoids. Surface fractures were simulated by using 31 direct local scattering edge sections.

4. 2. Basic estimation ratios

The basic characteristic that defines the properties of an object that reflects electromagnetic waves is ESS [7, 8]:

$$\sigma = \lim_{R\to\infty} 4\pi R^2 \frac{\left|\vec{p}^{\,\text{ïδ}} \cdot \vec{E}_S\right|^2}{\left|\vec{p}^{\,0} \cdot \vec{E}^0\right|^2}, \tag{1}$$

where R is the distance from the object to the point of observation; $\vec{p}^{\,\text{ïδ}}$, $\vec{p}^{\,0}$ is the polarization ort of the receiving and transmitting antenna, respectively; $\vec{E}_S$ is the complex amplitude of the field scattered in the direction of the point of signal reception; $\vec{E}^0$ is the complex field amplitude of the flat monochromatic Electromagnetic wave (EMW)that probes the object.

It is assumed that the probing is done by a flat monochromatic EMW with a single amplitude at polarization ort $\vec{p}^{\,0}$ and a propagation direction characterized by ort $\vec{R}^0$, which arrives at the surface of an object, located in free space (Fig. 2):

$$\vec{E}^0(\vec{x}) = \vec{p}^{\,0} \exp\left(jk_0\left(\vec{R}^0 \cdot \vec{x}\right)\right), \tag{2}$$

$$\vec{H}^0(\vec{x}) = \sqrt{\frac{\varepsilon_0}{\mu_0}}\left(\vec{R}^0 \times \vec{p}^{\,0}\right) \exp\left(jk_0\left(\vec{R}^0 \cdot \vec{x}\right)\right), \tag{3}$$

where k_0 is the wavenumber in free space ($k_0 = 2\pi/\lambda$, λ is the length of the incident monochromatic wave), ε_0, μ_0 are the absolute dielectric and magnetic permeability of vacuum, $\vec{x}$ is the radius-vector of a point at the surface of an object. The field, scattered by an object in direction $\vec{r}^{\,0}$, could be represented, using the Lorenz lemma, in the form [1, 7]:

$$\vec{p}^{\,np} \cdot \vec{E}_S = -jk_0 \frac{\exp\left(jk_0 R\right)}{4\pi R} \times$$
$$\times \int_S \left(\sqrt{\frac{\mu_0}{\varepsilon_0}} \left(\vec{p} \cdot \vec{H}^{\perp}\right) + \left(\vec{p} \times \vec{r}^{\,0}\right) \cdot \vec{E}^{\perp} \right) \exp\left(-jk_0\left(\vec{r}^{\,0} \cdot \vec{x}\right)\right) \mathrm{d}S, \tag{4}$$

where $\vec{E}^{\perp} = \vec{n} \times \vec{E}$, $\vec{H}^{\perp} = \vec{n} \times \vec{H}$, $\left(\vec{E}, \vec{H}\right)$ is the complete field; $\vec{n}$ is the ort of outer normal to the integration surface S that covers this object.

The surface S is chosen so that it coincided with the surface of an object everywhere except for the edges of fractures, where it proceeds along the toroidal surface of the circular cross section, "pulled" onto a fracture.

The surface could be represented as sum $S=S_1+S_0$, where S_1 coincides with the smooth surface sections, and S_0 is the totality of toroidal boundaries of edges. Thus, the integral in (4) is the sum of integrals along surfaces S_1 and S_0.

The field, scattered by smooth part of the surface of object S_1 in direction $\vec{r}^{\,0}$, could be represented as part of expression (4):

$$\vec{p}^{\,\text{ïδ}} \cdot \vec{E}_{S_1} = -jk_0 \frac{\exp\left(jk_0 R\right)}{4\pi R} \times$$
$$\times \int_{S_1} \left(\sqrt{\frac{\mu_0}{\varepsilon_0}} \left(\vec{p} \cdot \vec{H}^{\perp}\right) + \left(\vec{p} \times \vec{r}^{\,0}\right) \cdot \vec{E}^{\perp} \right) \exp\left(-jk_0\left(\vec{r}^{\,0} \cdot \vec{x}\right)\right) \mathrm{d}S. \tag{5}$$

The expression for the field, scattered by edge local scattering sections, could be represented in the form:

$$\vec{p}^{\,\text{ïδ}} \cdot \vec{E}_{S_0} = -jk_0 \sqrt{\frac{\mu_0}{\varepsilon_0}} \frac{\exp\left(jk_0 R\right)}{4\pi R} \left(\vec{p} \cdot \vec{F}\left(\vec{r}^{\,0}\right)\right), \tag{6}$$

where

$$\vec{F}(\vec{r}^{\,0}) = \int_{S_0} \left[\vec{H}^{\perp} - \sqrt{\frac{\varepsilon_0}{\mu_0}} \left(\vec{E}^{\perp} \times \vec{r}^{\,0}\right) \right] \exp\left(-jk_0\left(\vec{r}^{\,0} \cdot \vec{x}\right)\right) \mathrm{d}S.$$

The proposed basic estimation ratios (1) to (6) underlie the method for acquiring the radiolocation characteristics of an aircraft.

4. 3. Radiolocation characteristics of the Su-25 attack aircraft at different irradiation frequencies (wavelengths)

Calculation of scattering characteristics for the Su-25 AA was performed based on the following parameters:

– probing site angle – 3 degrees relative to the plane of the horizon (probing from the lower semi-sphere);

– a step of change in the probing azimuth is 0.02 degree; the azimuth is counted in degrees from the nasal angle of an aircraft (0 degrees is probing the nose, 180 degrees – probing the tail);

– polarization is horizontal.

The following RLC are given:

– pie charts of ESS and "non-coherent" ESS;

– average and median values for the instantaneous ESS for the main ranges of irradiation azimuths (nose is (0–45 degrees);

– side (45–135 degrees), tail (135–180 degrees);

– average and median values for the instantaneous EEs for twenty-degree ranges of irradiation azimuths.

A median value for ESS in a specific sector of irradiation angles is understood to be some non-random value of ESS, the probability of exceeding or not exceeding which in the assigned sector of angles is 0.5.

A "non-coherent" ESS (NESS) refers to the sum of ESS of the separate surface sections, which does not take into consideration the mutual phase shifts.

We give histograms for an amplitude multiplier of the reflected signal for different irradiation frequencies of the probing signal.

All of these characteristics are given for the case of compatible reception.

4. 3. 1. Radiolocation characteristics of the Su-25T model at irradiation frequency of 10 GHz (wavelength is 3 cm)

Fig. 3 shows a pie chart of ESS for the Su-25T AA model.

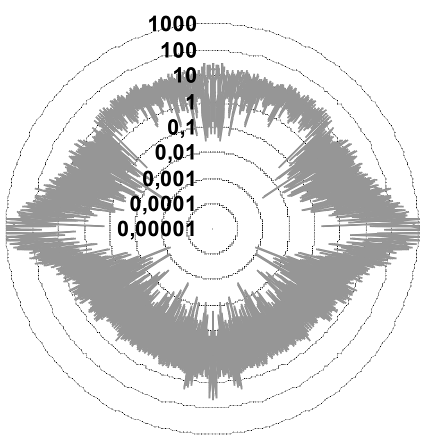

Fig. 3. Pie chart of effective scattering surface for the model of Su-25T anti-tank aircraft

Fig. 4 shows a pie chart of NESS for the Su-25T AA model.

An average ESS for the Su-25T AA model is 73.31 m^2. A circular median ESS (a value for ESS, which is used when calculating the detection range of an aircraft with a probability of 0.5) is 2.86 m^2.

Fig. 5 shows the average and median values of ESS for the basic ranges of irradiation azimuths (nose, side, tail).

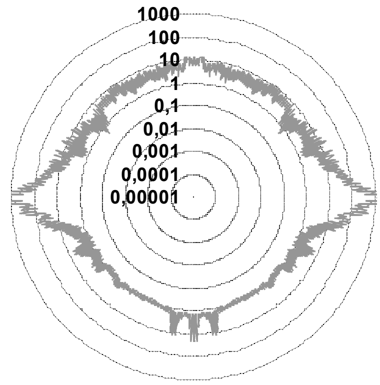

Fig. 4. Pie chart of the "non-coherent" effective scattering surface for the Su-25T anti-tank aircraft model

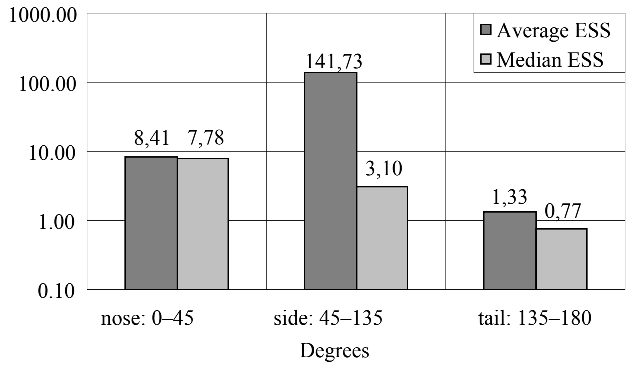

Fig. 5. Average and median values of effective scattering surface for the basic ranges of irradiation azimuths (nose, side, tail)

Fig. 6 shows the average and median values of ESS for ranges of 20 degrees.

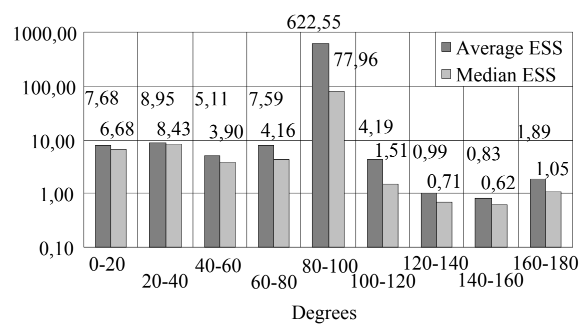

Fig. 6. Average and median values of effective scattering surface for the twenty-degree ranges of irradiation azimuths

Fig. 7 shows histogram of an amplitude multiplier (the square root of ESS) for the reflected signal for a range of irradiation azimuths of –20...+20 degrees (combat nasal angles). Bold line shows a density probability distribution function that could be used to approximate the histogram of the amplitude multiplier. In this case, the amplitude multiplier histogram could be approximated using the normal law of probability distribution with a density function:

$$p(x)=\frac{1}{\sqrt{2\pi}\,\sigma}\exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right), \tag{7}$$

where μ=2.566; σ=0.980.

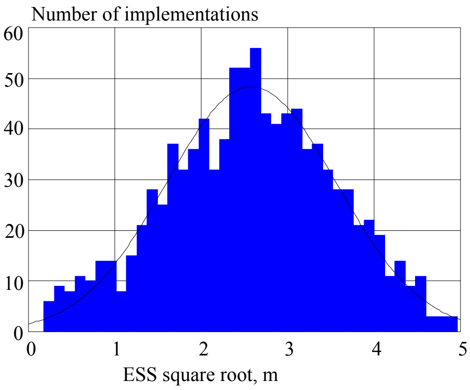

Fig. 7. Histogram of amplitude multiplier (the square root of the values for effective scattering surface) for the reflected signal

Hence, the radiolocation characteristics of the Su-25T model at irradiation frequency of 10 GHz (wavelength is 3 cm) are shown in Fig. 3–6. The patterns derived make up a radiolocation profile of the Su-25T anti-tank aircraft at a frequency of 10 GHz.

4. 3. 2. Radiolocation characteristics of the Su-25T attack aircraft at irradiation frequency of 1 GHz (wavelength is 30 cm)

Fig. 8 shows a pie chart of ESS for the Su-25T AA model.

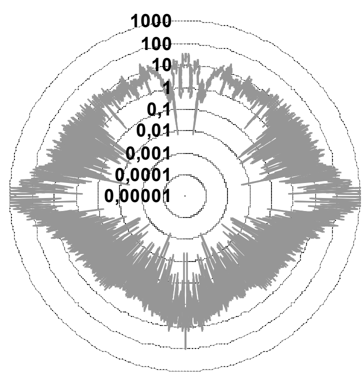

Fig. 8. Pie chart of effective scattering surface for the Su-25T anti-tank aircraft model

Fig. 9 shows a pie chart of NESS for the Su-25T AA model.

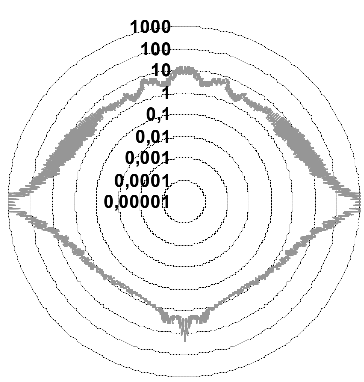

Fig. 9. Pie chart of the "non-coherent" effective scattering surface for the Su-25T anti-tank aircraft model

An average ESS for the Su-25T AA model is 55.13 m2; a circular median ESS is 2.66 m^2.

Fig. 10 shows the average and median values of ESS for the basic ranges of irradiation azimuths (nose, side, tail).

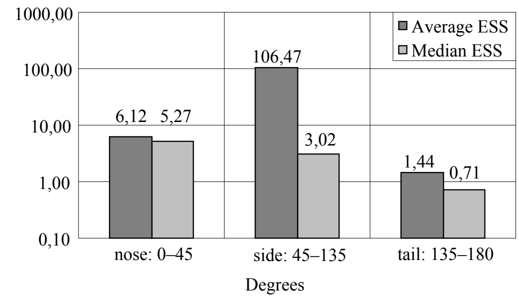

Fig. 10. Average and median values for the "non-coherent" effective scattering surface for the basic ranges of irradiation azimuths (nose, side, tail)

Fig. 11 shows the average and median values of ESS for ranges of 20 degrees.

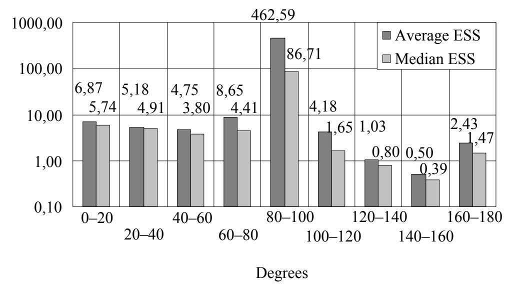

Fig. 11. Average and median value of effective scattering surface for the twenty-degree ranges of irradiation azimuths

Fig. 12 shows a histogram of an amplitude multiplier (the square root of ESS) for the reflected signal in the range of irradiation azimuths of –20...+20 degrees (combat nasal angles). Bold line shows a density probability distribution function that could be used to approximate the histogram of the amplitude multiplier. In this case, the amplitude multiplier histogram could be approximated by using the Weibull distribution with a density function:

$$p(x)=\frac{c}{b}\left(\frac{x}{b}\right)^{c-1}e^{-\left(\frac{x}{b}\right)^{c}}, \qquad (8)$$

where b=2.626; c=2.068.

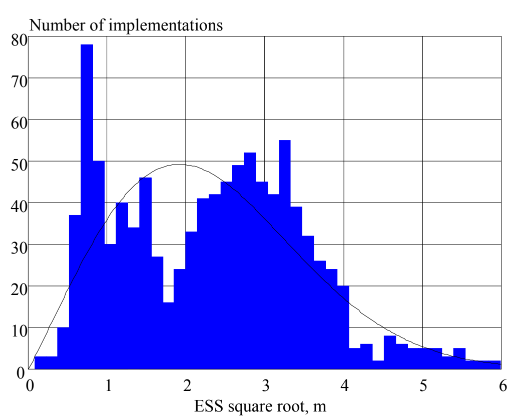

Fig. 12. Histogram of amplitude multiplier (the square root of the values for effective scattering surface) for the reflected signal

Thus, the radiolocation characteristics of the Su-25T model at irradiation frequency irradiation of 1 GHz (wavelength is 30 cm) are shown in Fig. 7–12. The patterns derived make up a radiolocation profile for the Su-25T anti-tank aircraft at a frequency of 1 GHz.

4. 3. 3. Radiolocation characteristics of the Su-25T attack aircraft at irradiation frequency of 166 MHz (wavelength is 1.8 m)

Fig. 13 shows a pie chart of ESS for the Su-25T AA model.

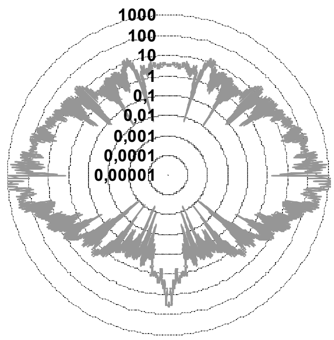

Fig. 13. Pie chart of effective scattering surface for the Su-25T anti-tank aircraft model

Fig. 14 shows a pie chart of NESS for the Su-25T AA.

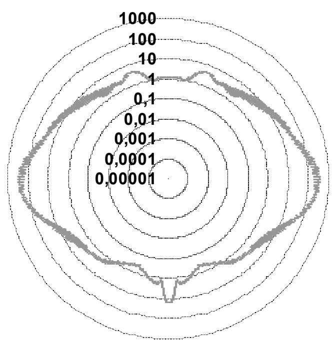

Fig. 14. Pie chart of the "non-coherent" effective scattering surface for the Su-25T anti-tank aircraft model

An average ESS of the Su-25T AA model is 53.88 m^2; a circular median ESS is 3.85 m^2.

Fig. 15 shows the average and median values of ESS for the basic ranges of irradiation azimuths (nose, side, tail).

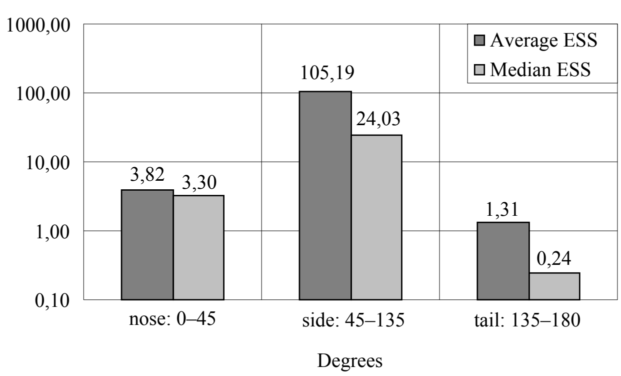

Fig. 15. Average and median values of effective scattering surface for the basic ranges of irradiation azimuths (nose, side, tail)

Fig. 16 shows the average and median values of ESS for ranges of 20 degrees.

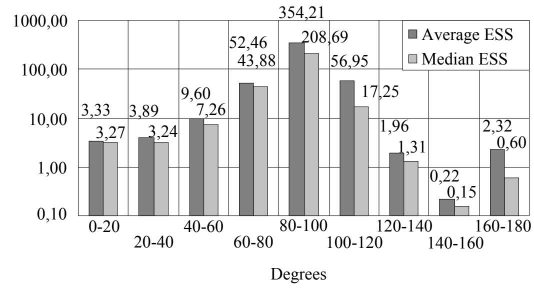

Fig. 16. Average and median values of effective scattering surface for the twenty-degree ranges of irradiation azimuths

Fig. 17 shows a histogram of an amplitude multiplier (the square root of ESS) for the reflected signal for a range of irradiation azimuths of –20...+20 degrees (combat nasal angles). Bold line shows a density probability distribution function that could be used to approximate the histogram of the amplitude multiplier. In this case, the amplitude multiplier histogram could be approximated using the normal law of probability distribution with a density function:

$$p(x)=\frac{1}{\sqrt{2\pi}\,\sigma}\exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right), \quad (9)$$

where μ=1.732; σ=0.980.

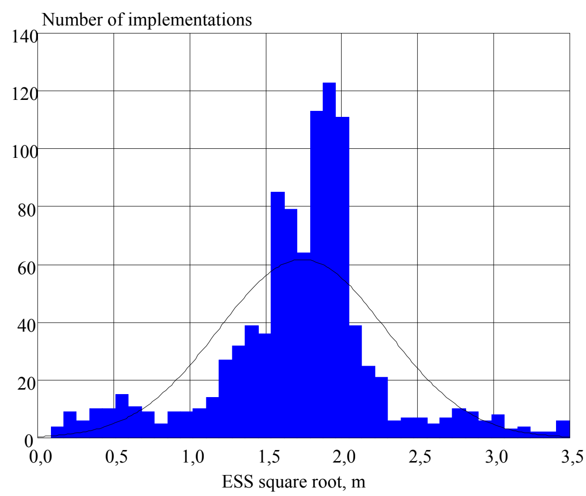

Fig. 17. Histogram of amplitude multiplier (the square root of the values for effective scattering surface) for the reflected signal

Hence, the radiolocation characteristics of the Su-25T model at irradiation frequency of 166 MHz (wavelength is 1.8 m) are shown in Fig. 13–17. The patterns derived make up a radiolocation profile for the Su-25T anti-tank aircraft at a frequency of 166 MHz.

5. Discussion of results of studying the characteristics of radiolocation scattering for the Su-25T anti-tank aircraft model at different wavelengths

We have proposed the model and substantiated the simulation principle, which made it possible to acquire radiolocation characteristics for the Su-25T anti-tank aircraft exposed to the irradiation by signals at different frequencies.

Typically, the evaluation of characteristics for the scattering of electromagnetic waves on complex bodies, which are partially covered with radio-absorbing materials, implies the consideration of geometric dimensions. It is shown that the radiolocation characteristics of such objects are significantly different from analogs of the corresponding geometric dimensions. However, still unresolved are the issues related to the construction of radiolocation profiles of flying objects. The reason for this could be the objective difficulties related to the lack of comprehensive consideration of the entire totality of prevailing factors. A variant to overcome respective difficulties could be the construction of mathematical models for the scattering of electromagnetic waves on complex bodies using elementary surfaces. This is exactly the approach employed in this work.

The advantage of the present study is the acquisition of scattering characteristics for the Su-25T anti-tank aircraft, based on the earlier constructed high-frequency calculation methods that comprehensively account for the entire totality of prevailing factors.

In the course of research, we built a model of the surface of the Su-25 attack aircraft, taking into consideration geometrical dimensions. The model is composed of smooth parts of the surface and the boundary local sections, and includes an antenna system, which is located under the nasal dielectric radome. However, modeling did not take into consideration the internal (an electromagnetic field of the aircraft when flying, due to the radiation of aviation equipment) and external (electromagnetic fields, which are induced by the interaction with the environment when flying) influences. These influences can be accounted for only in the course of a field experiment. Comparing the results from simulation and from experiment would make it possible to introduce appropriate changes to the proposed model.

Further development of this research could be the introduction of necessary changes to the proposed model and the principles of modeling taking into consideration (via theoretical substantiation) the internal and external influences on the radiolocation characteristics of aircraft at flight.

All this allows us to argue about the efficiency of detection and recognition of the aircraft.

Research into this area is expedient in order to build radiolocation profiles of military aircraft, including unmanned vehicles.

6. Conclusions

1. The result of this study is the constructed model of the surface of the Su-25T anti-tank aircraft. It is shown that it is necessary to split the surface of the plane into two groups: a smooth part of the surface and the edge local scattering sections. The smooth part of the aircraft surface was approximated using the sections of 63 triaxial ellipsoids. The surface fractures were simulated applying 31 direct local edge scattering sections.

2. A special feature of the proposed basic estimation ratios that underlie the method for obtaining the radiolocation characteristics of an aircraft is taking into consideration of the probing signal, which represents a flat monochromatic electromagnetic wave. That made it possible to select a model of the attack aircraft's surface so that the area coincided with the object's surface everywhere except in the vicinity of fractures that are accounted for separately. Thus, the modeled surface of the Su-25T anti-tank aircraft is the integrated sum of two planes: a smooth part of the aircraft surface, the surface of fractures.

3. We have established the features of influence exerted by irradiation (the centimeter, decimeter, meter ranges of wavelengths) on the analysis of radiolocation characteristics (a radiolocation profile) of the Su-25T attack aircraft. Thus, for a centimeter wavelength range, the average effective scattering surface of the Su-25T attack aircraft model is 73.31 m^2, while a circular median ESS is 2.86 m^2. For a decimeter range of irradiation wavelengths, the average ESS for the Su-25T attack aircraft model is 55.13 m^2, a circular median ESS is 2.66 m^2. At an irradiation in a meter wavelength range, the average ESS for the Su-25T attack aircraft model is 53.88 m^2, a circular median ESS is 3.85 m^2. In radiolocation, a value for the median ESS is applied when calculating the aircraft range detection with a probability of 0.5. Therefore, the results of our study show that the Su-25T anti-tank aircraft is most noticeable when irradiated with a radiolocation signal in a meter range. That demonstrates the feasibility of application of our research results.

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DEVELOPMENT OF THE PROCEDURE FOR FORMING NON-STATIONARY SIGNAL STRUCTURES BASED ON MULTICOMPONENT LFM SIGNALS

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Досліджено завадозахищеність існуючих радіоліній з шумоподібними сигналами та цифровими видами модуляції. Аналіз показує, що застосування таких сигналів в умовах радіоелектронного конфлікту не дозволяє забезпечити необхідний рівень показників завадостійкості та прихованості передавання радіоліній зв'язку. Встановлено, що причиною тому є наявність циклостаціонарності несучого коливання в сигналах з цифровими видами модуляції. Такі властивості спрощують виявлення та пошук сигналів за допомогою спектрально-кореляційних методів сучасних засобів радіоелектронної розвідки противника.

Для вирішення цієї проблеми запропоновано застосування нестаціонарних сигнальних конструкцій із змінною центральною частотою та спектральною щільністю потужності. Розроблено методику формування таких сигнальних конструкцій на основі процедури ортогоналізації Грама-Шмідта до ансамблю багатокомпонентних ЛЧМ сигналів з керованими спектральними характеристиками.

Запропоновано оцінювати різні структури сигнальних конструкцій багатокомпонентного сигналу по фазовим портретам сумарних сигналів в залежності від значень коефіцієнта масштабування. Визначено граничні значення цього коефіцієнта, при яких забезпечується ускладнення структури багатокомпонентного сигналу і запобігається виродження процесу в класичну ЛЧМ.

Проведено дослідження зміни ймовірності символьної помилки в каналі при використанні багатокомпонентних ортогональних сигнальних конструкцій в залежності від співвідношення сигнал/шум. Це дозволяє оцінити потенційну завадостійкість радіолінії за умови, що співвідношення сигнал/шум визначається за енергетичними показниками радіоканалу та спектральною щільністю шумів природного походження.

Структурна прихованість розроблених сигнальних конструкцій оцінювалася за допомогою енергетичного детектора і детектора циклостаціонарності. Встановлено, що при енергетичному детектуванні нестаціонарні сигнали, як і сигнали з будь-яким іншим видом модуляції, еквівалентні. Проте, при використанні детектора циклостаціонарності ймовірність виявлення нестаціонарних сигнальних конструкцій зменшується в 2–2,5 рази в порівнянні з іншими видами модуляції сигналів

Ключові слова: нестаціонарні багатокомпонентні сигнальні конструкції, ортогоналізація Грама-Шмідта, циклостаціонарність несучого коливання, структурна прихованість

1. Introduction

Broadband signals (BBS) are used in communication lines to provide structural and parametric security. Such signals are formed by direct-sequencing spread spectrum (DSSS) and/or frequency hopping spread spectrum (FHSS) [1, 2]. Various types of digital-frequency modulation (DFM) are used in BBS formation: amplitude, phase, frequency or combined modulation. However, the abovementioned modulation methods have a common disadvantage: cyclo-sta-