Development of regression mathematical models of distortion of the radar information situation with the help of corner reflectors

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Abstract
A 3-D model of corner reflectors of various types and sizes was built on the basis of the analysis of the results of mathematical modeling using the CST Studio automatic decision-making system. As a result of the simulation, the numerical values of the parameters of the effective scattering area were determined, which made it possible to clarify the dependence of the relative change of the effective scattering area of corner reflectors on the shape of the rib, to confirm the hypothesis regarding the quadratic dependence of the effective scattering area on the radiation frequencies. A comparative analysis of the modeling results allowed us to conclude that for different observation angles, the effective scattering area of a small-angle reflector corresponds on average to the effective scattering area of a Mi-8T helicopter. It was also established that large corner reflectors with a rib size of 120 cm are the most appropriate for simulating fighter jets. At the same time, the weight of the corner reflector needs to be significantly reduced, which becomes possible when using light materials, such as foam plastic, which is pasted over with foil of the appropriate thickness. Electrodynamic modeling was confirmed by an experiment in an anechoic chamber. As a direction of further research, conducting experiments on changing the parameters of the effective scattering area of corner reflectors depending on a number of controlled factors was chosen.

Key words: indicator, criterion, passive means of imitation, radio technical means, distortion, radar informative situation.

Introduction

One of the effective methods of misleading the enemy during hostilities is the use of means of simulating heterogeneous physical fields of real objects. At the same time, this method is used to simulate objects on any surfaces and natural backgrounds. Various models of weapons and military equipment are designed to simulate the shape, radar and thermal features, sound parameters, etc. This is due to the fact that the enemy today conducts comprehensive reconnaissance by various means in order to obtain reliable information about objects on the battlefield. One of the most difficult issues in the field of camouflage turned out to be the imitation of radar fields of ground, sea or air objects. For this purpose, corner reflectors of various sizes, shapes and operating principles are used [1]. The use of corner reflectors, on the one hand, showed a fairly high efficiency for distorting the radar informative situation, and on the other hand, caused an additional need for theory and practice regarding the scientific substantiation of rational parameters and methods of their use.

Material and methods

The raised problematic issue was raised and highlighted in a sufficient number of scientific studies and publications [2-17]. In particular, [2-4] is dedicated to highlighting the theoretical foundations of the construction and application of reconnaissance and control information systems of air defense, radio automation, as well as the design of receiving and amplifying devices. In [5, 6], the scattering characteristics of air and ground radar objects are considered and a method of calculating the radiation characteristics of two-mirror antennas with mirrors of resonant dimensions of finite thickness and conductivity is given. [7] presents a software product in the form of an asymptotic solver used for electrodynamic modeling in the frequency domain and based on physical optics. [8-10] is devoted to the explanation of the basics of antenna theory, an analysis of the parameters and shape of different types of antennas is carried out, the results of the development of axially symmetric antennas with a double reflector from a combination of given geometric parameters are considered, and the development of broadband directional two-reflector antennas in millimeter waves is proposed. [11-14] proposed the design of offset double reflector antennas to improve the level of isolation between the transmitter and receiver antennas, omnidirectional double reflector antennas with an arbitrary direction of the main beam in the plane of the site by connecting conical sections, conducted a quasi-optical analysis of the microwave antenna system with a double reflector. In [15], distorted reflector antennas are considered, the results of the analysis of the directional pattern and polarization characteristics are given. At the same time, [16] is devoted to the measurement of backscattering for metal open-ended spherical screens, and [17] presents the results of modeling the scattering of ultra-broadband pulses by air and subsurface resonant objects based on the solution of integral equations. Research [18] is devoted to obtaining the results of mathematical modeling, during which the value of the effective scattering surface of the model of the Su-27 aircraft and trihedral corner reflectors in the high-frequency range of wavelengths was obtained. The characteristics of the secondary radiation of trihedral corner reflectors, which are used as the main scattering element of the proposed radar airborne false target of towed tactical aircraft, are evaluated.

The obtained results of previous studies are quite significant and it is expedient to use them at the stage of substantiation of requirements for false targets to simulate the secondary radiation of various complex objects, which use corner reflectors as a reflective element. But it should be noted that the issue of modeling the use of passive means of imitation to distort the radar informative situation in the previous available studies is not fully covered.

Problem statement

Therefore, in order to solve the raised problematic issue, as well as to solve inconsistencies in the theory regarding possible ways of distorting the radar information situation, it is necessary to carry out modeling and determine the parameters of corner reflectors. Highlighting the results of modeling the use of passive means of imitation to distort the radar informative situation is the purpose of this article.

Results

Distortion of the radar environment with the help of corner reflectors, as was established above, depends on some extent on the location of the emitting and receiving antennas. The power of the reflected signal from the corner reflector to some extent depends on the main determining factors, among which the most important place is occupied by the ESR of the object of irradiation. Therefore, it is of interest to establish the dependence of the EPR of corner reflectors on their shape and size, the angle of irradiation and the signal frequency.

The research was carried out according to the above method of multifactorial experiment. As an indicator of the effectiveness of the distortion of the radar environment with the help of corner reflectors, the value of the relative EPR based on the power of the reflected signal, which is reradiated from the corner reflector, was taken. An experimental study was conducted to obtain the specified functions.

To conduct the research, a matrix of a non-composite plan of the experiment was chosen for two indicators: y_2 – relative EPR according to the power of the reflected signal from the eight-cell corner reflector of a rectangular shape, ($\sigma_{прям}$, dB·m ^{2}); y_2 – relative EPR according to the power of the reflected signal from the eight-cell corner reflector of a pyramidal shape, ($\sigma_{пір}$, dB·m ^{2}).

There are three most important factors for both indicators: x_1 – the frequency of the probing signal (*f*, GHz); x_2 – irradiation angle (*α*, deg.); x_3 is the length of the face of the corner reflector (*a*, cm).

The processing allowance is accepted as the optimization parameters. On the basis of a priori information, equal intervals of factor variation were chosen. Levels and intervals of variation of factors are given in table 1.

Table 1 – Levels and intervals of factor variation

Marking	Name	Dimensionality	Variation interval	The value of factors according to the levels of variation		
				-1	0	+1
X_1	frequency of the probing signal (*f*)	GHz	2	3	5	7
X_2	irradiation angle (α)	hail.	22.5	0	22.5	45
X_3	length of the face of the corner reflector (α)	see	15	30	45	60

Experimental data for y_1 – *relative EPR according to the power of the reflected signal from an eight-cell rectangular reflector*, the matrix of the experimental plan is given in Table 2.

Table 2 – Experiment planning matrix

Experiment number	X_0	X_1	X_2	X_3	$X_1 X_2$	$X_1 X_3$	$X_2 X_3$	X_1^2	X_2^2	X_3^2	Y_1
1	+	+	+	0	+	0	0	+	+	0	300.6
2	+	+	–	0	–	0	0	+	+	0	423.3
3	+	–	+	0	–	0	0	+	+	0	55.3
4	+	–	–	0	+	0	0	+	+	0	77.9
5	+	0	0	0	0	0	0	0	0	0	188.1
6	+	+	0	+	0	+	0	+	0	+	850
7	+	+	0	–	0	–	0	+	0	+	71.9
8	+	–	0	+	0	–	0	+	0	+	311.8
9	+	–	0	–	0	+	0	+	0	+	132
10	+	0	0	0	0	0	0	0	0	0	185.1
11	+	0	+	+	0	0	+	0	+	+	485.6
12	+	0	+	–	0	0	–	0	+	+	30.4
13	+	0	–	+	0	0	–	0	+	+	584
14	+	0	–	–	0	0	+	0	+	+	142.8
15	+	0	0	0	0	0	0	0	0	0	199.1

The regression equation has the form:

$$y_1 = b_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_{12} x_1 x_2 + b_{13} x_1 x_3 + b_{23} x_2 x_3 + b_{11} x_1^2 + b_{22} x_2^2 + b_{33} x_3^2$$

Determination of model coefficients:

$$b_0 = 190.7667$$
$$b_1 = 133.6$$
$$b_2 = -44.5125$$
$$b_3 = 231.7875$$
$$b_{12} = -25{,}025$$
$$b_{13} = 149{,}575$$
$$b_{23} = 3.5$$
$$b_{11} = 27.11667$$
$$b_{22} = -3.60833$$
$$b_{33} = 123.5417$$

The variance of S_y^2 the optimization parameter is found based on the results of experiments in the center of the plan (Table 2 experiments 5, 10, 15). To calculate the variance, we compile an auxiliary table. 3.

Table 3 – Auxiliary table for variance calculation S_y^2

Experiment number in the center of the plan	y	$\bar{y}$	$y-\bar{y}$	$(y-\bar{y})^2$
5	188.1	190.7667	-2.66667	7.11111
10	185.1		-5.66667	32.1111111
15	199.1		8.333333	69.4444444

$$S_E = (y_5 - \bar{y}_{5,10,15})^2 + (y_{10} - \bar{y}_{5,10,15})^2 + (y_{15} - \bar{y}_{5,10,15})^2 = 108.6667$$

$$s^2\{y_z\} = \frac{S_E}{3-1} = 54.33333$$

The variance of the regression coefficients will be:

$$s^2\{b_0\} = \frac{1}{3} s_y^2 = 18.29957$$

$$s^2\{b_i\} = \frac{1}{8} s_y^2 = 11.20616$$

$$s^2\{b_{il}\} = \frac{1}{4} s_y^2 = 15.8479$$

$$s^2\{b_{ii}\} = \frac{13}{48} s_y^2 = 16.49501$$

According to the regression equation, all coefficients are calculated using the method of least squares. To do this, we compile a system of normal equations:

$$15b_0 + 0b_1 + 0b_2 + 0b_3 + 0b_{12} + 0b_{13} + 0b_{23} + 8b_{11} + 8b_{22} + 8b_{33} = 4037.9$$
$$0b_0 + 8b_1 + 0b_2 + 0b_3 + 0b_{12} + 0b_{13} + 0b_{23} + 0b_{11} + 0b_{22} + 0b_{33} = 1068.8$$

$$0b_0+0b_1+8b_2+0b_3+0b_{12}+0b_{13}+0b_{23}+0b_{11}+0b_{22}+0b_{33}=\text{-356.1}$$
$$0b_0+0b_1+0b_2+8b_3+0b_{12}+0b_{13}+0b_{23}+0b_{11}+0b_{22}+0b_{33}=1854.3$$
$$0b_0+0b_1+0b_2+0b_3+4b_{12}+0b_{13}+0b_{23}+0b_{11}+0b_{22}+0b_{33}=\text{-100.1}$$
$$0b_0+0b_1+0b_2+0b_3+0b_{12}+4b_{13}+0b_{23}+0b_{11}+0b_{22}+0b_{33}=598.3$$
$$0b_0+0b_1+0b_2+0b_3+0b_{12}+0b_{13}+4b_{23}+0b_{11}+0b_{22}+0b_{33}=14$$
$$8b_0+0b_1+0b_2+0b_3+0b_{12}+0b_{13}+0b_{23}+8b_{11}+4b_{22}+4b_{33}=2222.8$$
$$8b_0+0b_1+0b_2+0b_3+0b_{12}+0b_{13}+0b_{23}+4b_{11}+8b_{22}+4b_{33}=2099.9$$
$$8b_0+0b_1+0b_2+0b_3+0b_{12}+0b_{13}+0b_{23}+4b_{11}+4b_{22}+8b_{33}=2608.5$$

After calculating this system of equations, we get the following coefficients:

$$b_0=188.5462$$
$$b_1=133.6$$
$$b_2=\text{-44.5125}$$
$$b_3=231.7875$$
$$b_{12}=\text{-25,025}$$
$$b_{13}=149{,}575$$
$$b_{23}=3.5$$
$$b_{11}=27.39423$$
$$b_{22}=\text{-3.60833}$$
$$b_{33}=123.8192$$

The regression equation for will take the form:

$$y=188{,}5462+133{,}6x_1-44{,}5125x_2+231{,}7875x_3-25{,}025x_1x_2+149{,}575x_1x_3+\\-3{,}5x_2x_3+27{,}39423x_1^2-3{,}60833x_2^2+123{,}8192x_3^2$$

We check the adequacy of the obtained model according to *F* the criterion. To calculate the $S^2_{ад}$ adequacy variance, we find the sum S_R of the squares of the deviations of the calculated values $\hat{y}_a$ from the experimental values y_a at all points of the plan (table 4).

Table 4 – Auxiliary table for calculating the sum of squared deviations of calculated values S_R

Experiment number	$\hat{y}_a$	y_a	y_a - y_a	$(y_a - y_a)^2$
1	300.6	278.6151	21.98494	483.3374064
2	423.3	417.6901	5.609936	31.47138077
3	55.3	61.46506	-6.16506	38.00801539
4	77.9	100.4401	-22.5401	508.0544897
5	188.1	190.7667	-2.66667	7.111111111
6	850	856.9426	-6.94263	48,20008639
7	71.9	94.21763	-22.3176	498.0765287
8	311.8	290.5926	21.20737	449.7526184
9	132	126.1676	5.832372	34.01656075
10	185.1	190.7667	-5.66667	32.11111111
11	485.6	498.0026	-12.4026	153.8235963
12	30.4	34.92756	-4.52756	20.4988367

13	584	587.5276	-3.52756	12.4437085
14	142.8	123.4526	19.34744	374.3232758
15	199.1	190.7667	8.333333	69.44444444

$$s_R = \sum (y_z - \hat{y}_z)^2 = 2760.67$$

We find the variance of adequacy

$$s_{ad}^2 = \frac{s_R - s_E}{N - k' - (n_0 - 1)} = 884.002168$$

The calculated value *F* is a criterion.

$$F_p = \frac{s_{ad}^2}{s^2\{y_z\}} = 16,2699786 < F_T = 19,3$$

Therefore, the obtained mathematical model (2) is adequate at the 5% level of significance as $F_p < F_T$.

Experimental data for y_2 *– relative EPR according to the power of the reflected signal from the eight-cell corner reflector of a pyramidal shape*, the matrix of the experimental plan is given in table 5.

Table 5 – Experiment planning matrix

Experiment number	X_0	X_1	X_2	X_3	$X_1 X_2$	$X_1 X_3$	$X_2 X_3$	X_1^2	X_2^2	X_3^2	Y_2
1	+	+	+	0	+	0	0	+	+	0	30.2
2	+	+	–	0	–	0	0	+	+	0	46.8
3	+	–	+	0	–	0	0	+	+	0	6.1
4	+	–	–	0	+	0	0	+	+	0	8.6
5	+	0	0	0	0	0	0	0	0	0	22.8
6	+	+	0	+	0	+	0	+	0	+	127.2
7	+	+	0	–	0	–	0	+	0	+	7.9
8	+	–	0	+	0	–	0	+	0	+	23.4
9	+	–	0	–	0	+	0	+	0	+	21.5
10	+	0	0	0	0	0	0	0	0	0	20.6
11	+	0	+	+	0	0	+	0	+	+	53.7
12	+	0	+	–	0	0	–	0	+	+	3,4
13	+	0	–	+	0	0	–	0	+	+	55.6
14	+	0	–	–	0	0	+	0	+	+	4.7
15	+	0	0	0	0	0	0	0	0	0	13.6

The regression equation has the form:

$$y_2 = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2$$

Determination of model coefficients:

$$b_0 = 19$$
$$b_1 = 19.0625$$

$$b_2 = \text{-}2.7875$$
$$b_3 = 27.8$$
$$b_{12} = \text{-}3.525$$
$$b_{13} = 29.35$$
$$b_{23} = \text{-}0.15$$
$$b_{11} = 9.7875$$
$$b_{22} = \text{-}5.8625$$
$$b_{33} = 16.2125$$

The variance of S_y^2 the optimization parameter is found based on the results of experiments in the center of the plan (Table 2 experiments 5, 10, 15). To calculate the variance, we compile an auxiliary table. 6.

Table 6 – Auxiliary table for variance calculation S_y^2

Experiment number in the center of the plan	y	$\bar{y}$	$y - \bar{y}$	$(y - \bar{y})^2$
5	22.8	19	3.8	14.44000
10	20.6		1.6	2.56
15	13.6		-5.4	29,16

$$S_E = (y_5 - \bar{y}_{5,10,15})^2 + (y_{10} - \bar{y}_{5,10,15})^2 + (y_{15} - \bar{y}_{5,10,15})^2 = 46,16$$
$$s^2\{y_z\} = \frac{S_E}{3-1} = 23.08$$

The variance of the regression coefficients will be:

$$s^2\{b_0\} = \frac{1}{3} s_y^2 = 11.92685$$
$$s^2\{b_i\} = \frac{1}{8} s_y^2 = 7.303674$$
$$s^2\{b_{il}\} = \frac{1}{4} s_y^2 = 10.32895$$
$$s^2\{b_{ii}\} = \frac{13}{48} s_y^2 = 10.75072$$

According to the regression equation, all coefficients are calculated using the method of least squares. To do this, we compile a system of normal equations:

$$15b_0 + 0b_1 + 0b_2 + 0b_3 + 0b_{12} + 0b_{13} + 0b_{23} + 8b_{11} + 8b_{22} + 8b_{33} = 446.1$$
$$0b_0 + 8b_1 + 0b_2 + 0b_3 + 0b_{12} + 0b_{13} + 0b_{23} + 0b_{11} + 0b_{22} + 0b_{33} = 152.5$$
$$0b_0 + 0b_1 + 8b_2 + 0b_3 + 0b_{12} + 0b_{13} + 0b_{23} + 0b_{11} + 0b_{22} + 0b_{33} = \text{-}22.3$$
$$0b_0 + 0b_1 + 0b_2 + 8b_3 + 0b_{12} + 0b_{13} + 0b_{23} + 0b_{11} + 0b_{22} + 0b_{33} = 222.4$$
$$0b_0 + 0b_1 + 0b_2 + 0b_3 + 4b_{12} + 0b_{13} + 0b_{23} + 0b_{11} + 0b_{22} + 0b_{33} = \text{-}14.1$$
$$0b_0 + 0b_1 + 0b_2 + 0b_3 + 0b_{12} + 4b_{13} + 0b_{23} + 0b_{11} + 0b_{22} + 0b_{33} = 117.4$$
$$0b_0 + 0b_1 + 0b_2 + 0b_3 + 0b_{12} + 0b_{13} + 4b_{23} + 0b_{11} + 0b_{22} + 0b_{33} = \text{-}0.6$$
$$8b_0 + 0b_1 + 0b_2 + 0b_3 + 0b_{12} + 0b_{13} + 0b_{23} + 8b_{11} + 4b_{22} + 4b_{33} = 271.7$$

$$8b_0 + 0b_1 + 0b_2 + 0b_3 + 0b_{12} + 0b_{13} + 0b_{23} + 4b_{11} + 8b_{22} + 4b_{33} = 209.1$$

$$8b_0 + 0b_1 + 0b_2 + 0b_3 + 0b_{12} + 0b_{13} + 0b_{23} + 4b_{11} + 4b_{22} + 8b_{33} = 297.4$$

After calculating this system of equations, we get the following coefficients:

$$b_0 = 15.39231$$
$$b_1 = 19.0625$$
$$b_2 = -2.7875$$
$$b_3 = 27.8$$
$$b_{12} = -3.525$$
$$b_{13} = 29.35$$
$$b_{23} = -0.15$$
$$b_{11} = 10.23846$$
$$b_{22} = -5.8625$$
$$b_{33} = 16.66346$$

The regression equation for will take the form:

$$y_2 = 15{,}39231 + 19{,}0625x_1 - 2{,}7875x_2 + 27{,}8x_3 - 3{,}525x_1x_2 + 29{,}35x_1x_3 + \\ - 0{,}15x_2x_3 + 10{,}23846x_1^2 - 5{,}8625x_2^2 + 16{,}66346x_3^2$$

We check the adequacy of the obtained model according to *F* the criterion. To calculate the $S^2_{ад}$ adequacy variance, we find the sum S_R of the squares of the deviations of the calculated values $\hat{y}_a$ from the experimental values y_a at all points of the plan (table 7).

Table 7 – Auxiliary table for calculating the sum of squared deviations of calculated values S_R

Experiment number	$\hat{y}_a$	y_a	y_a - y_a	$(y_a - y_a)^2$
1	30.2	36.12596	-5.92596	35,11702016
2	46.8	48.75096	-1.95096	3.806250925
3	6.1	5.050962	1.049038	1.100481694
4	8.6	3.575962	5.024038	25.24096246
5	22.8	19	3.8	14.44
6	127.2	122,1144	5.085577	25.86309264
7	7.9	7.814423	0.085577	0.00732341
8	23.4	25.28942	-1.88942	3.569919564
9	21.5	28.38942	-6.88942	47.46415033
10	20.6	19	1.6	2.56
11	53.7	54.56346	-0.86346	0.745565828
12	3,4	-0.53654	3.936538	15.49633506
13	55.6	60.63846	-5.03846	25.38609467
14	4.7	4.538462	0.161538	0.026094675
15	13.6	19	-5.4	29,16

$$s_R = \sum (y_z - \hat{y}_z)^2 = 229{,}983$$

We find the variance of adequacy

$$s^2_{ad} = \frac{s_R - s_E}{N - k' - (n_0 - 1)} = 61.2744305$$

The calculated value *F* is a criterion.

$$F_p = \frac{s^2_{ad}}{s^2\{y_z\}} = \quad 2{,}65487134 \quad < F_T = 19{,}3$$

Therefore, the obtained mathematical model (2) is adequate at the 5% level of significance as $F_p < F_T$.

An autonomous Python script based on the method of least squares was used to process statistical information obtained experimentally.

Conclusions

Therefore, the performed mathematical modeling made it possible to specify the dependence of the relative change of EPR KV on the shape of the edge, to confirm the hypothesis regarding the quadratic dependence of EPR on radiation frequencies.

A comparative analysis of the modeling results allowed us to conclude that for different observation angles the EPR of a small KV varies from 0.2 to 140 m ^{2} (on average 20...40 m ^{2}), which corresponds to the EPR of a Mi-8T helicopter.

It was also established that the most appropriate for simulating fighter jets are large KVs with a rib size of 120 cm. At the same time, the weight parameters of this KV need a significant reduction, which becomes possible when using light materials (for example: foam plastic), which is pasted over with foil, approximately 20 microns.

Electrodynamic modeling was confirmed by an experiment in an anechoic chamber of the radio engineering faculty of Igor Sikorsky Kyiv Polytechnic Institute.

In the future, there is a need to highlight the results of experimental studies regarding the change of EPR parameters depending on low controlled factors.

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