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DECISIVE RULE EXPERIMENTAL STUDIES TO DETECT OBJECTS ON THE BACKGROUND OF THE EARTH SURFACE USING POLARIZATION DIFFERENCES OF RADAR SIGNALS

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Abstract: The task of stationary and moving object detection against the background of the underlying surface (earth) by radar means becomes relevant. A decision rule is being developed to detect objects against the background of the earth surface using the polarization differences reflected from the earth and the objects of radar signals, represented as a measurement vector. **Methods:** They carry out the experimental studies of the decision function using the data of a full-scale experiment with radar sensing of a piece of land with various objects on it. They provide the numerical values of the information sign obtained estimates used in the decision rules and decision making quality indicators. **Results:** Experimental studies have shown that the developed decision rule allows detecting inhomogeneities (objects) on the earth surface with a correct detection probability of 0.95%, with the first-type probability of 10-4. **Conclusion:** The experimental studies, using field data, confirm the high quality indicators of the developed decision rule.

Keywords: decisive function; estimation; detection; polarization; experimental studies; vector; covariance matrix.

I. INTRODUCTION

The task of stationary and moving object detection against the background of the underlying surface (earth) by radar means becomes relevant. Radar can be located on the ground or on some carrier (aircraft or unmanned aerial vehicle). To detect objects, it is necessary to use the differences in the properties of the reflected signals from the objects and the underlying surface. The signals reflected from the object are determined by the secondary radiation of the currents induced on the object elements. The polarization properties of such signals depend on the object shape, its electrical properties (dielectric and magnetic permeability and conductivity), the size of its individual elements relative to the wavelength, the location of its elements in the picture plane relative to the radar basis [1]. Radars made in the form of polarization meters receive a signal on two channels simultaneously that are orthogonal by polarization. At that, the signal is first emitted at one polarization, and the signal reflected from the object is received on two channels orthogonal by polarization. Then the second signal is emitted, orthogonal in polarization to the first one, and after reflection from the object it is also received on two channels simultaneously [2]. The signal amplitudes and phases at the output of the receiving channels will be proportional to the complex amplitudes of the signals reflected from the objects. The results of such a measurement can be presented in the form of a complex measurement vector [3]:

$$\dot{\vec{\mathbf{U}}}_i = \left(\dot{U}_{11}(t_i)\ \dot{U}_{21}(t_i)\ \ \dot{U}_{22}(t_i)\right)^T \quad (1)$$

where the first index denotes the emitted polarization, the second index denotes the taken polarization.

The samples of the received signals are recorded at discrete time points of measurements, i= 1…N.

II. METHOD AND MATERIAL

The principle of decision making about the presence of stationary objects on the earth surface under the conditions of complete a priori uncertainty is based on the determination of differences in the probabilistic characteristics of the reflected signal from a homogeneous portion of the earth surface and from a similar portion of the earth surface, the uniformity of which is disturbed by the presence of an object on it. The decision making procedure about the absence of fixed objects on the earth surface under the conditions of complete a priori uncertainty consists in validity check of the hypothesis - the reflections on the analysed site and on the compared surrounding earth surface are homogeneous.

If the radar data contradicts this hypothesis, then it is rejected, i.e. a decision is made on the pres-ence of an object that violates the uniformity of reflections.

At that the following errors are possible:

1) the errors of the first kind, when this hypothesis is rejected erroneously (in fact, it is true);

2) the errors of the second kind, erroneous acceptance of the hypothesis H0, if it is incorrect.

A geometric illustration of the measurement data obtaining and processing procedure is shown on Fig. 1. Here - the total number of pixels of the radio image under study (white area), - the number of pixels of the radio image fragment used to evaluate the characteristics of the background reflection (light gray area), - the number of pixels in the radio image fragment being analysed for object detection (dark gray area).

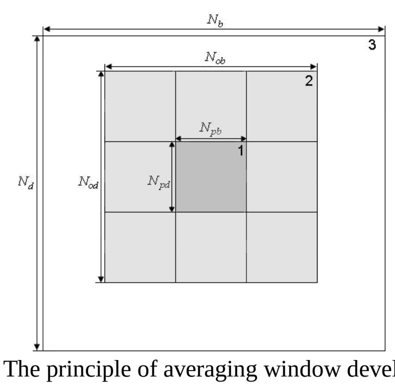

Fig. 1: The principle of averaging window development

Within the framework of statistical solution theory, it is shown that all types of decision rules are based on the crucial function L development and its comparison with a certain threshold, the value of which is determined by the selected quality criterion [4].

$$L = \frac{W_1(U_{1n})}{W_0(U_{0n})} \begin{cases} >= h_\alpha & \text{hypothesis } H_0 \text{ is rejected} \\ < h_\alpha & \text{hypothesis } H_0 \text{ adopted} \end{cases} \quad (2)$$

Where, $W_0(U_{on})$, $W_1(U_{1n})$- probability densities of random variable sample values corresponding to the acceptance and non-acceptance of the hypothesis H0, respectively.

Under the conditions of complete a priori uncertainty, instead of the expectation vector and the covariance matrix, only their estimates can be used [5]:

$$\dot{\vec{\boldsymbol{\mu}}} = (\dot{\mu}_1, \dot{\mu}_2, \dot{\mu}_3)^T = \frac{1}{N}\sum_{i=1}^{N} \dot{\vec{\mathbf{U}}}_i \quad (3)$$

where N is the volume of the averaged sample of vectors $\dot{\vec{\mathbf{U}}}_i$.

The estimate of the covariance matrix in the complex unitary space for the selection of vectors is determined according to the following expression:

$$\hat{\dot{\mathbf{R}}} = \{\dot{R}_{kn}\} = \frac{1}{N-1}\sum_{i=1}^{N}\left(\dot{\vec{\mathbf{U}}}_i - \dot{\vec{\boldsymbol{\mu}}}\right)\left(\dot{\vec{\mathbf{U}}}_i - \dot{\vec{\boldsymbol{\mu}}}\right)^{*T}, k,n = 1,..,3 \quad (4)$$

Here and hereinafter * is the sign of complex conjugation.

The expressions for the probability densities of sample values of the reflected signal vectors, cor-responding to the acceptance and non-acceptance of the hypothesis H0, can be written accordingly as [6]:

$$W_{0'}(\dot{\vec{\mathbf{U}}}_i) = \frac{1}{(2\pi)^N\left(\det\hat{\dot{\mathbf{R}}}_{оф}\right)^N}\exp\left[-\frac{1}{2}(\dot{\vec{\mathbf{U}}}_i - \dot{\vec{\mu}}_{оф})^{*T}\hat{\dot{\mathbf{R}}}_{оф}^{-1}(\dot{\vec{\mathbf{U}}}_i - \dot{\vec{\mu}}_{оф})\right]$$

$$W_{1'}(\dot{\vec{\mathbf{U}}}_i) = \frac{1}{(2\pi)^N\left(\det\hat{\dot{\mathbf{R}}}_{уа}\right)^N}\exp\left[-\frac{1}{2}(\dot{\vec{\mathbf{U}}}_i - \dot{\vec{\mu}}_{уа})^{*T}\hat{\dot{\mathbf{R}}}_{уа}^{-1}(\dot{\vec{\mathbf{U}}}_i - \dot{\vec{\mu}}_{уа})\right] \quad (5)$$

Where, $\dot{\vec{\boldsymbol{\mu}}}_{оф}$, $\dot{\vec{\boldsymbol{\mu}}}_{уа}$, $\hat{\dot{\mathbf{R}}}_{оф}$, $\hat{\dot{\mathbf{R}}}_{уа}$ - the estimates of the expectation vectors and the covariance matrices of the bordering fragment and the analysis section, respectively.

The probability density function is Gaussian, since the measurements are influenced by a large number of independent random factors, each of which has only a small effect [7].

In this case, the decision rule is to calculate the decision function

$$L = \left(\frac{\det \hat{\dot{\mathbf{R}}}_{o\phi}}{\det \hat{\dot{\mathbf{R}}}_{ya}} \right)^{Kya} \exp\left\{ \sum_{i=1}^{K_{ya}} \left(\left(\dot{\mathbf{U}}_{i,ya} - \dot{\mu}_{\text{оф}} \right)^{*\mathrm{T}} \hat{\dot{\mathbf{R}}}_{o\phi}^{-1} \left(\dot{\mathbf{U}}_{i,ya} - \dot{\mu}_{\text{оф}} \right) - \left(\dot{\mathbf{U}}_{i,ya} - \dot{\boldsymbol{\mu}}_{\text{ya}} \right)^{*\mathrm{T}} \hat{\dot{\mathbf{R}}}_{ya}^{-1} \left(\dot{\mathbf{U}}_{i,ya} - \dot{\boldsymbol{\mu}}_{\text{ya}} \right) \right) / 2 \right\} \quad (6)$$

and compare it with the threshold hα to decide on the presence (the hypothesis H_0) or the absence of object heterogeneity on the earth surface.

The main feature of this decisive function is that the evaluation of the control sample distribution parameters is carried out within the limits of the radio image fragment being analysed to detect heterogeneity. The evaluation of the distribution parameters for the H0 hypothesis is carried out within the radio image fragment bordering the analysis area during the meter scanning period [8]. Thus, the training and the control samples are formed in the process of the radar view sector scanning.

When they calculate the threshold value, the Neumann – Pyrsson criterion is used, since there is no a priori information about the probabilities of states and losses during decision making.

The level of reaction to heterogeneity characterizes the potential for the detection of objects with-in the proposed procedures.

III. RESULTS

The studies were conducted using field data, with remote sensing of the earth surface by radar within the area of several square kilometres, on which various buildings were located. 48 pixels were used when they calculate the estimates of reflected signal probability characteristics based on relations (3) and (4). The number of probes was equal to 5. Thus, the sample size made N = 240, and the relative estimation errors made about 0.05.

In order to assess the response to expectation vector inhomogeneity estimates, we used the measures in the form of component modules $|\dot{\mu}_1|, |\dot{\mu}_2|, |\dot{\mu}_3|$ and the Euclidean norm

$$\|\vec{\dot{\mu}}\| = \sqrt{|\dot{\mu}_1|^2 + |\dot{\mu}_2|^2 + |\dot{\mu}|^2} \quad (8)$$

Due to the probabilistic nature of the processed data and decision-making procedures about the presence of inhomogeneities in reflections, the value distribution histograms of the above mentioned measures were used as the tool of these estimates response description to these inhomogeneities.

When they develop histograms for the case of object (inhomogeneities) absence, thresholds were determined empirically, which were exceeded in 0.05 cases maximum. These thresholds are the estimates of critical region boundaries, the probabilities of exits from which do not exceed 0.05 if there are no inhomogeneities (the probabilities of the first kind errors).

The fig. 2-3 shows the histograms of component estimate modules for the expectation vectors at a hangar object absence and presence, creating the heterogeneity in reflections.

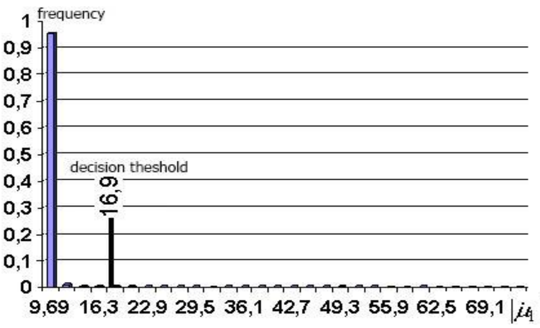

Fig 2: Histogram without objects.

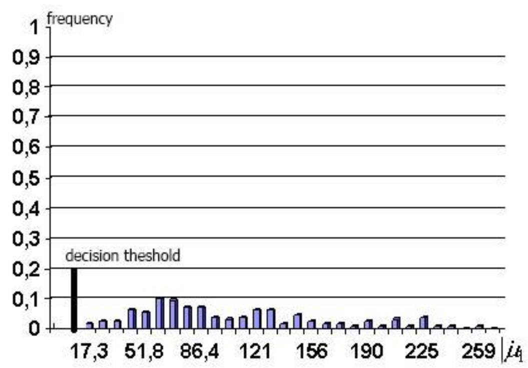

Fig. 3: Histogram with a hangar object.

Fig. 4 shows the value of the Euclidean norm for the difference of expectation vectors on analysis plots and the bordering fragments normalized to the maximum value

$$\|\dot{\boldsymbol{\mu}}\| = \|\dot{\boldsymbol{\mu}}_{\text{ya}} - \dot{\boldsymbol{\mu}}_{\text{оф}}\| \quad (9)$$

where: $\dot{\boldsymbol{\mu}}_{\text{ya}}$ - the expectation vector estimate on the analysis site, $\dot{\boldsymbol{\mu}}_{\text{оф}}$ -the expectation vector estimate on the bordering fragment.

To study the reaction of covariance matrix estimates, we used the Euclidean norm consistent with the Euclidean norm of vectors

$$\|\hat{\dot{\mathbf{R}}}\|_e = \sqrt{\sum_{i=1}^{3}\sum_{j=1}^{3} |a_{ij}|^2} = \sqrt{\mathbf{Sp}\hat{\dot{\mathbf{R}}}\hat{\dot{\mathbf{R}}}^T} = \sqrt{\sum_{i=1}^{3} \lambda_i^2} \quad (10)$$

Where a_{ij} - the covariance matrix elements, λ_i - eigenvalues.

Fig. 5 and fig. 6 shows the histograms of covariance matrix Euclidean norm distribution at the ab-sence and the presence of a hangar object.

The analysis of the obtained experimental data showed that, in the presence of objects, the values of the Euclidean norm of the covariance matrix estimates exceed the established threshold with a minimum frequency of 0.97. This indicates a sufficiently high response to the presence of heterogeneity.

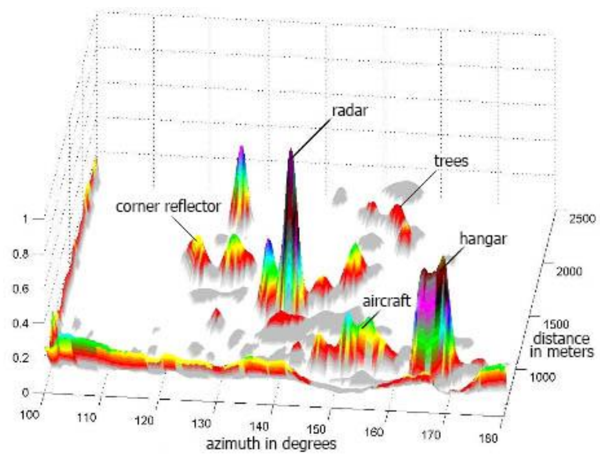

Fig. 4: The value of the normalized Euclidean norm of expectation vector difference for the analysis plots and bordering fragments.

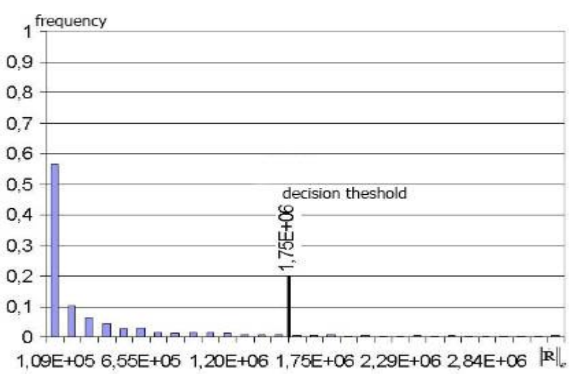

Fig. 5: Distribution histogram $\|\hat{\mathbf{R}}\|_e$ without objects

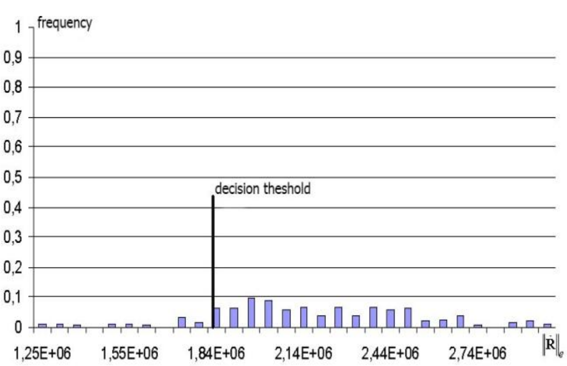

Fig. 6: Distribution histogram $\|\hat{\mathbf{R}}\|_e$ with a hangar object.

Figure 7 shows the radiogram obtained at the output of the radar receiving channel, when they probed the studied plot of land with various objects on it. Fig. 8 shows the values of the decisive function calculated in accordance with the abovementioned method for this plot.

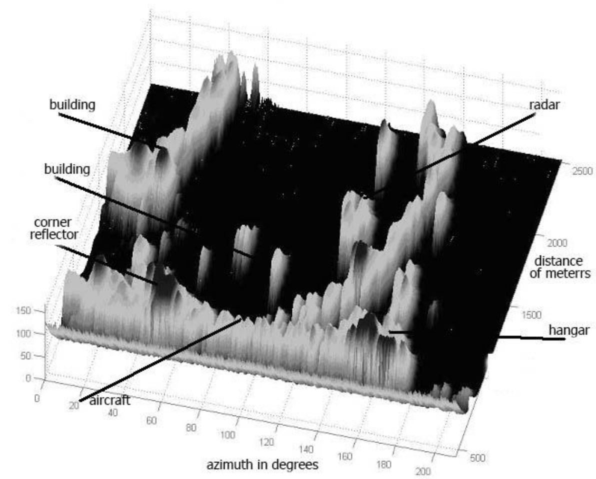

Fig. 7: Plot radiogram

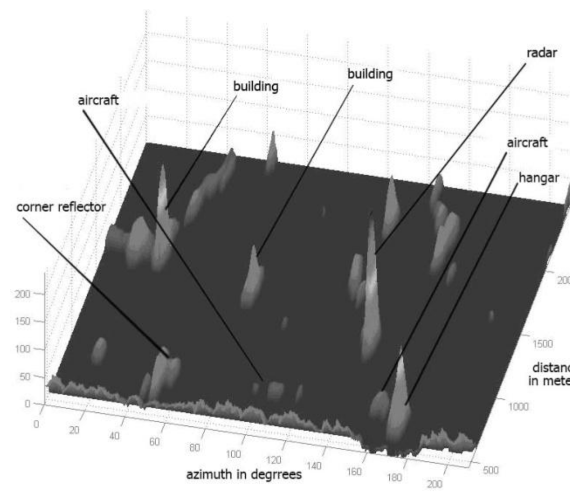

Fig.

Fig: 8: Decisive function values.

These figures indicate a high sensitivity of the decisive function to the polarization differences of received signals with the presence of objects on the earth surface.

IV. CONCLUSIONS

The developed decision rule uses the Bayesian approach for statistical testing of hypotheses. The decision rule is to calculate the decision function and compare it with a threshold. At that, experimental data are presented in the form of a sample of vectors and are described by multidimensional probability densities with Gaussian distributions [9]. They use the expectation estimates of the input data vector samples and their covariance matrices. When they test the hypothesis about the presence of an object on the earth surface, the Neumann–Pearson criterion is used [10]. To demonstrate the operability of the decision rule, experimental studies were carried out using field data, when the radar probed the earth surface with various different structures. Experimental studies have shown that the developed decision rule allows to detect inhomogeneities (objects) on the earth surface with a correct detection probability of 0.95%, with the first-type probability of 10^{-4}.

1. The developed decision rule allows to detect various objects on the earth surface with high quality indicators.
2. The Baessian approach to a decision rule development allows the use of optimal solutions.
3. The experimental studies, using field data, confirm the high quality indicators of the developed decision rule.

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