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V. BYKOV [1]**,** Leading Researcher of the Department of Technical Radiophysics,
Doctor of Technical Sciences, Senior Researcher
E-mail: bykov@karazin.ua
G. OSINOVYJ [2] **,** Head of project department, PhD
K. KOZIS [2]**,** Senior Researcher, candidate of technical sciences

[1] V. N. Karazin Kharkiv National University
4 Maidan Svobodi, Kharkiv, 61000 Ukraine
[2] Yuzhnoye State Design Office named after M. K. Yangel
3 Kryvorizhska Str., Dnipro, 49008 Ukraine
E-mail: info@yuzhnoye.com

METHODS OF ACTIVE AND PASSIVE ELECTRONIC PROTECTION OF SMALL GROUND OBJECTS FROM RADIOMETRIC MILLIMETER DETECTION SYSTEMS

We evaluate the probability and detection range of small-sized ground objects, including mobile objects, by passive-and-active radiometric detection and identification systems of millimeter range. We applied various methods allowing us to take into account a great number of factors (strength and multi-positional structure of a lighting source, pass bandwidth of a receiver of a radiometric (RM) system, characteristics of an antenna of a lighting source and RM system) and conditions for RM system sighting (sighting angles, dimensions and configuration of an object, influence of atmospheric hydrometeors) which affect the process of detection or non-detection of small-sized ground objects. Analytical expressions and formulas obtained in this study allow evaluation of the influence of applied methods and protection means on the detection process; i.e., evaluation of the efficiency of means for reduction of signature of small-sized ground mobile objects from radiometric detection systems of millimeter range.

The paper presents a theoretical model for determining the probability and range of detection of a small ground object by a radiometric system. This model takes into account the possibility of using an active-passive radiometric system as well as active and passive means of reducing object visibility. The model made it possible to obtain generalized formulas both for the object-to-background radio brightness contrast and for the detection range of the object in the presence of illumination sources.

Based on numerical simulation, it was shown the effectiveness of the worked-out model. In addition, it is shown that due to the use of an adjustable source of noise illumination, it is possible to significantly reduce the visibility of the object in dynamic conditions. The results of the paper outline the ways of development of modern high-tech methods of passive and active protection of ground objects from radiometric reconnaissance and weapon guidance systems.

Keywords: *millimeter range, matrix correlation-extreme detection systems, passive-and-active protection systems, mask coatings.*

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INTRODUCTION

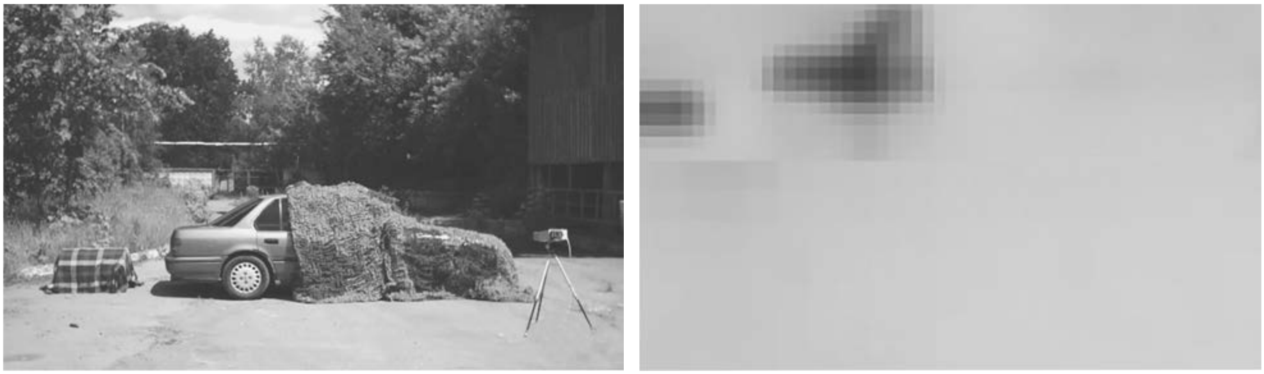
In general, protection of objects of military and special equipment from millimeter radiometric detection systems consists of using active and passive methods and means that allow shielding of the object radiation and decreasing their reflectance in a wide frequency range, and thus reducing the radiometric visibility [1, 4—7]. Here, radiometric visibility means the ability to determine from a certain distance and with a certain level of probability the presence of ground objects that, in a general case, may be moving.

METHODS OF PASSIVE AND ACTIVE ELECTRONIC PROTECTION OF GROUND OBJECTS

The method of passive radio-electronic protection involves the use of masking coatings. These include, for example, net camouflage coatings (Fig. 1 and 2). These coatings are used for partial (Fig. 1) or complete (Fig. 2) shelter of the protected object. This allows you to change the thermal profile of the object and reduce its radiative capacity.

Fig. 1 shows a violation of the thermal profile of the object due to its partial shelter. This approach can be used to mask stationary and moving objects when correlation-extreme recognition systems are used. In this case, the value of the correlation function between the real object and its reference image can be significantly reduced. This approach is also appropriate when masking large objects, which, in principle, cannot be completely covered with a masking coating.

There are two types of complete shelter of the object using a masking coating. In the case of the "Cloak" type shelter (Fig. 2, *a*), the masking coating is in contact with the surface of the object, partially reproducing its contours. This type of coating is convenient to use for moving objects, for example, military equipment on the march. Shelters of the "Tent"



a *b*

Figure 1. Photo (*a*) and radiometric image (*b*) of the ground object partially covered with mesh camouflage coatings

a *b*

Figure 2. Examples of "Cape" (*a*) and "Tent" (*b*) type shelters for reducing the visibility of the ground object using a net-type camouflage coating

type (Fig. 2, *b*) are usually used for stationary objects or for the equipment in a camp. This type of shelter allows masking the equipment with free access to its surface.

An example of an active radio-electronic protection method is the equalization of the radio-brightness temperatures of an object and the background at the input of a radiometric receiver of a passive radiometric detection system.

This method suggests the use of an own illumination source that generates a noise signal in the direction of the object to be protected. The power of the illumination source gradually increases until the "object — background" contrast reaches a minimum, in particular, zero value. Contrast refers to the temperature difference between the radio brightness of the object and the background. Feedback between the power of the illumination source and the "object — background" contrast is provided by the radiometric sensor, which is located on the same carrier as the source. This makes it possible to significantly reduce the detection rate of the protected object by an external passive radiometric system [1, 3, 5].

In order to illustrate the effectiveness of the specified methods of reducing the visibility of objects, it is first necessary to consider the method of determining the probability and range of detection of small-sized objects by an active-passive radiometric system.

METHOD FOR ESTIMATING THE PROBABILITY AND DETECTION RANGE OF SMALL GROUND OBJECTS BY MATRIX RADIOMETRIC PASSIVE-ACTIVE SYSTEMS OF MILLIMETERS BAND

The probability D of correctly detecting an object in a radiometric image is determined by its signal-to-noise ratio and can be calculated by the formula [2]:

$$D = \frac{1}{2}\left[1 + \Phi\left(\frac{T_g + \Delta T_0}{\sigma}\right)\right]. \qquad (1)$$

Here

$$\Phi(x) = \frac{2}{\sqrt{2\pi}}\int_0^x \exp(-t^2/2)$$

is the error function, $\Delta T = T_s - T_g$ is a contrast between the brightness temperature of an object (T_s) and background (T_g), T_0 is a temperature threshold value, exceeding which indicates the presence of a signal, i.e., the visualization of the object against the background, and σ is RMS of the noise of the radiometric system. Note that the temperature threshold also includes the background temperature, since it is a random value. Therefore, the formula (1) includes the difference $T_0 - T_g$ instead of T_0.

Let's introduce a new value $q = DT/s$, which characterizes the value of the signal-to-noise ratio. The dependence of probability D on q is shown in Fig. 3.

In Fig. 3, one can see two horizontal dashed lines that show the lower ($D = 0.1$) and upper ($D = 0.9$) limits of object detection. Probability values that exceed the upper limit ($D \geq 0.9$) correspond to the case of stable detection of the object. At the same time, probability values that are smaller than the lower limit ($D \leq 0.1$) correspond to the case of persistent non-detection of the object. It should be noted that the constructed dependence ($D = f(q)$) allows for the upper and lower limits of the probability of detection to calculate the corresponding values of the signal-to-noise ratio q. In our case, they are $q = 4$ and $q = 5.91$, respectively.

Let's consider the contrast of radio brightness temperature of the "object — background" scene for the case of using an active-passive radiometric detection system. In general, the radio brightness temperature of any part of the scene will be determined by eigen radiation and reflected radiation of the illumination source and the attenuation of radiation in the atmosphere along the path of the radiometric system — scene. Since both illumination source and eigen radiation have a noisy nature, interference phenomena can be neglected, and the total thermal contrast can be considered as the sum of contrasts of different origins.

The passive radiometric component of radio brightness contrast can be calculated by the formula [2]:

$$\Delta T_1 = \frac{4d^2 S(\theta,\alpha)\Delta\chi T_{12} K(R_r)}{R_r^2 \pi \lambda^2}, \qquad (2)$$

where $\Delta\chi$ is the difference in the emissivity of the object surface and the background, T_{12} is difference between the object and the background temperatures, that is, the contrast-forming temperature of the radio brightness, $K(R)$ is the attenuation coefficient of radiation in the atmosphere due to passing through the path R, Q is a filling factor of the antenna radiation pattern, $R = H\sec\theta$ is the length of the route of the

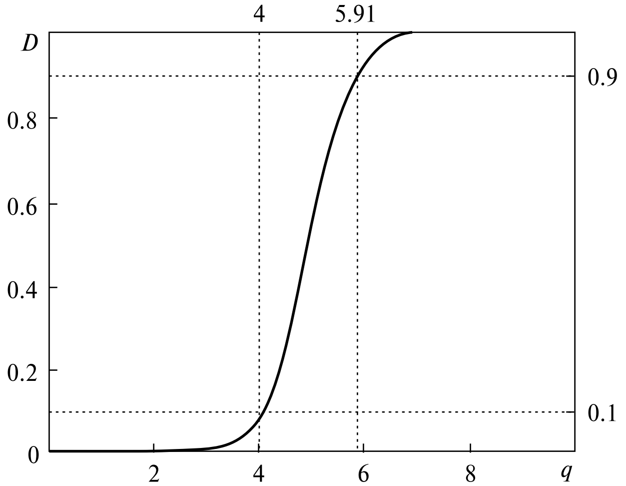


Figure 3. Dependence of probability *D* of correctly detecting an object in a radiometric system on the signal-to-notice ratio *q*

visible scene — radiometric system, *H* is the height of the location of the radiometric system carrier above the surface of the earth, θ is the angle of inclination of the object sighting, counted from the nadir.

The filling factor of the radiation pattern of the antenna of the radiometric system is calculated according to the formula:

$$Q = \frac{4S}{\pi L^2}, \qquad (3)$$

where *S* is the surface area of the object, $L = \lambda R_r / d$ is the cross-sectional area of the antenna radiation pattern with the earth's surface, R_r is the detection range of the object, i.e. the length of the path of the radiometric system — the object, *d* is the diameter of the antenna of the radiometric system.

For small objects, the filling factor meets the condition $Q \le 1$.

Due to the fact that the emissivity of a terrestrial object with a metal coating is small $\Delta\chi \le 1$ compared to the emissivity of the background of the earth's surface $\Delta\chi \ge 0.8...0.9$, the radiometric contrast ΔT_1 is a negative value.

Using the obtained formulas, we can write down the final formula for the passive component of the contrast:

$$\Delta T_1 = \frac{4d^2 S(\theta,\alpha)\Delta\chi T_{12} K(R_r)}{R_r^2 \pi\lambda^2}. \qquad (4)$$

The active component of radio brightness contrast is the result of the reflection of the noise illumination source radiation on the object and the background. It represents the contrast between the radio brightness of the object and the background that can be calculated via the radar equation [3]:

$$\Delta T_2 = \frac{P_t G_t G_r \Delta\sigma\lambda^2 K(R_r + R_t)}{(4\pi)^3 k\Delta f R_r^2 R_t^2}. \qquad (5)$$

This component, obviously, depends on the power of the illumination source P_t, the distance between the source of illumination and the object R_t, which, in turn, depends on the height of the source carrier and the angle of irradiation, and the detection range of the object R_r. Also, this value depends on other values included in the equation (4). Among them are the difference in the effective scattering surfaces of the object and the background $\Delta\sigma$, the bandwidth of the receiver Δf, the radiation efficiency of the antennas of the irradiation source G_t and the radiometric receiver G_r, and the attenuation of radiation in the atmosphere $K(x)$.

In addition, it should be noted that there may be several illumination sources. On the one hand, it can be the source of illumination of an active-passive radiometric detection system, and on the other hand, it can be the source of illumination itself, which is used as a means of active protection against detection. Both "radar" components are calculated according to the formula (5) but for different intensities G_t and distances between source of illumination and object R_t.

Since the component ΔT_2 is a positive value due to the fact that the reflectivity of the object is actually greater than the reflectivity of the background, the total contrast of radio brightness temperature of the object — background $\Delta T = \Delta T_1 + \Delta T_2$ can have any sign, and, in particular, be equal to zero under certain conditions. It should be noted that the situation can change radically, provided that the means of passive masking is not successfully chosen for the relevant background.

Thus, in general, the total contrast of object-to-background is calculated as follows:

$$\Delta T = \frac{4d^2 S\Delta\chi T_{12} K(R_r)}{R_r^2 \pi\lambda^2} + \frac{G_r \Delta\sigma\lambda^2}{(4\pi)^3 k\Delta f R_r^2} \times$$

$$\times \left(\frac{P_M G_M K(R_r + R_t)}{R_t^2} + \frac{P_t G_t K(2R_r)}{R_r^2} \right). \qquad (6)$$

Here P_M, G_M are the parameters of the “masking” illumination source, which is placed on the distance R_t from the object, and P_t, G_t are the parameters of the illumination source of the active radiometric system.

Using the formula (6), one can calculate the object detection range. Assuming the use of a passive radiometric system and a transparent atmosphere $K(R_r) = K(R_r + R_t) = 1$, we have the formula for calculating the detection range:

$$R_r = \sqrt{\frac{1}{\Delta T}\left(\frac{4d^2 S\Delta\chi T_{12}}{\pi\lambda^2} + \frac{G_r \Delta\sigma\lambda^2 P_M G_M}{(4\pi)^3 k\Delta f \Delta T R_t^2}\right)}. \quad (7)$$

AN EXAMPLE OF EVALUATING THE EFFECTIVENESS OF ACTIVE AND PASSIVE METHODS OF REDUCING THE VISIBILITY OF A SMALL GROUND OBJECT

As a demonstration of the effectiveness of active and passive protection methods, we will consider a model problem. As the test object, we took a metal object against a forest-grass background. To simplify the problem, we assume that the object has the shape of a rectangle. The plane *xOy* coincides with the surface of the earth, and the surface area of the object in this plane is 25 m^2. The surface area of the object in the *xOz* plane is 9 m^2, and in the *yOz* plane — 17 m^2. The dimensions are chosen in such a way that the object-background contrast depends on the detection direction of the object. The angle θ is the angle between the *Oz* axis, which is directed towards the sky, and the detection line, and the angle α is the angle between the *Ox* axis and the projection of the detection line in the *xOy* plane. With this choice of object and coordinate system, we have the following dependence of *S* on the detection direction:

$$S(\theta,\alpha) = 25\cos\theta\cos\alpha + 17\sin\theta\cos\alpha +$$

$$+25\cos\theta\sin\alpha + 9\sin\theta\sin\alpha\ .$$

The value of the difference in the emissivity of the object and the background for metal against the background of grass (forest) is $\Delta\chi = -0.9$, the value of the radiothermal temperature that forms the contrast is T_{12} = 200 K, which corresponds to the reference data for the difference in temperature of metal radiation against the background of the earth’s surface (grass, sand, wood).

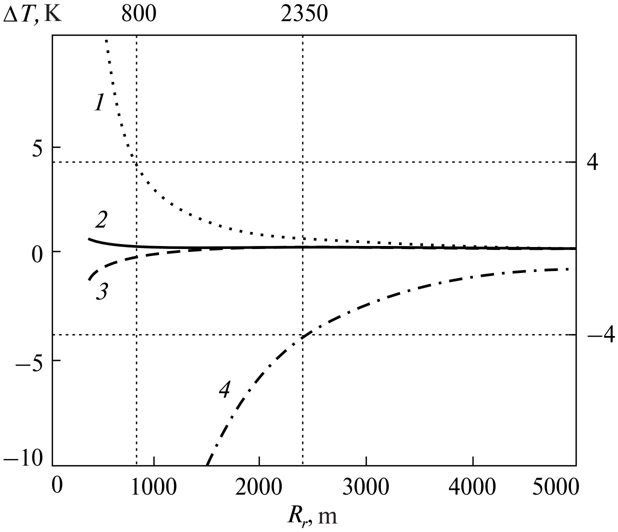
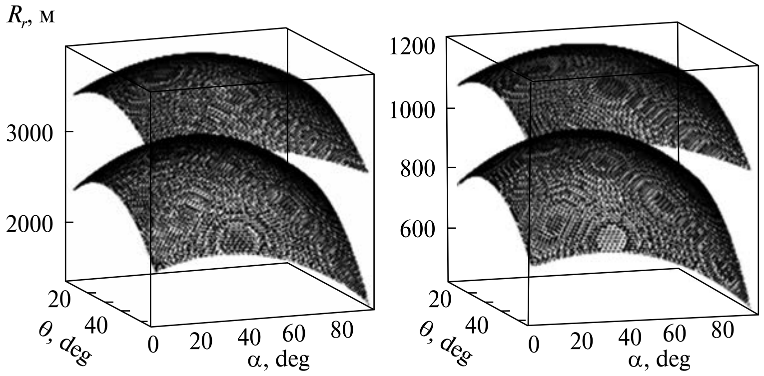


Figure 4. Dependencies of object-to-background contrast ΔT on the detection range R_r for the test object with the own source of noice illumination. Line *1* corresponds to $P_M = 1$ W, line *2* — $P_M = 0.9$ W, line *3* — $P_M = 0.89$ W, line *4* — $P_M = 0$ W

The parameters of the antenna of the radiometric system are chosen so that the antenna directivity is 40 dB, and the main lobe diagram has a width of 2θ = 1.1°...1.2°. For a radiometric system of an 8-millimeter range, this is achieved, for example, when using a parabolic antenna with a diameter of $d = 500$ mm, $G_r = 3.855\times10^4$.

We will consider the use of masking coating and source of noise illumination as passive and active reduction of object visibility, correspondingly. As a masking coating, consider a net-type camouflage coating (Fig. 1) that reduces the contrast of object-to-background by 10 dB. Moreover, the own source of noise illumination is located at a height of 1 km above the ground.

Fig. 4 demonstrates the possibility of reducing the object-to-background contrast due to the successful power selection of the illumination source. We see that in the absence of a source of illumination $P_M = 0$ W (line *4* in Fig. 4), the contrast has a negative, relatively large value and allows detection of the test object from a distance of 2350 m, which corresponds to a probability of detection of 0.1 (see Fig. 1). Provided that the power of the illumination source is 1 W (line *1* in Fig. 4), the contrast has a significantly



a *b*

Figure 5. Polar dependencies of detection range of the test object without using masking coating (upper surfaces) and with it (lower surfaces): *a* — for $P_M = 0$ W, *b* — for $P_M = 1$ W

positive value, and the detection range is only 800 m. For illumination source powers of 0.89 W (line *3* in Fig. 4) and 0.9 W (line *2* in Fig. 4), the contrast has small negative and positive values, respectively. Calculations show that, in this case, the object detection distance will not exceed 350...400 m.

To demonstrate the effectiveness of the masking coating, Fig. 5 shows the calculated polar dependences of the detection range of the test object without coating and with it for cases with relatively high contrast. So, Fig. 5, *a* corresponds to the situation of the absence of a source of illumination ($P_M = 0$ W), and Fig. 5, *b* is calculated for $P_M = 1$ W case. We can see that the masking coating reduces the detection range by almost three times in both cases.

Thus, it is clear that well-chosen means of active and passive visibility reduction can significantly decrease the probability and detection range of the object on the surface of the earth. Their combination makes it possible to successfully counteract the systems of radiometric reconnaissance, detection and guidance of weapons. At the same time, in real combat, to successfully use the active protection method, it is necessary to have an unmanned aerial vehicle equipped with a source of noise illumination and a radiometric system to ensure automatic adjustment of the source power in dynamic external conditions.

The object is equipped with an active protection system in the form of its own source of noise illumination with a power of P_M .

CONCLUSIONS

The paper examines the theoretical foundations of assessing the probability and capability of detecting small-sized ground objects by radiometric active-passive systems of reconnaissance, detecting and weapons guidance under the conditions of using active and passive means of reducing visibility. A general formula was obtained for determining the object-to-background radio brightness temperature contrast and estimating the probability of object detection depending on the value of this contrast.

As a method of passive protection, the well-known method of using masking coatings is considered. As an active protection, the use of an own source of noise illumination with the possibility of adjusting its power to reduce the object-to-background contrast via using a radiometric system is proposed.

The simplest test object as a metal parallelepiped on the grassy ground was considered, and the effectiveness of the proposed methods of active and passive reducing of object visibility was numerically proven.

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В. Биков [1]**,** пров. наук. співроб. кафедри техн. радіофізики, д-р техн. наук, старш. наук. співроб.
E-mail: bykov@karazin.ua
Г. Осіновий [2], нач. проєктного відділу, д-р філософії
К. Козіс [2], старш. наук. співроб., канд. техн. наук

[1] Харківський національний університет імені В. Н. Каразіна
4, Майдан Свободи, Харків, Україна, 61000
[2] Державне підприємство «Конструкторське бюро «Південне» ім. М. К. Янгеля»
вул. Криворізька 3, Дніпро, Україна, 49008

МЕТОДИ АКТИВНОГО І ПАСИВНОГО ЗАХИСТУ МАЛОРОЗМІРНИХ НАЗЕМНИХ ОБ’ЄКТІВ ВІД МАТРИЧНИХ РАДІОМЕТРИЧНИХ ПАСИВНО-АКТИВНИХ СИСТЕМ ВИЯВЛЕННЯ МІЛІМЕТРОВОГО ДІАПАЗОНУ

Розроблені і удосконалені моделі і методи положено в основу створеної в роботі методики оцінки ймовірності і дальності виявлення малорозмірних, зокрема рухомих, наземних об’єктів пасивно-активними радіометричними системами виявлення і ідентифікації міліметрового діапазону. Методика дозволяє ураховувати велику кількість факторів (потужність і багатопозиційну побудову джерела підсвічування, ширину полоси пропускання приймача радіометричної (РМ) системи, характеристики антени джерела підсвічування і РМ-системи) і умов візування РМ-системи (кути візування, розміри і конфігурацію об’єкта, вплив атмосферних гідрометеорів), які впливають на процес виявлення чи невиявлення малорозмірних наземних об’єктів. Отримані в роботі аналітичні вирази дозволяють оцінити вплив на процес виявлення застосованих методів і засобів захисту, і таким чином оцінити ефективність засобів зниження помітності малорозмірних наземних рухомих об’єктів від радіометричних систем виявлення міліметрового діапазону.

Розглянуто теоретичну модель для визначення ймовірності та дальності виявлення радіометричною системою малогабаритного наземного об’єкта. Дана модель враховує можливість використання активно-пасивної радіометричної системи, а також активних і пасивних засобів зниження видимості об’єктів. Модель дозволила отримати узагальнені формули як для контрасту радіояскравості об’єкта до фону, так і для дальності виявлення об’єкта за наявності джерел освітлення.

На основі чисельного моделювання показано ефективність розробленої моделі. Крім того, показано, що за рахунок використання регульованого джерела шумового освітлення можна значно знизити видимість об’єкта в динамічних умовах. Результати роботи окреслюють шляхи розвитку сучасних високотехнологічних методів пасивного та активного захисту наземних об’єктів від систем радіометричної розвідки та наведення зброї.

***Ключові слова*:** міліметровий діапазон, матричні кореляційно-екстремальні системи виявлення, активні і пасивні системи захисту, маскувальні покриття.