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Detection Range Estimation of Small UAVs at a Given Probability of Their Identification

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Abstract: *The results of the development of a scientific and methodological apparatus that provide an assessment of the de-tection range of small-sized unmanned aerial vehicles are presented. The general problems of radar detection of small objects are considered. A mathematical formulation of the research problem is carried out from the stand-point of detecting radar signals in noise based on a probabilistic approach. Substantiated are the parameters of radar stations, which are of the most significant importance for increasing the reliability of detecting objects with a small effective scattering surface. The functional dependences of the detection range of small unmanned aerial vehicles on the value of the signal-to-noise ratio in the channel and the sensitivity of the receiving devices are given. The dependence of the detection range on the wavelength of radiation from radar stations has been studied. A quantitative assessment of the probabilities of correct detection of small targets and false alarms is presented for various values of the decision threshold. Nomograms have been developed to assess the capabilities of detectors of unmanned aerial vehicles of the Phantom 3 type. The requirements for the structure of radar signals used to detect small targets are substantiated.*

Keywords: *detection of small targets, detection range of unmanned aerial vehicles, probability of correct signal detection, nomograms for assessing the capabilities of detectors*

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Оценка дальности обнаружения малоразмерных БПЛА при заданной вероятности их идентификации

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Аннотация: *Представлены результаты разработки научно-методического аппарата, обеспечивающего проведение оценки дальности обнаружения малоразмерных беспилотных летательных аппаратов. Рассмотрены общие проблемы радиолокационного обнаружения малоразмерных объектов. Осуществлена математическая постановка задачи исследования с позиций обнаружения радиолокационных сигналов в шумах на основе вероятностного подхода. Обоснованы параметры радиолокационных станций, имеющих наиболее существенное значение для повышения достоверности обнаружения объектов с малой эффективной поверхностью рассеивания. Приведены функциональные зависимости дальности обнаружения малоразмерных беспилотных летательных аппаратов от значения отношения сигнал/шум в канале и чувствительности приемных устройств. Исследована зависимость дальности обнаружения от длины волны излучений радиолокационных станций. Представлена количественная оценка вероятностей правильного обнаружения малоразмерных целей и ложной тревоги при различных значениях порога принятия решения. Разработаны номограммы для оценки возможностей обнаружителей беспилотных летательных аппаратов типа Phantom 3. Обоснованы требования к структуре радиолокационных сигналов, используемых для обнаружения малоразмерных целей.*

Ключевые слова: *обнаружение малоразмерных целей, дальность обнаружения беспилотных летательных аппаратов, вероятность правильного обнаружения сигнала, номограммы оценки возможностей обнаружителей*

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Introduction

Small-sized unmanned aerial vehicles (UAVs) are widely used in various fields of human activity, from high-altitude panoramic shooting of the terrain to the delivery of small-sized cargo [1–3].

The economic accessibility of small-sized UAVs for the consumer and the ease of their control open up the possibility of unauthorized use of such devices [4, 5]. Consequently, the issues of suppressing the illegal use of small UAVs are relevant for law enforcement agencies and departments.

At the same time, the small size of such devices and the use of composite materials for their manufacture significantly complicate the solution of the problem of their timely detection [6, 7]. Therefore, the development of a scientific and methodological apparatus for assessing the possibilities of timely detection of small-sized UAVs is a priority area of research, which has a pronounced practical focus for law enforcement agencies [8–10].

Taking into account these aspects, this article proposes the results of assessing the possibility of radar detection of Phantom-class quadrocopters [11–13].

Statement of the problem of UAV detection from the standpoint of statistical decision theory

The task of detecting small UAVs is proposed to be considered from the standpoint of receiving and processing radar signals reflected from the target [14–16]. In the general case, such a task is based on the elements of decision theory [17, 18], according to which it is necessary to make a reasonable choice between two alternative hypotheses H_0 and H_1, obtained from the results of statistical processing of the received implementations of the input samples $x(t)$, about the presence or absence they have a useful signal.

So, in accordance with the hypothesis $H_0: x(t) = n(t)$, the processed sample of the input implementation $x(t)$ contains only noise $n(t)$. And the hypothesis $H_1: x(t) = s(t) \oplus n(t)$ characterizes the situation, according to which, in the processed sample of the accepted implementation $x(t)$, in addition to the noise component, there is a useful radar signal reflected from the target $s(t)$.

In the analytical representation of the hypothesis H_1, the symbol $\oplus$ indicates the additive nature of the interaction of the useful signal $s(t)$ with the noise components $n(t)$ [19, 20].

Further, we will assume that the channel noise can be described by a Gaussian distribution:

$$p_0(x) = \frac{1}{\sqrt{2\pi\sigma_0^2}} \exp\left(-\frac{x^2}{2\sigma_0^2}\right). \quad (1)$$

In formula (1), x is the measured amplitude value of the input sample $x(t)$, which, in the absence of a useful signal in it, will be equal to the amplitude value of the noise components n in the receiving path; σ_0^2 is the channel noise dispersion.

If there is a useful signal $s(t)$ reflected from the target with an amplitude value s in the processed sample of the input implementation $x(t)$, the resulting distribution (1) is transformed to the following form:

$$p_1(x) = \frac{1}{\sqrt{2\pi\sigma_0^2}} \exp\left(-\frac{(x-s)^2}{2\sigma_0^2}\right). \quad (2)$$

Graphically, the procedures for detecting a radar signal in the processed sample can be interpreted from the standpoint of searching for the area determined by the plots of distributions $p_0(x)$ and $p_1(x)$, in accordance with formulas (1) and (2) [20, 21]. For the situation under consideration, these graphs are shown in Fig. 1.

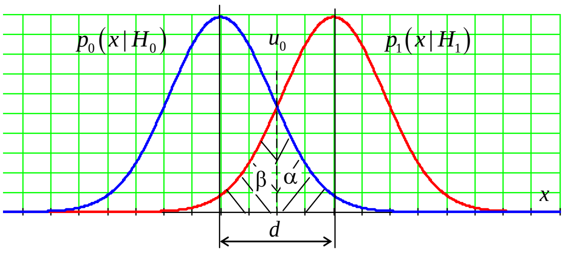

Fig. 1. Graphs Characterizing the Distribution of Conditional Probabilities Corresponding to Alternative Hypotheses about the Presence and Absence of a Useful Signal in the Processed Sample

On Fig. 1 $p_0(x|H_0)$ is the distribution of the measured value of the input realization in the presence of only noise in it, which can be characterized as a conditional probability corresponding to the hypothesis $H_0\colon x(t) = n(t)$. And $p_1(x|H_1)$ – respectively, is the distribution of the measured value of the input realization, in which, in addition to noise, a useful signal was contained. This distribution characterizes the conditional probability corresponding to the hypothesis $H_1\colon x(t) = z(t) \oplus n(t)$.

Obviously, only in the case when the measured value of x unambiguously falls into one of the areas limited by the functions of conditional probabilities $p_0(x|H_0)$ and $p_1(x|H_1)$, it is possible to make a fairly correct decision about the presence or absence of a useful signal in the processed implementation (infinity of the "tails" of distributions hypothetically leaves the possibility of an incorrect decision).

In [15], the probabilities that lead to the occurrence of errors are defined as an error of the first kind α and an error of the second kind β. So, the error of the first kind α characterizes the probability of a false alarm, i.e. making a decision about the presence of a useful signal in the processed sample, although it was actually absent. In other words, the decision was made to reject the hypothesis H_0, although it was true. An error of the second kind β, called "missing the target", occurs when the hypothesis H_0 is accepted, although in fact the hypothesis H_1 is true.

As a result, the total probability of erroneous decisions p_ε will be determined in accordance with the expression:

$$p_\varepsilon = \alpha p_1 + \beta p_0. \qquad (3)$$

It should be noted that the false alarm value α is determined by the area of the figure under the conditional probability function $p_0(x|H_0)$, limited by a preselected threshold G:

$$\alpha = \int_{u_0}^{\infty} \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{x^2}{2\sigma_0^2}\right) dx. \qquad (4)$$

Accordingly, the value of the target skip β is determined by the area bounded by the conditional probability function $p_1(x|H_1)$ as follows:

$$\beta = \int_{\infty}^{u_0} \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{(x-s)^2}{2\sigma_0^2}\right) dx. \qquad (5)$$

Note that expressions (4) and (5) were obtained taking into account the normalization of the noise variance. In practice, quite often, as the threshold value for making a decision, u_0, the intersection point of the graphs of the conditional probabilities $p_0(x|H_0) = p_1(x|H_1)$ is chosen. In this case, the value of the total error probability will be determined as follows:

$$p_\varepsilon = 0.5(\alpha + \beta). \qquad (6)$$

Taking into account formulas (4) and (5), expression (6) can be transformed to the form:

$$p_\varepsilon = \int_{\mathrm{M}[s]=d/2}^{\infty} \frac{0.5}{\sqrt{2\pi}} \exp\left(-\frac{x^2}{2\sigma_0^2}\right) dx + \int_{\infty}^{\mathrm{M}[s]=d/2} \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{(x-s)^2}{2\sigma_0^2}\right) dx. \qquad (7)$$

Here $\mathrm{M}[s]$ is the average value of the amplitude values of the sample of the input implementation $s(t)$; and $d = \max[p_1(x|H_1)] - \max[p_0(x|H_0)]$ is the difference between the maximum values of $p_0(x|H_0)$ and $p_1(x|H_1)$.

Taking into account the considered concepts, the problem of detecting small UAVs is defined as the search for conditions under which the maximum value of the probability of making a correct decision about the presence of a radar signal reflected from the target is ensured:

$$D = \int_{u_0}^{\infty} \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{(x-s)^2}{2\sigma_0^2}\right) dx \to \max \text{ at } \alpha \to \min. \qquad (8)$$

Those, while minimizing the magnitude of false alarms. According to Fig. 1 condition (8) will be best provided with an increase in the value of d, which determines the energy differences between the parameters of the channel noise and the useful signal.

From such positions, the probability of correct detection is a function of the current ratio of the signal power to the noise power spectral density, which in the framework of the work will be considered as the signal-to-noise ratio (SNR) [14, 17].

In turn, the energy parameters of the useful signal are determined both by the technical capabilities of the paths for its formation and processing, and by the parameters of the target, in particular, by the size of its effective scattering surface (ESS) [22].

Substantiation of radar parameters for UAV detection

The difficulty of detecting small-sized UAVs is primarily due not only to the small value of their ESS [23], but also to their rather small geometric dimensions. Therefore, an important point in the development of detectors is the choice of the wavelength of the transmitter signal, carried out taking into account the provision of the following requirements for the radar system [23–26]:

– the maximum range of the radar, which decreases with increasing frequency as a result of an increase in the attenuation of radio wave energy in the real atmosphere;

– resolution in terms of angular coordinates and the error of their measurement, which is determined by the width of the radiation pattern, the geometric dimensions of the antenna, and improves with increasing frequency, i.e. with shortening of the wavelength;

– probability of detection, depending on the range, sensitivity of the radar receiver, SNR at the receiving point, as well as the method of processing the burst of pulses.

It should be taken into account that since the main parameter of the detected object is its effective scattering surface [23], the maximum geometric dimensions of the object of detection should be at least 16 times greater than the radar wavelength.

Then, for small UAVs of the Phantom 3 type, see Fig. 2, the value of λ will be $\lambda = \frac{\sqrt{0.3^2+0.3^2}}{16} \approx 0.025$ m.

Note that the calculated value of λ corresponds to a frequency of $f\,[\text{MHz}] = \frac{300}{0.025\ [\text{meter}]} = 12000$ MHz (12 GHz), which belongs to the so-called *X*-band.

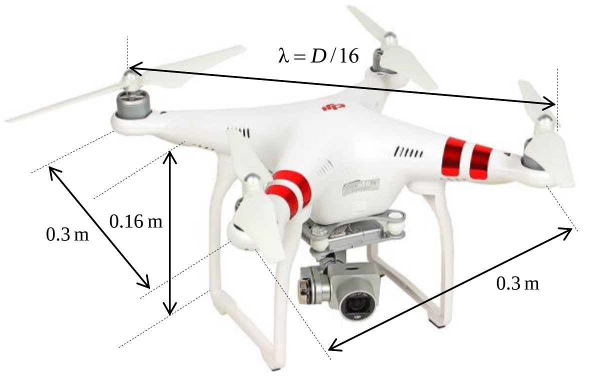

Fig. 2. General View of a Small-Sized Phantom 3 UAV

As already noted, the energy parameters of the detected signal are determined by the ESS of the target, which characterizes the ratio of the power density reflected from the small-sized UAV to that incident on it, in the process of irradiating it from the side of the radar [25, 27].

Theoretically, the ESS value can only be calculated for simple geometric shapes made of a homogeneous conductive material. For other objects, the ESS is determined experimentally by irradiating them in an anechoic chamber. It should be understood that the value of the ESS of the same object will be different depending on the range of the radar. So for the *X*-band ESS of a small-sized Phantom 3 UAV, according to [23] is σ = 0.06 m².

Then, knowing the radar parameters and the ESS value of a small UAV, it is possible to calculate its detection range, which will be determined by the formula [19, 27]:

$$R = \sqrt[4]{\frac{P\,G^2 \sigma\, \lambda^2 q}{P_{\min}(4\pi)^3}}, \tag{9}$$

where $P_{\min}$ is the threshold sensitivity of the receiving device; G is the antenna gain (provided that one system works for reception and transmission); σ is the ESS of the target (small UAV); q is the SNR; λ is the radar wavelength.

On Fig. 3 shows graphs of the function $R(q)$ for various values of the sensitivity of the radar receiver $P_{\min} = 10^{-14}$; 10^{-12} W.

An analysis of the presented results shows that a detection range of the order of 2 km is actually not achievable for radars whose receiver sensitivity is worse than $1{\times}10^{-14}$. The results are obtained for the conditions: P = 200 W; G = 23 dB; and λ = 2.5 cm.

Graphs in Fig. 3 are built for the upper part of the *X*-band, it should be understood that reducing the frequency provides a reduction in attenuation in free space. But at the same time, the ESS of the object also decreases.

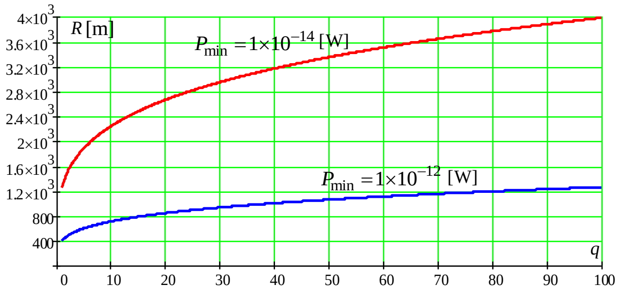

Fig. 3. Dependence of the Detection Range of Small UAVs on the SNR at Different Values of the Radar Sensitivity

So, the transition to the lower part of the *X*-band, i. e. the choice of λ = 3.75 cm will lead to a 1.5-fold decrease in the ESS of a small UAV, but the level of signal attenuation will also decrease. On Fig. 3 shows plots of $R(q)$ for $P_{\min} = 10^{-14}$ when operating in the upper and lower parts of the *X*-band, taking into account the 1.5-fold reduction in the ESS of a small UAV. On Fig. 4 points *A* and *B* show the level of detection range provided by the radar at λ = 2.5 cm and λ = 3.75 cm.

Note that the transition to the lower part makes it possible to increase the noise immunity of detection by 1.8 dB, which for the level q = 6 dB provides an increase in the range by 190 m.

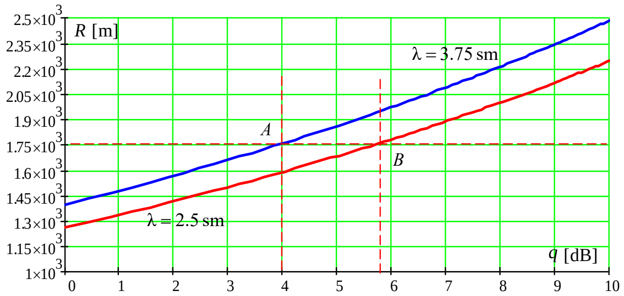

Fig. 4. Dependence of the Detection Range of a Small UAV on the SNR at Different Values of the Radar Wavelength

Quantitative assessments of UAV detection

To obtain quantitative estimates characterizing the detector of small UAVs with the considered parameters, we assume that the radar uses a single pulse for detection. Then the probability of correct detection as a function of SNR (measured when receiving one pulse) will be calculated as [27, 28]:

$$\mathrm{P}_{\Pi\mathrm{O}} = \begin{cases} 0.5\,[1 + \Phi(\sqrt{q} - u_0) & \text{at } \sqrt{\sigma} \geq u_0; \\ 0.5\,[1 - \Phi(u_0 - \sqrt{q}) & \text{at } \sqrt{\sigma} < u_0, \end{cases} \quad (10)$$

where $\Phi(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} \exp\left(-\frac{t^2}{2}\right) dt$; q is the SNR; u_0 – detection threshold.

In this case, the value of the conditional false alarm probability α will be determined as [28]:

$$\alpha = \exp\left(-\frac{u_0^2}{2}\right). \quad (11)$$

On Figs. 5 and 6 show plots of $D(q)$ and $\alpha(u_0)$.

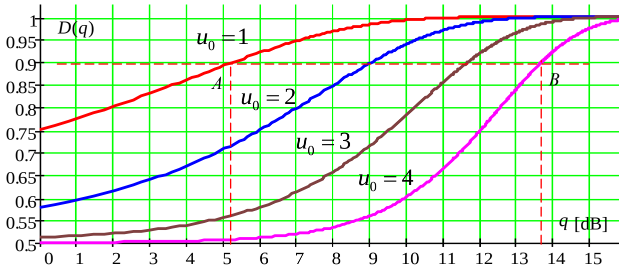

Fig. 5. Dependence of the Probability of Correct Detection of Small UAVs on the SNR for Different Values of the Decision Making Threshold

Analysis of the obtained results shows the following. The smaller the threshold value u_0, the higher the detection probability for the same SNR value. On Fig. 5 shows points A and B corresponding to the level $D = 0.9$ at $u_0 = 1$ and $u_0 = 4$. And if in the first case the indicated detection was provided at an SNR of about 5.2 dB, then in the second case the SNR was 13.8 dB.

At the same time, it should be taken into account that the process of detecting small-sized UAVs should be carried out taking into account the minimization of the probability of false alarms.

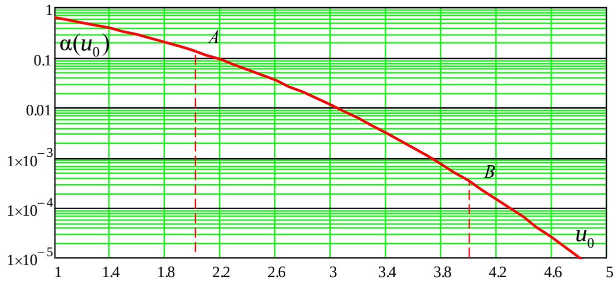

Fig. 6. Dependence of the Conditional False Alarm Probability on the Value of the Decision Threshold

So, according to the graph in Fig. 6, at $u_0 = 2$, the false alarm value reaches a value of the order of $\alpha = 0.105$ (point A in Fig. 6). And an acceptable result $\alpha = 2{\times}10^{-3}$ is provided only with $u_0 = 4$ (point B in Fig. 6).

Taking into account the results obtained, it seems interesting to combine the graphs in Figs. 3 and 5 in a single format SNR, see Fig. 7.

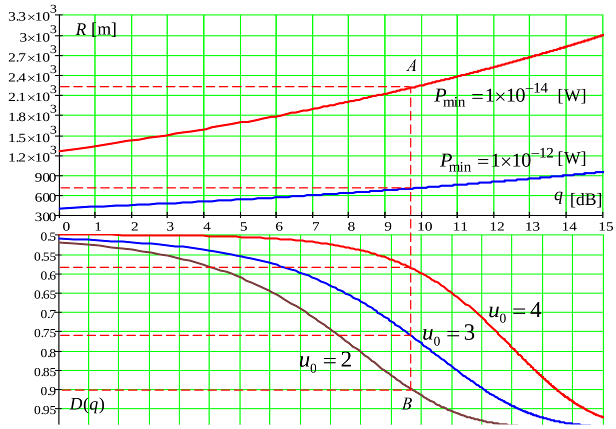

Fig. 7. Nomogram for Assessing the Capabilities of Small UAV Detectors

Let us define the result of graph matching as nomograms for estimating the detection range of small UAVs for a given probability of correct decision making and sensitivity of radar receivers.

So, for $D = 0.9$ (point B in Fig. 7), the detection range $R = 2.3$ km (point A in Fig. 6) will be possible only if the SNR in the channel is about 9.8 dB and the sensitivity of the radar receiver is $P_{\min} = 10^{-14}$ W.

A further increase in the efficiency of the radar when detecting small UAVs is associated with the implementation of the signal in the form of a burst of pulses [19]. When small-sized UAVs move even at a speed of 100 m/s and linear dimensions of 0.3 m, the burst duration should not exceed 15–30 ms. Then, to ensure the pulse power equal to at least $E = 6$ mJ with a total radar power of 200 W, the pulse duration should be $\tau = 2.5$ ms. Therefore, for a duty cycle equal to $Q = 2$, there will be no more than 4 pulses in a burst.

The dependence of the probability of correct detection of small UAVs on the SNR under the conditions of processing single pulses and a burst of four pulses is shown in Fig. 8.

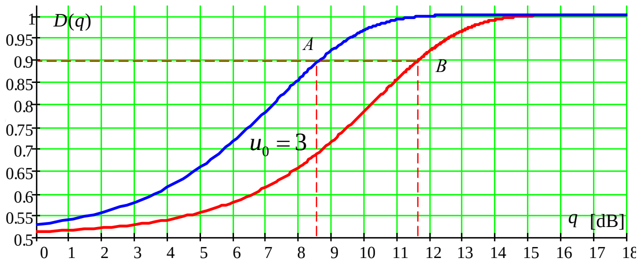

Fig. 8. Dependence of the Probability of Correct Detection of Small-Sized UAVs on SNR with Coherent Accumulation of 4 Pulses (Point *A*) and with Processing of one Pulse (Point *B*)

The results obtained allow us to conclude that for a burst containing only four pulses, incoherent processing will not bring a significant effect. Coherent accumulation in the case of receiving all pulses will provide an increase in noise immunity by about 2.5 dB, see Fig. 8.

Conclusion

Conducted studies to address the issues of detection of small-sized UAVs have shown that the main problems are associated with their low effective dispersion surface. Considering that the effectiveness of radars is determined not only by their technical characteristics, but also by the channel and target parameters, it is proposed to use nomograms to assess the detection capabilities of small UAVs, which allow for a given SNR level to determine the probability of correct detection, depending on the sensitivity of the radar receiver.

A further increase in the detection efficiency of small-sized UAVs can be associated with an increase in the radar power, the gain of antenna systems, an improvement in the sensitivity of the receiving path, a transition to a higher frequency range, and the use of joint time-frequency analysis methods presented in [29–31].

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