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Target detection probability of a moving drone in a land-based stationary background radar

A S Anikin, A V Khristenko and A V Ochirtarov
Tomsk State University of Control Systems and Radioelectronics, 40, Lenina ave., Tomsk, 634050, Russia

E-mail: rbk@sibmail.com

Abstract. In this paper the authors presented a method of detecting small drone using a background radar under conditions of fluctuations of an effective background scattering surface described by the normal probability density of instantaneous values radar cross section. The paper considered the detection of a moving drone between the radar and the background. The drone moves towards the background. The detection threshold is determined by the Neumann-Pearson test. It is shown that the detector based on consistent filters provides detection of small drones under conditions of multiplicative interference at small fluctuations of the effective surface of background scattering.

1. Introduction

Progress in materials science, microelectronics and aircraft engineering over the last decade has resulted in creating drone. The miniaturization of on-board equipment using nanotechnology has led to a significant reduction in mass and size characteristics and the widespread use of small drones.

The following examples of the use of small drones are known:

- when filming celebrations and events;
- information on the spatial and temporal distribution of meteorological parameters in the interests of The Federal Service for Hydrometeorology and Environmental Monitoring;
- in solving logistics problems at oil and gas fields;
- during pesticide treatment in agriculture;
- in Amur tiger training, etc.

Smaller drones are particularly suitable for use as carriers of various sensors in the field of acoustic, video or radio engineering reconnaissance.

The use of the drone for military purposes has an impact on the economic situation around the world, as evidenced by the results of drone attacks on oil production facilities in Saudi Arabia. The problem of airspace control and monitoring with respect to small drones has now been partially resolved. In particular, the anti-aircraft missile systems are equipped with drone detection systems using acoustic, optical, infrared and electromagnetic signals. However, the effectiveness of the existing facilities is becoming insufficient with respect to the more advanced low-flying, small-size drones in terms of their technical characteristics. The problem of detecting such targets in the radio range is complicated by the presence of high power radio wave passive interference reflected from the underlying surface. The intensive development of detection systems for small drones in the radio range is being carried out in the direction of modernization of Doppler methods of selection of moving targets, or improvement of detectors in relation to the methods of background radar. Active radars implementing those methods are used in perimeter security systems.

The background radar is a promising area of development of radar means for detecting small moving low-size scattering targets observed in conditions of high level of reflected underlying surface of radio signals. The basis of the background radar location is the method of detecting moving objects (registered on October 13, 1983) and the scientific discovery "Regularities of manifestation of a moving object" by Academicians Prangishvili I.V., Doctor of Technical Sciences Anuashvili A.N. and Doctor of Technical Sciences Maklakov V.V. (Resolution of the Russian Academy of Sciences dated February 18, 1992) of The Institute of Control Sciences of the Russian Academy of Sciences [1]. The scientific discovery consists in "the manifestation of temporary changes in the parameters of the reflected signals of the background during the interaction of the moving object in front of it with the coherent radiation from the stationary background". The background (Figure 1) is understood as some stationary object forming reflected radio waves in the direction of the receiver as a result of irradiation by a radiation source.

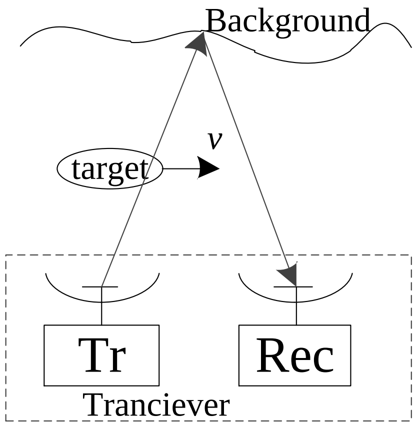

Figure 1. Scheme of the experiment for the opening of temporary changes in the reflected signals parameters (*v* – velocity of target, Tr – transmitter, Rec – reciever).

The authors of the paper [1] note that when implementing the background radar method in the detection problem, the main difficulty is the separation of signals scattered by the target among the signals reflected by elements of the terrain. The authors draw this conclusion from a comparison of the powers of these signals by the ratio of the target cross-sectional area (15 ... 25 cm^2) to the area of the first Fresnel zone (0.25 m^2) equivalent to a two-position radar. To study the possibilities of extracting signals from the target when implementing the background radar method, they conducted an experiment in the building using a stationary transceiver with a non-scanning antenna.

The first experimental and theoretical studies of the background radar method are associated with the study of the spectral characteristics of the radio signal reflected from the background during the movement of an object in front of it [1, 2] in laboratory conditions. A fairly wide range of questions on the study of the background radar method in the problem of detecting air targets “airplane” and “cruise missile” moving at a speed of 200 m/s is presented in [2]. The monostatic effective scattering surface of these targets does not exceed 0.01 m^2.

Objects of natural or artificial origin that have been pre-selected in the protected area of the detection system may serve as a background. The authors of the discovery recorded temporary changes in the intensity of the received signal when the target moved transversely to the line "T-R device-background" [3-6].

The first application of scientific discovery in radio engineering systems is noted in the works of F.S. Alymov, V.N. Sablin, V.V. Razeviga and V.V. Chapursky [2] and dates back to 1984. In this paper we consider the detection zones, energy and frequency ratios in the detection of objects, as well as approaches to the processing of the received signal. Later, in 1990, the background method of radar location was proposed in the patent: «The detection technique is based upon the fact that if a vehicle with low radar cross section passes between a source of radar energy and a suitable radar receiver, the location of the vehicle can be detected by virtue of the reduced radar energy received from the vehicle» [7]. This method was subsequently developed in the works of foreign scientists in the field of bistatic radar [8-12]. In these works, in particular, probabilities of correct detection in the presence of Gaussian noise and fluctuating noise were obtained. However, these studies did not take into account fluctuations of the background surface.

The antenna output signal is the sum of four signals:

- the first signal is the propagation of the radio wave from the transmitter to the background and then to the receiver;
- the second signal is the propagation of the radio wave from the transmitter to the target, then from the target to the background, and then from the background to the receiver;
- the third signal is the propagation of the radio wave from the transmitter to the background, then from the background to the target, and then from the target to the receiver;
- the fourth signal is the propagation of the radio wave from the transmitter to the target, then from the target to the background, then from the background to the target, and then to the receiver.

The last signal is 30-40 dB smaller in terms of the level of other signals and is usually not taken into account.

The first signal is called a direct signal, the second and third are the same signals and are called reflected.

For achieving the energy delay profile via experimental tests, large financial expenses are needed. That is why, the task of achieving realizations of the propagation traces impulse response using the energy delay profile taken from publications is a subject of interest. However, there are no approaches developed to form impulse response realizations for near-ground traces under the conditions of frequency-selective depressions.

In this paper, we consider digital modeling of realizations for the signal passing through the near-ground propagation trace in a temporal domain using the energy delay profile for near-ground traces under the conditions of frequency-selective depressions.

The background radar method can be implemented in single-position, two-position and multi position radar systems.

Under certain conditions, the background radar is a kind of two-position "peek-a-boo" radar. In particular, when the target scatters the radio wave diffusely. The gates wich differ in range correspond to the background method of the radar location of a moving target and the stationary object forming the reference radio signal. This distinguishes the background radar method from coherent pulse methods.

In this paper, we call the background radar as a technical means of extracting information about a moving target from its modulated reflected signals by terrain objects and related to different, in general, resolution elements.

The work of moving target detectors in background radars is usually based on the difference in spectra reflected from the background of the radio signal when there is no target or on comparison with the threshold of different ways of averaging the phase detector output signal or phase detector spectrum readings. However, the methods proposed by the authors are heuristic. In this paper we will consider the application of the statistical theory of hypothesis testing in the problem of detection of small drones in the background radar.

The purpose of the paper is to investigate the detection characteristics of a small drone in the background radar. By detection characteristics we will understand the probability of correct detection and false detection. The presented results complement the existing ones and can be used to assess the quality of drone detection using background radar.

2. Method of a small drone detection

Let us consider the problem of binary detection of small targets on the background of noise of the active radar receiving path. Let us assume that a small drone moves at a constant speed at a certain angle to the normal, perpendicular to the line of sighting "radar background".

The motion parameters (heading angle, speed, range) of a small drone along a linear trajectory are known, and there is a pre-selected object acting as a background. Let the detection of a small drone be carried out by processing a set of *n* amplitudes of the beat signal in the radar, determined by each probing linear frequency modulation (LFM) radio signal for a certain observation interval t = [0; T]. The amplitude of the *i* beat signal corresponds to the *i* sounding LFM radio pulse. The time form of the useful signal when the small drone is moving is described by the formula:

$$A_{\Sigma}(t)=A_{refl}(t)\sqrt{1+k_A{}^2+2\cdot k_A\cdot\cos\left[\Delta\varphi(t)\right]}, \tag{1}$$

where

t - the moment of time corresponding to the reception of the *i* runout signal;

$A_{refl}(t)$ - the amplitude of the reflected signal;

k_A - the coefficient equal to the ratio of amplitudes of the envelope of the direct and reflected target signals at the receiving location

$$k_A=\sqrt{\frac{4\pi}{\sigma_t}\cdot\frac{\left(D_f-D_t\right)^2\cdot D_t^2}{D_f^2}},$$

σ_t - the target radar cross-section (RCS),

D_t - the distance to the target;

D_f - the distance to the background;

$\Delta\varphi(t)$ - a phase difference between direct and reflected signals.

A useful signal modulated by the multiplicative noise is observed against the background of additive Gaussian noise in the receiving path. The interval of correlation of the noise of the receiving path does not exceed units of microseconds. The duration of the useful signal is units of seconds. Therefore, neglecting the correlation of noise samples $n(t)$, we accept it as white Gaussian noise with a zero mean value and probability density of instantaneous values:

$$\mathrm{W}_n(n)=\frac{1}{\sqrt{2\pi}\sigma_n}\mathrm{e}^{-\frac{1}{2}\left(\frac{n}{\sigma_n}\right)^2},$$

where

σ_n – root mean square (RMS) of termal noise recieve.

Let us imagine the observed signal $Y(t)$ in the form of the sum of the useful signal $A_{\Sigma}(t)$ and the noise of the receiving path $n(t)$:

$$Y(t)=A_{\Sigma}(t)+n(t). \tag{2}$$

The amplitude of the reflected signal at the interval of useful signal observation $A_{\Sigma}(t)$ changes randomly (random process), which is mainly caused by temporary fluctuations of the effective surface of background scattering in the element of resolution of the background radar. Those fluctuations are described by a normal distribution law and represent a multiplicative interference with the useful signal (1). The determination of conditional distribution densities of instantaneous values probabilities (2) in the presence and absence of a moving target for the specified multiplicative interference meets serious mathematical difficulties. Therefore, let us consider the classical problem of useful signal detection (1) against the background of additive normal uncorrelated noise. The solution to this problem is a correlation method of detection or an equivalent method of detection based on a consistent filter [6].

The structure of the optimal detector of a small-sized mobile drone for the conditions under consideration is shown in Figure 2.

The detection algorithm for a small drone is expediently implemented in the digital processing unit of the aggregate of signal amplitudes from the received pulse sequence. However, to implement this algorithm, in particular, to set the threshold, accurate knowledge is required, for example, of such parameters as the coordinates (angular position) of the phase center (point) of the reflection of the background surface, the values of the current bistatic angles, and the three-dimensional shape of the bistatic effective target and background scattering surface. In addition, the moment of the beginning of the flight time of a small unmanned aerial vehicle relative to the radar-background line of sight is unknown. Under the conditions of a priori uncertainty regarding these parameters, the application of well-known approaches to its elimination greatly complicates the above algorithm and the structural diagram of the optimal detector. To obtain a practically feasible algorithm for detecting a small-sized mobile unmanned aerial vehicle, we make a number of simplifications with respect to the observation model $Y(t)$. These simplifications will lead to the implementation of a quasi-optimal detection algorithm.

The pulse characteristic of the matching filter $h(\tau)$ for the useful signal $A(t)$ is its mirror copy shifted in time by t_0. The structural scheme of a small drone detector at known parameters of its motion with the use of consistent filters is shown in Figure 2. If z_p exceeds the threshold, then the drone is detected (hypothesis H_1). Otherwise, the drone was not detected (hypothesis H_0).

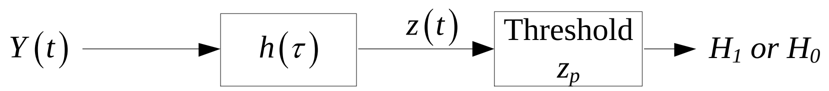

Figure 2. Structural scheme of a small drone detector with the use of a consistent filter at known parameters of its motion and initial phase.

The reference signal $A(t)$ has a random initial phase caused by the reflection of radio waves from the target, underlying surface and background. When radio waves reflect from those objects, the additional phase interference is random. To eliminate the dependence of the reference signal on the influence of the random phase attack in the reflection of radio waves, we use a structural scheme of the detector signal of known shape with a random initial phase. In this scheme, the detector contains two quadrature generators of reference signals.

In this case, the processing of the observed signal in the task of detecting a small target will consist in comparison with the threshold of the next decisive statistics:

$$z(t)=\sqrt{\left[\int_{-\infty}^{\infty} Y(t)A_0^c(t-\tau)d\tau\right]^2+\left[\int_{-\infty}^{\infty} Y(t)A_0^s(t-\tau)d\tau\right]^2}, \tag{3}$$

$Y(t)$ - the observable implementation of the signal at the detector input;
$A_0^c(t)$ - the cosine component of the reference signal for the matching filter $h_c(t)$;
$A_0^s(t)$ - the sine component of the reference signal for the matching filter $h_s(t)$.

Thus, if the motion parameters of a small drone are known, the detector can be represented by the scheme on the agreed filters at sufficiently stable characteristics of the background reflection.

In practice, the motion parameters of a small drone (trajectory, heading angle and speed) are not known. In this case the detector should be built according to the parallel scheme: each branch will contain a scheme (Figure 3). The branches of the parallel scheme will be distinguished by impulse reactions "tuned" to certain parameters of motion of a small drone.

3. The results of modeling the small drone detection in the near-ground propagation trace

To test the performance of the small drone detection algorithm by modeling, certain scenarios will be considered. The detection threshold z_p was chosen by the criterion of Neyman-Pearson based on the given probability of false detection P_F according to the known expression [13]:

$$\int_{z_p}^{\infty} W\left(z / H_0\right) dz = P_F \,, \tag{4}$$

where
H_0 - the null hypothesis that there is no signal.

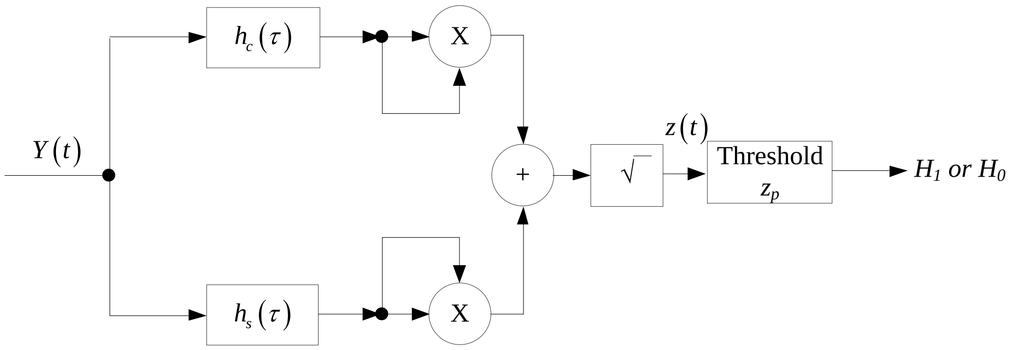

Figure 3. Structural scheme of a small drone detector with the use of a consistent filter at known parameters of its motion and initial phase.

The results of modeling the algorithm of detection of the small drone in the form of remote dependencies of statistical estimates of the probabilities of correct detection of *D* for some scenarios are presented below. Each estimate of the probability of correct detection is obtained by 1,000 iterations. In all scenarios, we will have the following data:

- the width of the transmitters antenna pattern in an azimuth plane equal to 1 degree by half the power level;
- the width of the transmitters antenna pattern in a vertical plane equal to 25 degrees by half the power level;
- Radiation power of 1 mW,
- average value of RCS $m_{\sigma t}$ = 36 m^2;
- RMS fluctuations of RCS target $\sigma_{\sigma t}$ = 0.1 m^2;
- average background RCS value $m_{\sigma f}$ = 300 m^2;
- signal-to-noise ratio when the target is positioned at a background of 30 dB.

Let us assume that the distance from the radar to the background D_f is 1,100 m. The movement speed of the small drone is 7 m/s and its direction coincides with the perpendicular to the radar background line.

Let us consider scenario. For the scenario we take RMS of background fluctuations $\sigma_{\sigma f}$=1 m^2, the interval of time correlation of background RMS fluctuations is set to $\tau_{\sigma f}$ = 0.01 s.

Below are the graphs of the correct detection probability for different distances to the target D_t for different false detection probabilities, P_F (Figure 4).

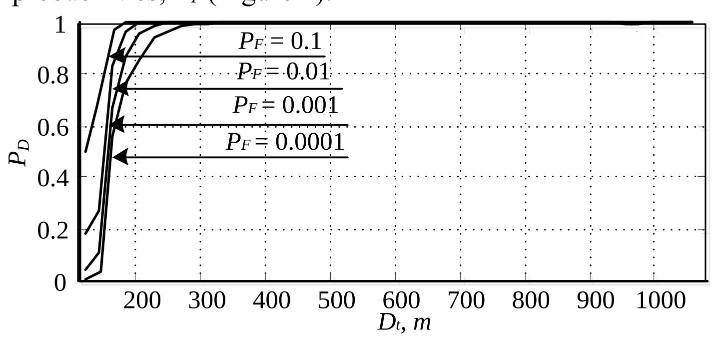

Figure 4. Estimates of the probability of correct detection depending on the target range for scenario 1, D_f = 1.100 m; v = 7 m/s; $\sigma_{\sigma f}$ = 1 m^2; $\tau_{\sigma f}$ = 0.01 s.

The analysis of the presented curves shows that the probability of correct detection of a small drone increases with approaching the background object. The increased fluctuations in the effective surface of the background object lead to a decrease in the probability of correct detection. Besides, at high signal to noise ratio the probability of correct detection of a small drone with a distance from the radar and approaching the background, all other things being equal, increases non-linearly. The presence of fluctuations in the effective background scattering surface reduces the probability of correct detection: with increasing RMS fluctuations of the effective background scattering surface, the probability of correct detection decreases.

4. Conclusions

The following conclusions can be drawn from the materials presented.

1. The approaches to the detection of moving targets in background radars presented in the literature are based on:
    - difference between the spectra reflected from the radio signal background in the presence and absence of a target;
    - comparison with the threshold of heuristic methods of averaging the output signal of a phase detector;
    - comparison with the threshold of the phase detector signal spectrum.
2. The presented method of detection of small-size drone for fluctuating background is quasi-optimal.
3. The use of a consistent filter detector provides acceptable detection performance for a small drone at low levels of fluctuations in the effective background scattering surface.
4. The increase in the mean square fluctuations of the effective background scattering surface leads to a decrease in the probability of correct detection under other equal conditions.

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