

THEORETICAL ESTIMATION OF TARGET DETECTION PROBABILITY IN SCANNING RADAR SYSTEMS

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Abstract. This paper addresses the problem of estimating target detection probabilities in surveillance radar systems operating with scanning antenna beams. Reliable evaluation of detection characteristics is a key task in radar engineering, since it determines the effectiveness of radar systems in monitoring airspace and detecting moving objects. Traditionally, such characteristics are obtained through large-scale experimental testing involving operational radar systems and numerous real targets. However, these experiments require substantial financial and time resources. Therefore, the development of theoretical and computational methods for estimating detection probabilities is of significant practical importance. The aim of this study is to develop a method for calculating unconditional probabilities of target detection for a surveillance radar system performing periodic scanning of a solid angle using a narrow beam. The research considers the detection of signals reflected from targets with random amplitude and initial phase, which corresponds to realistic radar observation conditions. The proposed methodology is based on radar detection theory and the Neyman – Pearson criterion. At the first stage, the radar energy potential is calculated using the radar equation in order to ensure a specified probability of correct detection under a fixed probability of false alarm. Based on these parameters, conditional detection probabilities are calculated for targets located at different distances within the radar operating range. In the second stage, a method is developed to determine unconditional detection probabilities that account for the cyclic scanning of the radar beam and the motion of the target toward the radar with constant velocity. The target trajectory is divided into small segments corresponding to radar scan cycles, and the cumulative probability of detection is calculated using an iterative probabilistic approach. The proposed method was implemented in computer programs that calculate conditional and unconditional detection probabilities for a wide range of radar parameters. Numerical experiments demonstrate the influence

of target velocity and scanning time on detection probability and detection range boundaries. The results show that increasing the target velocity or the radar scanning period significantly reduces the effective detection range. The developed method provides a practical tool for evaluating radar detection performance without conducting expensive field experiments.

Keywords: radar detection, probability of detection, surveillance radar, radar equation, Neyman–Pearson criterion, radar signal processing, radar performance modeling.

1. Introduction

Radar systems are a fundamental component of modern surveillance, navigation, and defense infrastructures, ensuring reliable detection and tracking of objects under various environmental and operational conditions. The effectiveness of radar systems is primarily determined by their detection performance, which is commonly characterized by the probability of detection under a constraint on the probability of false alarm [1]. This metric directly affects the reliability of decision-making processes in both civilian and military applications.

The theoretical basis of radar detection is grounded in statistical signal processing and detection theory. In particular, the Neyman–Pearson criterion provides an optimal framework for signal detection in noise by maximizing the probability of detection for a fixed false alarm rate [2]. For fluctuating targets, whose reflected signals exhibit random amplitude variations, probabilistic models such as the Swerling models are widely used to describe detection performance under realistic conditions [3]. These models form the foundation for calculating conditional probabilities of target detection.

The received signal power in radar systems is determined by the radar equation, which establishes a relationship between transmitted energy, propagation conditions, antenna parameters, and target radar cross-section [1]. This relationship enables the evaluation of the radar energy potential required to ensure specified detection characteristics at a given range. Practical aspects of radar signal processing, including detection threshold selection and signal-to-noise ratio estimation, are extensively discussed in [4, 5].

In modern surveillance radar systems employing scanning antenna beams, the detection process is inherently temporal. The radar periodically scans the observation space, and a target may be detected over multiple observation intervals. System-level parameters such as scanning strategy, revisit time, and antenna beamwidth significantly influence detection performance [6]. Under these conditions, it is necessary to distinguish between conditional detection probability, defined for a

single observation, and unconditional detection probability, which accounts for multiple independent detection attempts during repeated scans.

Recent studies have explored detection performance in multi-scan radar systems, emphasizing how integrating observations across multiple scans enhances detection capability, especially for weak or low-SNR targets. For example, multi-frame track-before-detect (MF-TBD) algorithms that accumulate signal energy over successive scans have been shown to improve detection performance and robustness in automotive and moving platform radar systems compared to single-scan processing [7]. In parallel, system-level aspects of detection and tracking in dynamic environments have been extensively studied in [8-10], highlighting the necessity of incorporating temporal dynamics into radar performance analysis.

In recent years, there has been growing interest in data-driven approaches to radar signal detection. Deep learning-based methods have demonstrated promising results in detecting low-probability-of-intercept (LPI) radar signals and improving robustness in complex noise environments [11, 12]. However, despite these advances, analytical methods based on classical statistical detection theory remain essential due to their interpretability, lower computational complexity, and suitability for system-level design and performance prediction.

Experimental methods for evaluating radar detection characteristics are highly reliable but require substantial financial, technical, and organizational resources, particularly when full-scale radar systems and real targets are involved [13]. Consequently, analytical and computational approaches for estimating detection probabilities without large-scale experimental testing remain an important and active area of research.

However, existing approaches predominantly focus on conditional detection probability or simplified multi-scan models and often do not fully account for the combined influence of cyclic antenna scanning and target motion within a unified probabilistic framework.

The novelty of this work lies in the development of an iterative probabilistic method for estimating unconditional detection probability that explicitly incorporates both antenna scanning periodicity and target motion dynamics. The proposed approach enables the evaluation of cumulative detection probability over multiple observation cycles and reveals the functional relationship between system temporal parameters and detection performance.

The proposed model is based on several simplifying assumptions. The target is assumed to move toward the radar along a rectilinear trajectory with constant velocity, while successive radar scan cycles are considered statistically independent. These assumptions make it possible to derive analytical expressions for cumulative detection probabilities. Although real radar scenarios may

involve maneuvering targets and correlated observations, the proposed model provides a useful first-order approximation suitable for theoretical performance assessment.

The study focuses on analyzing radar detection methods, calculating the radar energy potential, and developing methodologies for computing both conditional and unconditional detection probabilities, as well as implementing computational algorithms for these calculations.

2. Analysis of Methods for Radar-Based Object Detection

Radar technology is a branch of radio electronics that provides information about objects by means of reception and analysis of radio waves [1]. Objects of radar observation may include aircraft, missiles, ships, and automobiles, as well as natural objects such as clouds and planets.

The technical means for obtaining information about objects via reception and analysis of radio waves are called radar stations (RS) or radars [1].

The process of obtaining information about objects using radars can be divided into the following stages:

- detection of objects;
- measurement of coordinates and motion parameters;
- resolution;
- recognition of objects.

Detection involves making a decision concerning the presence or absence of an object in each designated region of space while maintaining minimally acceptable probabilities of erroneous decisions. Measurement consists of generating estimates of the coordinates and motion parameters of objects with minimally acceptable errors. Resolution involves performing detection and measurement tasks for a selected object in the presence of other objects. Recognition entails determining the classification of an object (for example, civilian aircraft, military fighter, or bomber) [1].

In radar technology, information about an object is obtained through the perturbation of the medium by the object, in particular via the effect of the object emitting radio waves [1]. Various types of radio-wave emission by an object exist: secondary emission, re-emission, and intrinsic emission of radio waves. In the first two cases, the radar transmits a powerful probing radio signal toward the object; in the latter case, irradiation of the object is not required.

Radar operation using secondary emission and re-emission (relay) is referred to as active radar, whereas radar operation utilizing the intrinsic emission of the object is referred to as passive radar [1].

In general, an object is not required to emit or re-emit radio waves, which makes secondary emission necessary in many situations to obtain radar information about the object. The radar's probing signal, incident on the object (primary electromagnetic wave), induces forced oscillations of electric charges within the object, causing it to generate its own electromagnetic field similarly to an antenna. This field constitutes a secondary, i.e., reflected, electromagnetic wave - the radar signal received by the radar and carrying information about the object.

The amplitude of the signal partially characterizes the size and reflective properties of the object. The time delay of the received signal relative to the start of the probing signal is used to measure the distance R , and the frequency of oscillations, due to the Doppler effect, provides information about the object's velocity. The direction of arrival of the reflected wave contains information about the object's angular coordinates [1].

Active radar systems can be classified as co-located or separated. In a co-located radar, the transmitting and receiving devices are positioned together (Figure 1) [1].

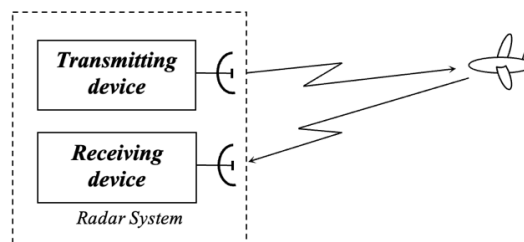


Fig. 1 – Combined radar station.

In a separated radar system, the transmitting and receiving devices are positioned at a distance d from each other (Figure 2) [1].

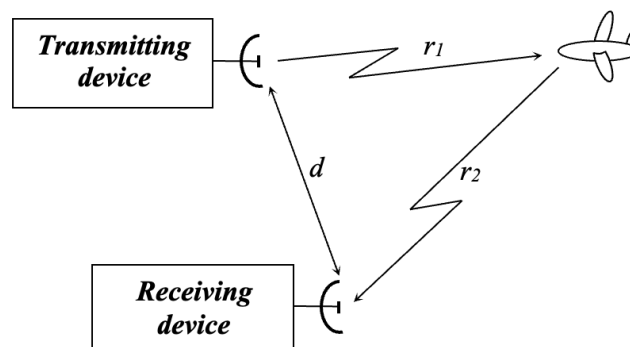


Fig. 2 – Distributed radar system.

In the case of passive radar, the object is not irradiated by electromagnetic waves. Electromagnetic oscillations are generated by the elements of the object itself: its heated parts

(thermal emission in the infrared or millimeter-wave range), radio-technical communication, navigation, and radar devices, as well as oscillating particles and ionized regions of the atmosphere in the vicinity of the object (radio emission during missile launch or a nuclear explosion) [1]. Reception can be performed by one or several separated receiving devices.

The present work focuses on a co-located radar station utilizing the secondary emission of radio waves by the object.

As a result of the radar detection process, a decision must be made regarding the presence or absence of an object within the resolution cell of the radar coverage area. The decision is made under two mutually exclusive hypotheses:

A_1 - the object is present

A_0 - the object is absent

The decision is made by a detector (either a device or a human operator) based on the analysis of the signal $y(t)$, received from the resolution cell and processed by the radar receiver.

If an object is present within the resolution cell, the radar receiver input contains a mixture of the useful signal $s(t)$ (resulting from the secondary emission of the object) and interference $n(t)$ (noise that is always present at the input due to the thermal motion of charge carriers):

$$y(t) = s(t) + n(t) \quad (2.1)$$

This formulation corresponds to the classical problem of statistical signal detection in [1, 2].

If no object is present within the resolution cell, only interference is received at the radar receiver input:

$$y(t) = n(t) \quad (2.2)$$

Due to noise and fluctuations of the useful signal, each hypothesis (A_1, A_0) may correspond to two possible decisions:

A_1^* -object present

A_0^* -object absent

Thus, four possible combinations of the random events “decision” and “hypothesis” arise in the detection process:

$(A_1^*; A_1)$ - correct detection;

$(A_0^*; A_1)$ - missed detection;

$(A_1^*; A_0)$ - false alarm;

$(A_0^*; A_0)$ - correct rejection.

The performance measures of detection under the condition that the object is present are defined as:

$D = P(A_1^*|A_1)$ - probability of correct detection,

$\widehat{D} = P(A_0^*|A_1)$ -probability of missed detection.

The performance measures under the condition that the object is absent are defined as:

$F = P(A_1^*|A_0)$ - probability of false alarm,

$\widehat{F} = P(A_0^*|A_0)$ - probability of correct rejection.

Since

$$D + \widehat{D} = 1$$

$$F + \widehat{F} = 1$$

it is sufficient to consider only the conditional probabilities of correct detection D and false alarm F .

In radar detection theory, the Neyman–Pearson criterion, adopted from mathematical statistics, is widely used. According to this criterion, the optimal detector maximizes the probability of correct detection for a given constraint on the probability of false alarm [1, 2].

The value of the probability of false alarm for a resolution cell is determined based on practical considerations. Since a radar system scans a large number of resolution cells, the probability of false alarm is typically set to low values in order to avoid frequent false alerts, usually in the range:

$$F = 10^{-5} \div 10^{-8}$$

[1].

In the initial data for the present study, the value

$$F = 10^{-6}$$

is specified.

Various methods for processing received signals and detecting objects are employed in radar systems. These include correlation processing, filtering, and correlation–filtering methods for coherent signals, as well as noncoherent signal processing and noncoherent digital integration, among others [1].

In the present work, particular attention is given to coherent signal processing methods and their optimal detection according to the Neyman–Pearson criterion. It is well established that the optimal detector makes a decision regarding the presence or absence of an object in a resolution cell based on the value of the correlation integral:

$$z = \int_{-\infty}^{\infty} y(t)s(t)dt \quad (2.3)$$

This formulation corresponds to the matched filter approach, which is optimal for signal detection in additive noise under the Neyman–Pearson criterion [1, 2].

If the value of the correlation integral exceeds a threshold z_0 , i.e.,

$$z \geq z_0$$

the detector decides that an object is present in the resolution cell; if

$$z < z_0$$

the detector decides that the object is absent. The threshold value z_0 is selected based on the specified probability of false alarm for the resolution cell [2].

For the case of coherent signal processing and optimal detection, several scenarios are possible: the signal may have completely known parameters, or a random initial phase, or random amplitude and initial phase. The case of a signal with fully known parameters is considered below.

In this case, the probabilities of false alarm and correct detection are given by:

$$F = 0,5(1 - \Phi(q_0)) \quad (2.4)$$

$$D = 0,5(1 - \Phi(q_0 - q)) \quad (2.5)$$

where:

$\Phi(u) = \frac{2}{\sqrt{2\pi}} \int_0^u e^{-\frac{x^2}{2}} dx$ - is the probability integral (Gaussian distribution function),

$q_0 = \sqrt{\frac{2}{EN_0}} z_0$ - is the normalized threshold level,

$q = \sqrt{\frac{2E}{N_0}}$ - the detection parameter.

The detection parameter q is equal to the signal-to-noise ratio in terms of voltage at the output of the optimal (matched) filter, where E is the energy of the signal received by the radar and N_0 is the noise power spectral density at the receiver input [1, 2].

Detection of a signal with random initial phase. In this case, the probabilities of correct detection and false alarm are given by:

$$D = \int_{q_0}^{\infty} x I_0(qx) e^{-\frac{q^2+x^2}{2}} dx \quad (2.6)$$

$$F = \int_{q_0}^{\infty} x e^{-\frac{x^2}{2}} dx = e^{-\frac{q_0^2}{2}}, \quad (2.7)$$

where:

$$I_0(u) = \frac{1}{2\pi} \int_0^{2\pi} e^{u \cos(x-x_0)} dx \quad (2.8)$$

is the modified Bessel function of the first kind of zero order.

Thus, in this case, the normalized threshold level is directly determined from the probability of false alarm:

$$q_0 = \sqrt{-2 \ln F}$$

These expressions correspond to the classical results of statistical signal detection theory for noncoherent detection with unknown phase [2].

Detection of a fluctuating signal with random amplitude and initial phase. In this case, the probabilities of false alarm and correct detection are given by:

$$F = e^{-\frac{q_0^2}{2}} \quad (2.9)$$

$$D = F^{\frac{1}{1+E/N_0}} \quad (2.10)$$

Signals received by radar systems from real objects (such as aircraft, missiles, ships, and automobiles) located at random ranges typically exhibit random amplitudes and initial phases. In accordance with the specifications of the present study, the signal is also assumed to have random amplitude and initial phase.

These expressions correspond to classical models of fluctuating targets in statistical radar detection theory [1, 2].

3. Calculation of the radar energy potential

In accordance with the research specifications, it is required to calculate the energy potential of a radar system with the following characteristics:

- Radar antenna aperture area: $S_A = 6 \text{ m}^2$;
- Antenna utilization factor: $k_A = 0.6$;
- Antenna noise temperature: $t_a = 1$;
- Wavelength of the transmitted signal: $\lambda = 5 \text{ cm}$;
- Receiver noise figure: $F_r = 3$;
- Minimum radar range: $R_{min} = 20 \text{ km}$;
- Maximum radar range: $R_{max} = 200 \text{ km}$;
- Total signal losses during propagation and in the equipment: $10 \lg L = 13 \text{ dB}$.

The radar operates against a target with an effective radar cross-section (RCS) of $\sigma = 2 \text{ m}^2$.

Calculating the energy potential of the radar system involves determining the required energy of the transmitted signal so that the target can be detected at the maximum range with the specified detection performance, namely a conditional probability of correct detection D given a conditional probability of false alarm F . For this task, the assigned values are:

$$D = 0.3 \text{ and } F = 10^{-6}$$

The task requires calculating the energy potential of the radar system for a signal reflected from a target with random amplitude and initial phase.

The calculation is based on the radar equation, which relates the energy of the received signal E_r to the energy of the transmitted signal E_t , the target range R (distance from the radar to the target), and the characteristics of both the target and the radar system:

$$E_r = \frac{E_t G \sigma A}{(4\pi R^2)^2 L} \quad (3.1)$$

where:

G - antenna gain of the radar system,

A - effective antenna aperture,

L - total signal losses during propagation and in the equipment,

σ - effective radar cross-section (RCS) of the target.

This formulation corresponds to the standard radar energy budget used in radar engineering [1].

According to signal detection theory, in order to ensure the required detection performance (a probability of correct detection D for a given probability of false alarm F), the energy of the received signal E_r must exceed the receiver noise power spectral density N_0 by a factor of the detectability coefficient ν_0 :

$$E_r \geq \nu_0 N_0 \quad (3.2)$$

For the case of detection of a signal with random amplitude and initial phase, the detectability coefficient corresponding to the specified detection characteristics (D and F) is determined from the equation:

$$D = F^{\frac{1}{1+\nu_0}}$$

from which it follows that:

$$\nu_0 = \frac{\lg F}{\lg D} - 1 \quad (3.3)$$

Substituting equation (3.2) into the radar equation (3.1) yields the relation for the required transmitted signal energy:

$$E_t \geq \frac{(4\pi R^2)^2 L \nu_0 N_0}{G \sigma A} \quad (3.4)$$

These expressions are based on the classical radar energy budget and statistical detection theory for fluctuating targets [1, 2].

Relation (2.4) must hold for targets located at any distance within the radar's operational range. Therefore, for the calculation of the radar's energy potential, the maximum range R_{max} should be used. For shorter ranges, the detection performance will inherently be better (higher probability of correct detection D for a fixed probability of false alarm F).

According to noise theory, the power spectral density N_0 is calculated as:

$$N_0 = kT^0(F_r + t_a - 1) \quad (3.5)$$

where:

$k = 1,38 \cdot 10^{-23} \text{ J/K}$ is Boltzmann's constant, and

T^0 is the absolute temperature in Kelvin (typically $T^0 = 300 \text{ K}$).

Since the antenna gain G and effective aperture A are related to the antenna aperture area S_A by:

$$A = k_A S_A \quad (3.6)$$

$$G = \frac{4\pi}{\lambda^2} A \quad (3.7)$$

the required transmitted signal energy can be expressed as:

$$E_t \geq \frac{(4\pi R_{max}^2)^2 L \left(\frac{\lg F}{\lg D} - 1 \right) kT^0(F_r + t_a - 1)}{\sigma \frac{4\pi}{\lambda^2} (k_A S_A)^2} \quad (3.8)$$

After simplification, this becomes:

$$E_t \geq \frac{4\pi}{\sigma} \left(\frac{\lambda R_{max}^2}{k_A S_A} \right)^2 L \left(\frac{\lg F}{\lg D} - 1 \right) kT^0(F_r + t_a - 1) \quad (3.9)$$

Substituting the specified values into equation (3.9) gives:

$$E_t \geq \frac{4\pi}{2} \left(\frac{5 \cdot 10^{-2} (200 \cdot 10^3)^2}{0.6 \cdot 6} \right)^2 10^{1.3} \left(\frac{\lg 10^{-6}}{\lg 0.3} - 1 \right) 1,38 \cdot 10^{-23} \cdot 300(3 + 1 - 1) = 5 \text{ J}$$

Thus, by selecting a transmitted signal energy of $E_t = 5 \text{ J}$, the required detection performance at the maximum radar range $R_{max} = 200 \text{ km}$ is ensured: a conditional probability of correct detection $D = 0.3$ for a conditional probability of false alarm $F = 10^{-6}$.

These calculations are based on the classical radar energy budget and statistical detection theory for fluctuating targets [1, 2].

From the radar equation (3.1), it follows that as the target approaches the radar (i.e., as the target range R decreases), the energy of the signal received by the radar increases. Consequently, according to equation (2.10), the conditional probability of correct target detection also increases.

4. Calculation of conditional probabilities of object detection

In accordance with the detection characteristics for a signal reflected from a target with random amplitude and initial phase (2.9), (2.10), the conditional probability of correct detection D for a target located at a range R from the radar is calculated as:

$$D = \frac{1}{F^{1+E(R)/N_0}} \quad (4.1)$$

where:

F is the specified conditional probability of false alarm ($F = 10^{-6}$)

N_0 is the receiver noise power spectral density (3.5), and

$E(R)$ is the energy of the signal received from the target, calculated using the radar equation:

$$E(R) = E_r = \frac{E_t G \sigma A}{(4\pi R^2)^2 L} \quad (4.2)$$

These expressions allow determining the variation of the probability of correct detection with target range for signals with random amplitude and phase [1, 2].

Using relations (3.6) and (3.7), which link the antenna gain G and effective antenna aperture A to the antenna aperture area S_A and utilization factor k_A , the conditional probabilities of correct target detection were calculated over the range of distances from R_{min} to R_{max} according to equations (4.1) and (4.2).

The calculations were performed using a computer, and the results are presented in the graph (Figure 3).

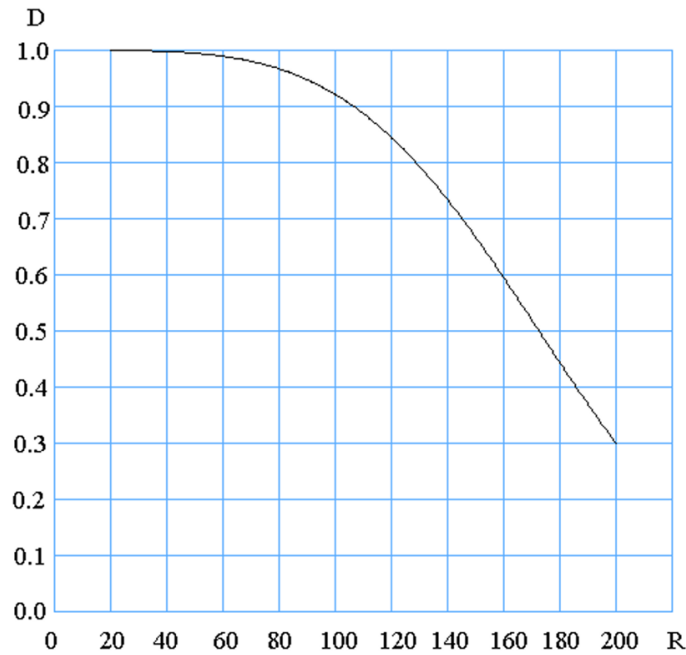


Fig. 3 – Conditional detection probabilities across the radar operating range.

Analysis of the graph indicates that at the maximum range, the conditional probability of correct detection is $D = 0.3$, which is consistent with the calculated energy potential of the radar system. As the target approaches the radar, the conditional probability of detection increases, reaching a value of 1 at the minimum range.

5. Development of a method for calculating unconditional probabilities of object detection

It is required to calculate the unconditional probabilities $P(R)$ of detecting a target over the range of distances $R_{min} \leq R \leq R_{max}$ for the radar and target motion models described below.

The radar performs a scan of the solid angle Ω_0 using a narrow beam (Figure 4).

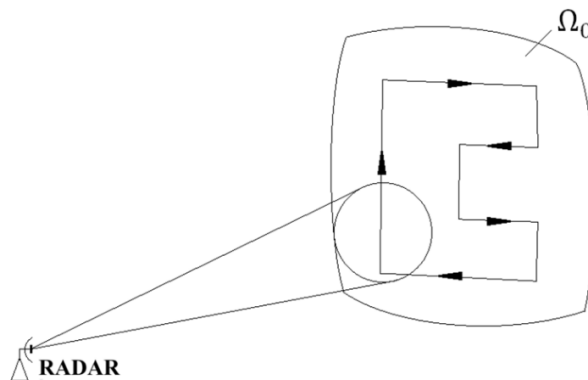


Fig. 4 – The radar scans a solid angle Ω_0 .

The time required for the radar to complete a single scan of the solid angle Ω_0 is T_{scan} . After completing one scan of Ω_0 , the radar immediately begins the next scan, and so on.

The target starts moving toward the radar at a constant speed V from a distance exceeding the radar's maximum range R_{max} . During motion, the target remains within the solid angle Ω_0 and does not change its angular position. As it approaches the radar, the target becomes available for detection starting from range R_{max} . However, the radar may fail to detect the target at R_{max} because, at the moment the target enters the radar coverage area, the beam may be directed toward a different part of the solid angle Ω_0 .

Once the radar completes a full scan of Ω_0 after the target enters its coverage, the radar beam is guaranteed to make a single contact with the target. The first contact of the radar beam with the target occurs at a distance within the range from $R_{max} - VT_{scan}$ to R_{max} . Since the probability of detection is low at long ranges, the target may not be detected during the first scan cycle.

The radar still has the opportunity to detect the target in the second scan cycle, at a distance within the range from $R_{max} - 2VT_{scan}$ to $R_{max} - VT_{scan}$; in the third scan cycle, at a distance from $R_{max} - 3VT_{scan}$ to $R_{max} - 2VT_{scan}$; and so on, until the target leaves the coverage area, approaching the radar to a distance less than R_{min} .

The unconditional probabilities $P(R)$ of detecting a target can be determined in two ways:

Conduct experiments, based on their results, construct a graph of the estimated unconditional probability of detection $P_{exp}(R)$.

Calculate the unconditional probabilities $P(R)$ theoretically.

The aim of this work is to calculate the unconditional probabilities of target detection theoretically. However, it is useful first to understand the methodology for constructing the graph of the estimated unconditional probability $P_{exp}(R)$ based on experimental results.

The experiments consist of performing a series of a large number N of independent trials (ideally, $N \rightarrow \infty$). In each trial, the target moves toward the radar at a constant speed V from a distance exceeding the radar's maximum range R_{max} . The radar performs a scan of the solid angle Ω_0 using a narrow beam, attempting to detect the target. The time required for the radar to complete a single scan of Ω_0 is T_{scan} . After completing one scan, the radar immediately begins the next scan, and so on. During motion, the target remains within the solid angle Ω_0 and does not change its angular position.

Independence of the trials implies that in each trial, the moments when the radar starts its periodic scan of the solid angle and when the target begins to move are independent. Therefore, the ranges at which the radar detects the target in different trials are also independent.

Let R_n denote the range at which the radar detects the target in the n -th trial. After performing N independent trials, an array of detection ranges is obtained: $R_1, R_2, R_3, \dots, R_N$. Without loss of generality, assume that the array is ordered such that $R_1 \geq R_2 \geq R_3 \geq \dots \geq R_N$; otherwise, the trials can simply be renumbered.

The experimental results can be represented graphically (Figure 5).

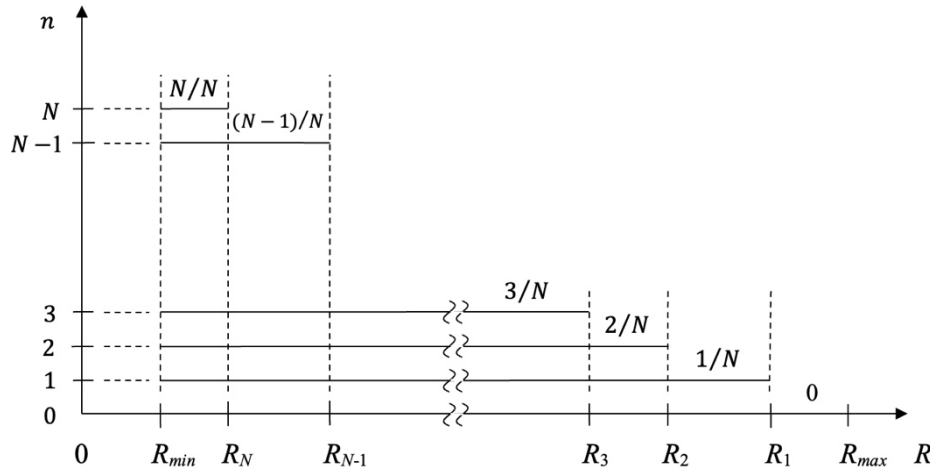


Fig. 5 – Results of object detection experiments.

In the graph shown in Figure 5, for each trial n ($n = 1, 2, 3, \dots, N$, the trial number plotted along the vertical axis), a horizontal line segment represents the range of distances from R_n (the range at which the target was detected in the n -th trial) down to the minimum radar range R_{min} . For each distance R within the interval $R_{n+1} \leq R \leq R_n$, the relative number of detected targets n/N is indicated above the horizontal segment. This value serves as the estimate of the unconditional probability $P_{exp}(R)$ of detecting the target at distance R based on the experimental results. It should be noted that the values shown in Figure 5 represent cumulative unconditional detection probabilities. For a given distance R , the probability corresponds to the fraction of trials in which the target has already been detected before reaching that distance.

The interval $R_{n+1} \leq R \leq R_n$ corresponds to distances at which exactly n targets out of N have already been detected. Therefore, the estimated cumulative unconditional probability within this interval is equal to n/N . For distances greater than R_n , the n -th target has not yet been detected, whereas for distances smaller than R_{n+1} , at least $(n + 1)$ targets have already been detected.

Using the graphical representation of the experimental results, it is straightforward to construct the graph of the estimated unconditional probability of detection $P_{exp}(R)$. For this, for each distance interval $R_{n+1} \leq R \leq R_n$, the relative number of detected targets n/N from the series of

experiments is plotted along the vertical axis, and a horizontal line segment is drawn at this level (Figure 6).

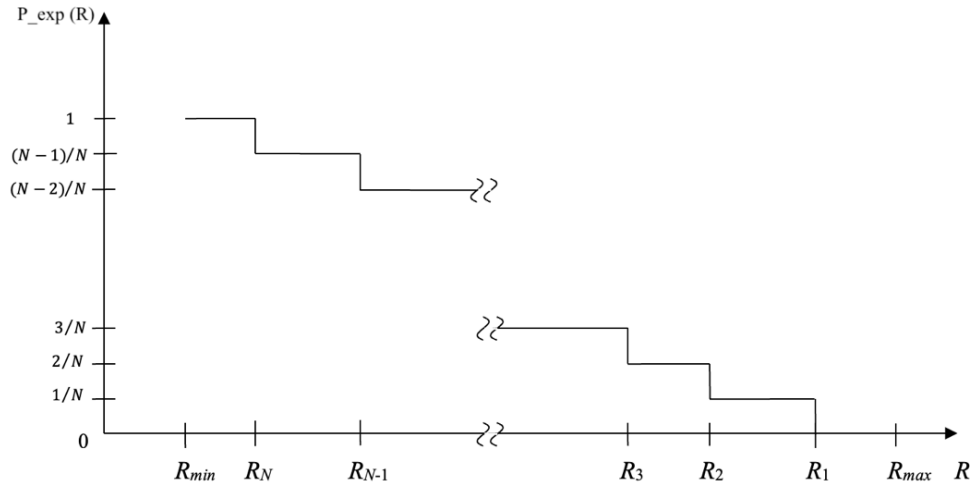


Fig. 6 – Graph of the estimated unconditional detection probability derived from a series of experiments.

Let $R_{scan} = V \cdot T_{scan}$ denote the distance traveled by the target during the time of a single radar scan of the solid angle.

The first scan-cycle segment, corresponding to the distance traveled by the target during the first radar scan cycle after entering the radar coverage area, from $R_{max} - R_{scan}$ to R_{max} , is divided into m subsegments of length $\Delta r = R_{scan}/m$ (Figure 7). It is assumed that the subsegment length Δr is sufficiently small so that the conditional probability of detection can be considered constant over this segment:

$$D_i = D(R_{max} - (i - 1)\Delta r) \approx D(R_{max} - i\Delta r) \text{ where } i = 1, 2, 3, \dots, m$$

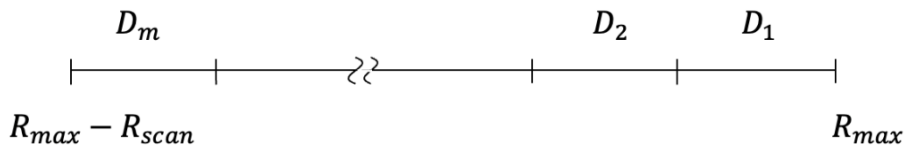


Fig. 7 – Subdivision of the first scan-cycle segment into m subsegments.

The number of trials l_1 in which the radar detects the target on the first subsegment, from $R_{max} - \Delta r$ to R_{max} , is calculated as:

$$l_1 = N \cdot \frac{\Delta r}{R_{scan}} \cdot D_1$$

where:

$N \cdot \frac{\Delta r}{R_{scan}}$ is the number of trials in which the radar had contact with the target while it moved along the first subsegment, and D_1 is the conditional probability of detecting the target on the first subsegment, given that the radar had contact with it.

The quantity $N \cdot \Delta r / R_{scan}$ does not represent the cumulative number of radar contacts accumulated over several scan cycles. Instead, it represents the number of trials in which the target is located within the considered subsegment at the moment of a radar contact. Since the first contact position within each scan-cycle segment is assumed to be uniformly distributed over the interval R_{scan} , the expected number of such contacts is identical for all subsegments and equals $N \cdot \Delta r / R_{scan}$.

Additional contacts occurring during subsequent scan cycles are taken into account through the recursive terms Q_{m+i} , Q_{2m+i} , and so forth, rather than through the factor $N \cdot \Delta r / R_{scan}$ itself.

The probability of detecting the target on the first subsegment is

$$P_1 = Q_1 = \frac{l_1}{N} = \frac{\Delta r}{R_{scan}} \cdot D_1 = \frac{1}{m} \cdot D_1 \quad (5.1)$$

The number of trials l_2 in which the radar detects the target on the second subsegment, from $R_{max} - 2\Delta r$ to $R_{max} - \Delta r$

$$l_2 = N \cdot \frac{\Delta r}{R_{scan}} \cdot D_2$$

and the probability of detecting the target on the second subsegment is

$$Q_2 = \frac{l_2}{N} = \frac{\Delta r}{R_{scan}} \cdot D_2 = \frac{1}{m} \cdot D_2 \quad (5.2)$$

The probability of detecting the target on either the first or second subsegment is

$$P_2 = \frac{l_1 + l_2}{N} = P_1 + Q_2 \quad (5.3)$$

By the same reasoning, the probability of detecting the target after it passes all m subsegments, i.e., by the time it reaches the distance $R_{max} - R_{scan}$, is:

$$P_m = \frac{l_1 + l_2 + \dots + l_m}{N} = P_{m-1} + Q_m \quad (5.4)$$

The second scan-cycle segment over which the target moves during the second radar scan cycle, from $R_{max} - 2R_{scan}$ to $R_{max} - R_{scan}$, is also divided into m subsegments, which are numbered from $m + 1$ to $2m$ (Figure 8). The numbering of the subsegments corresponding to the second scan cycle continues sequentially.

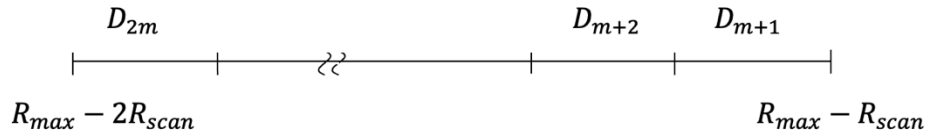


Fig. 8 – Subdivision of the second scan-cycle segment into m subsegments.

In the last equality, the number of trials l_1 , in which the target was detected on the first subsegment, is subtracted from the total number of trials $N \cdot \frac{\Delta r}{R_{scan}}$ in which the radar had contact with the target on the $(m + 1)$ -th subsegment, since only the trials in which the target is detected for the first time on this subsegment are considered.

The probability of detecting the target on the $(m + 1)$ -th subsegment is

$$Q_{m+1} = \frac{l_{m+1}}{N} = \left(\frac{1}{m} - Q_1 \right) \cdot D_{m+1} \quad (5.5)$$

$$Q_{m+1} = \frac{l_{m+1}}{N} = \left(\frac{1}{m} - Q_1 \right) \cdot D_{m+1}$$

The probability of detecting the target by the time it has passed all $(m + 1)$ subsegments, i.e., at a distance $R_{max} - R_{scan} - \Delta r$, is

$$P_{m+1} = \frac{l_1 + l_2 + \dots + l_m + l_{m+1}}{N} = P_m + Q_{m+1} \quad (5.6)$$

Similarly, the number of trials l_{m+2} in which the radar first detects the target on the $(m + 2)$ -th subsegment, i.e., at a distance from $R_{max} - R_{scan} - 2\Delta r$ to $R_{max} - R_{scan} - \Delta r$, is

$$l_{m+2} = \left(N \cdot \frac{\Delta r}{R_{scan}} - l_2 \right) \cdot D_{m+2}$$

and the probability of detection on this subsegment is

$$Q_{m+2} = \frac{l_{m+2}}{N} = \left(\frac{1}{m} - Q_2 \right) \cdot D_{m+2} \quad (5.7)$$

The probability of detecting the target by the time it has passed all $(m + 2)$ subsegments, i.e., at a distance $R_{max} - R_{scan} - 2\Delta r$, is

$$P_{m+2} = \frac{l_1 + l_2 + \dots + l_{m+1} + l_{m+2}}{N} = P_{m+1} + Q_{m+2} \quad (5.8)$$

For the last, $2m$ -th subsegment of the second scan cycle, the number of trials l_{2m} in which the radar first detects the target is

$$l_{2m} = \left(N \cdot \frac{\Delta r}{R_{scan}} - l_m \right) \cdot D_{2m}$$

the probability of detection on this subsegment is

$$Q_{2m} = \frac{l_{2m}}{N} = \left(\frac{1}{m} - Q_m \right) \cdot D_{2m} \quad (5.9)$$

and the probability of detecting the target by the time it has passed all $2m$ subsegments, i.e., at a distance $R_{max} - 2R_{scan}$, is

$$P_{2m} = \frac{l_1 + l_2 + \dots + l_{2m-1} + l_{2m}}{N} = P_{2m-1} + Q_{2m} \quad (5.10)$$

The third scan-cycle segment over which the target moves during the third radar scan cycle, from $R_{max} - 3R_{scan}$ to $R_{max} - 2R_{scan}$, is also divided into m , which are numbered from $2m + 1$ to $3m$ (Figure 9). The numbering of the subsegments corresponding to the previous scan cycles continues sequentially

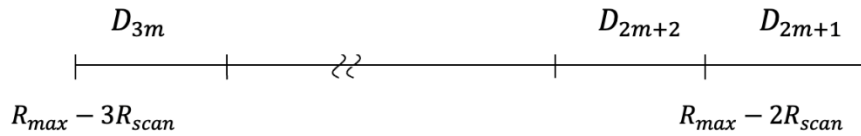


Fig. 9 – Subdivision of the third scan-cycle segment into m subsegments

The number of trials l_{2m+1} in which the radar first detects the target on the $(2m + 1)$ -th subsegment is

$$l_{2m+1} = \left(N \cdot \frac{\Delta r}{R_{scan}} - l_1 - l_{m+1} \right) \cdot D_{2m+1}$$

In the last equality, the number of trials l_1 , in which the target was detected on the first subsegment, and the number of trials l_{m+1} , in which the target was detected on the $(m + 1)$ -th subsegment, are subtracted from the total number of trials $N \cdot \frac{\Delta r}{R_{scan}}$, since only trials in which the target is detected for the first time on the $(2m + 1)$ -th subsegment are considered.

The probability of detecting the target on the $(2m + 1)$ -th subsegment is

$$Q_{2m+1} = \frac{l_{2m+1}}{N} = \left(\frac{1}{m} - Q_1 - Q_{m+1} \right) \cdot D_{2m+1} \quad (5.11)$$

The probability of detecting the target by the time it has passed all $(2m + 1)$ subsegments, i.e., at a distance $R_{max} - 2R_{scan} - \Delta r$, is

$$P_{2m+1} = \frac{l_1 + l_2 + \dots + l_{2m} + l_{2m+1}}{N} = P_{2m} + Q_{2m+1} \quad (5.12)$$

Similarly, the probability of detection on the $(2m + 2)$ -th subsegment is

$$Q_{2m+2} = \frac{l_{2m+2}}{N} = \left(\frac{1}{m} - Q_2 - Q_{m+2} \right) \cdot D_{2m+2} \quad (5.13)$$

and the probability of detecting the target by the time it has passed all $2m + 2$ subsegments is

$$P_{2m+2} = \frac{l_1 + l_2 + \dots + l_{2m+1} + l_{2m+2}}{N} = P_{2m+1} + Q_{2m+2} \quad (5.14)$$

Continuing this reasoning, the probability of detection on the $3m$ -th subsegment is

$$Q_{3m} = \frac{l_{3m}}{N} = \left(\frac{1}{m} - Q_m - Q_{2m} \right) \cdot D_{3m} \quad (5.15)$$

and the probability of detecting the target by the time it has passed all $3m$ subsegments is

$$P_{3m} = \frac{l_1 + l_2 + \dots + l_{3m-1} + l_{3m}}{N} = P_{3m-1} + Q_{3m} \quad (5.16)$$

The fourth scan-cycle segment over which the target moves, from $R_{max} - 4R_{scan}$ to $R_{max} - 3R_{scan}$, is again divided into m subsegments, numbered from $3m + 1$ to $4m$.

For the probabilities of detecting the target on these subsegments, obtain:

$$Q_{3m+1} = \left(\frac{1}{m} - Q_1 - Q_{m+1} - Q_{2m+1} \right) \cdot D_{3m+1} \quad (5.17)$$

$$Q_{3m+2} = \left(\frac{1}{m} - Q_2 - Q_{m+2} - Q_{2m+2} \right) \cdot D_{3m+2} \quad (5.18)$$

$$Q_{3m+3} = \left(\frac{1}{m} - Q_3 - Q_{m+3} - Q_{2m+3} \right) \cdot D_{3m+3} \quad (5.19)$$

...

$$Q_{4m} = \left(\frac{1}{m} - Q_m - Q_{2m} - Q_{3m} \right) \cdot D_{4m} \quad (5.20)$$

For the probabilities of detecting the target by the time it has passed these subsegments and all preceding subsegments:

$$P_{3m+1} = P_{3m} + Q_{3m+1} \quad (5.21)$$

$$P_{3m+2} = P_{3m+1} + Q_{3m+2} \quad (5.22)$$

$$P_{3m+3} = P_{3m+2} + Q_{3m+3} \quad (5.23)$$

...

$$P_{4m} = P_{4m-1} + Q_{4m} \quad (5.24)$$

The fifth scan-cycle segment is again divided into m subsegments, and the probabilities of detecting the target on these subsegments are computed as:

$$Q_{4m+1} = \left(\frac{1}{m} - Q_1 - Q_{m+1} - Q_{2m+1} - Q_{3m+1} \right) \cdot D_{4m+1} \quad (5.25)$$

$$Q_{4m+2} = \left(\frac{1}{m} - Q_2 - Q_{m+2} - Q_{2m+2} - Q_{3m+2} \right) \cdot D_{4m+2} \quad (5.26)$$

$$Q_{4m+3} = \left(\frac{1}{m} - Q_3 - Q_{m+3} - Q_{2m+3} - Q_{3m+3} \right) \cdot D_{4m+3} \quad (5.27)$$

...

$$Q_{5m} = \left(\frac{1}{m} - Q_m - Q_{2m} - Q_{3m} - Q_{4m} \right) \cdot D_{5m} \quad (5.28)$$

The probabilities of detecting the target by the time it has passed all these subsegments, and all previous subsegments are:

$$P_{4m+1} = P_{4m} + Q_{4m+1} \quad (5.29)$$

$$P_{4m+2} = P_{4m+1} + Q_{4m+2} \quad (5.30)$$

$$P_{4m+3} = P_{4m+2} + Q_{4m+3} \quad (5.31)$$

...

$$P_{5m} = P_{5m-1} + Q_{5m} \quad (5.32)$$

These derivations allow us to formulate the algorithm for calculating the unconditional probabilities $P(R)$ of detecting a target within the range $R_{min} \leq R \leq R_{max}$:

Divide the distance interval $R_{max} - R_{min}$ into M scan-cycle segments of length. In what follows, the term scan-cycle segment refers to a path interval of length R_{scan} , whereas the term subsegment refers to a subdivision of a scan-cycle segment of length Δr .

$$R_{scan} = V \cdot T_{scan}$$

where:

$$M = \left\lceil \frac{R_{max} - R_{min}}{R_{scan}} \right\rceil$$

and number the scan-cycle segments from right to left – see Figure 10.

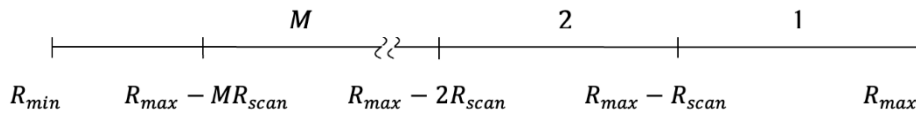


Fig. 10 – Subdivision of the range interval $R_{max} - R_{min}$ into M scan-cycle segments.

Each resulting scan-cycle segment corresponds to the path traveled by the target during one radar scan cycle. If the values $R_{max} - R_{min}$ and R_{scan} are not multiples of each other, then dividing the interval $R_{max} - R_{min}$ into scan-cycle segments of length R_{scan} will produce a remaining interval of length $R_{max} - R_{min} - MR_{scan}$, which is smaller than R_{scan} .

Each scan-cycle segment is further divided into m subsegments of length $\Delta r = R_{scan}/m$ (see Figures 7-9).

In the computer program used for numerical calculations, $m = 75$ was adopted. This value provides sufficiently small subsegments so that the conditional probability of detection may be

considered approximately constant within each subsegment. Additional refinement of the subdivision was found to have a negligible effect on the calculated unconditional probability curves.

Test calculations were performed for $m = 50, 75$ and 100 . The differences between the resulting unconditional probability curves were negligible; therefore, $m = 75$ was selected as a compromise between computational accuracy and execution time.

Let's assume that the length of the subsegment Δr is small enough that the conditional probability of detecting the target on this subsegment can be considered constant, i.e.,

$$\begin{aligned} D_{(j-1)m+i} &= D(R_{\max} - (j-1)R_{\text{scan}} - (i-1)\Delta r) \approx \\ &\approx D(R_{\max} - (j-1)R_{\text{scan}} - i\Delta r) \end{aligned}$$

where: $j = 1, 2, 3, \dots, M$; $i = 1, 2, 3, \dots, m$.

The conditional probability $D_{(j-1)m+i}$ of detecting the target at a distance $R = R_{\max} - (j-1)R_{\text{scan}} - (i-1)\Delta r$ given that the radar beam is directed at the target, is calculated as:

$$D_{(j-1)m+i} = \frac{1}{F^{1+E(R)/N_0}}$$

where:

$F = 10^{-6}$ is the given probability of false alarm,

$R = R_{\max} - (j-1)R_{\text{scan}} - (i-1)\Delta r$ is the target distance,

$E(R)$ is the signal energy received from the target by the radar, given by equation (4.2),

N_0 is the noise power spectral density of the receiver, given by equation (3.5).

The unconditional probabilities $P_{(j-1)m+i}$ of detecting the target at the distance $R = R_{\max} - (j-1)R_{\text{scan}} - (i-1)\Delta r$ are calculated using the formulas:

$$P_{(j-1)m+i} = P_{(j-1)m+i-1} + Q_{(j-1)m+i} \quad (5.33)$$

$$Q_{(j-1)m+i} = \left(\frac{1}{m} - \sum_{k=1}^{j-1} Q_{(k-1)m+i} \right) D_{(j-1)m+i} \quad (5.34)$$

$$j = 1, 2, 3, \dots, M; \quad i = 1, 2, 3, \dots, m \quad (5.35)$$

When using these formulas, it should be assumed that

$$P_0 = 0 \text{ and } \sum_{k=1}^0 Q_{(k-1)m+i} = 0$$

Using the developed calculation methodology, a computer program has been designed and tested that allows calculating the conditional probabilities of detection over the radar's range for given radar and target characteristics.

The program takes the following input data:

$E_{emit} = 5 J$ – energy of the emitted signal;

$S_A = 6 m^2$ – antenna aperture area of the radar;

$k_A = 0.6$ – aperture utilization factor of the antenna;

$t_a = 1$ – relative antenna noise temperature;

$\lambda = 5 cm$ – wavelength of the emitted signal;

$F_n = 3$ – receiver noise factor of the radar;

$R_{min} = 20000 m$ – minimum radar range;

$R_{max} = 200000 m$ – maximum radar range;

$F = 10^{-6}$ – conditional probability of false alarm;

$10\lg L = 13 dB$, L – total signal energy losses due to propagation and radar processing;

$\sigma = 2 m^2$ – effective radar cross-section (RCS) of the target.

The program calculates and outputs the conditional probabilities of target detection across the radar range from R_{min} to R_{max} in the form of a graph. The results of the program are shown in Figure 3.

By modifying the radar parameters and the target's RCS, the program can be used to calculate conditional probabilities of detection for any scenarios of interest to the developers.

When specifying the input data, the program requires parameters similar to those used in the calculation of conditional probabilities, as well as additional data on:

the target closing velocity relative to the radar, $V = 700 m/s$;

the duration of a single radar scan cycle over the solid angle, $T_{scan} = 15 s$.

The results of the program for the specified input data are presented in Figure 11.

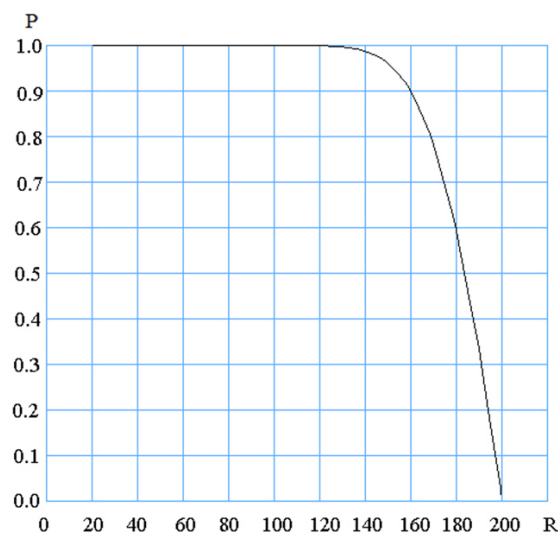


Fig. 11 – Unconditional probabilities of object detection over the radar operating range.
 Object speed $V = 700 m/s$, scan time $T_{scan} = 15 s$.

During a single radar scan cycle over the solid angle, the target travels a distance:

$$R_{scan} = V \cdot T_{scan} = 10.5 \text{ km}$$

During the first scan cycle (the first one after the target crosses the boundary $R_{max} = 200 \text{ km}$), the radar is guaranteed to have contact with all N targets involved in the N experiments. Since the conditional probability of detection at maximum ranges is close to 0.3 (see Figure 3), the radar will detect approximately 30% of the targets during the first scan cycle.

The data in Figure 11 confirm this: at the end of the first scan cycle:

$$R = R_{max} - R_{scan} = 189.5 \text{ km}$$

the unconditional probability of detection is equal to 0.3.

At the end of the second scan cycle

$$R = R_{max} - 2R_{scan} = 179 \text{ km}$$

the probability of detection is approximately

$$1 - (1 - 0.3) \cdot (1 - 0.45) = 0.615$$

where:

$(1 - 0.3)$ is the probability of not detecting the target during the first scan cycle;

$(1 - 0.45)$ is the probability of not detecting the target during the second scan cycle.

According to Figure 11, at the end of the second scan cycle

$$R = R_{max} - 2R_{scan} = 179 \text{ km}$$

the unconditional probability of detection is equal to 0.61.

The graph of unconditional detection probabilities makes it possible to determine the range thresholds at which the radar will detect a given proportion of targets with certainty.

For example, as follows from Figure 11, by the range of 180 km the radar detects 60% of all approaching targets, by 160 km – 90%, and by 120 km – 100% of the targets.

By varying the radar parameters, the target radar cross-section (RCS), the target velocity, and the scan time of the solid angle, the unconditional probabilities of detection can be calculated using the developed program for any scenarios of interest.

Figure 12 presents the unconditional detection probabilities calculated by the program for input data that differ from those used for Figure 11 only in the target velocity: in Figure 12, the target velocity is increased by a factor of 5, from 700 m/s to 3500 m/s .

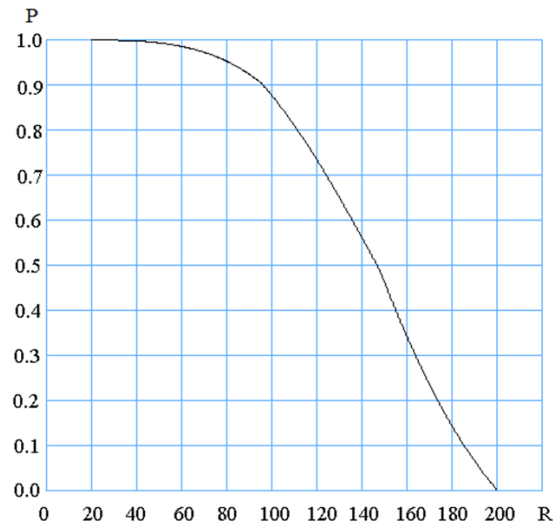


Fig. 12 – Unconditional probabilities of object detection over the radar operating range.
 Object speed $V = 3500 \text{ m/s}$, scan time $T_{scan} = 15 \text{ s}$

As follows from Figure 12, an increase in the target velocity leads to a reduction in the range thresholds at which the radar is capable of detecting the target with a given probability.

Thus, with a probability of 0.6, the radar detects the target at a range of 135 km (instead of 180 km , as shown in Figure 11), and with a probability of 0.9 – at a range of 95 km (instead of 160 km).

A further increase in the target velocity from 3500 m/s to 7000 m/s (see Figure 13) brings the detection thresholds even closer to the radar. It should be noted that at such high target velocities, there is a probability of 0.05 that the radar will fail to detect the target over the entire range interval.

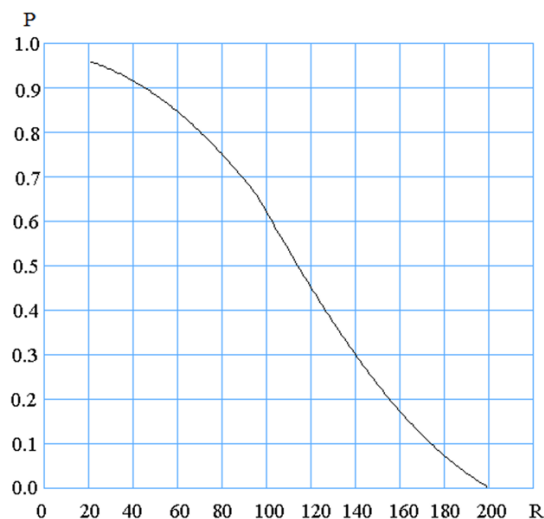


Fig. 13 – Unconditional probabilities of object detection over the radar operating range.
 Object speed $V = 7000 \text{ m/s}$, scan time $T_{scan} = 15 \text{ s}$.

A decrease in the target velocity from 700 m/s to 350 m/s (see Figure 14) shifts the detection range thresholds farther away from the radar.

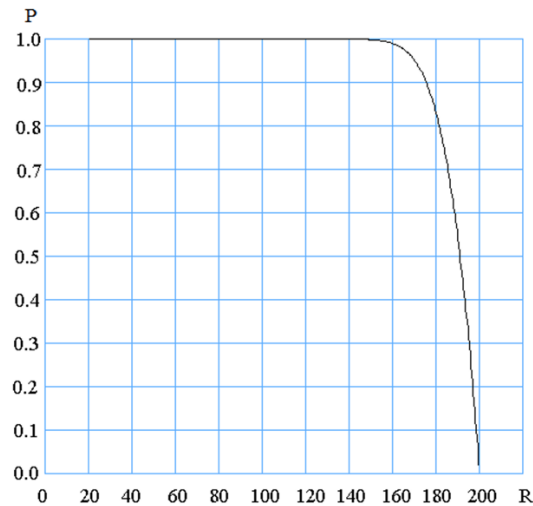


Fig. 14 – Unconditional probabilities of object detection over the radar operating range.
 Object speed $V = 350 \text{ m/s}$, scan time $T_{scan} = 15 \text{ s}$.

It is also of interest to analyze how the scan time of the solid angle affects the detection range thresholds.

Figure 15 presents the unconditional detection probabilities calculated by the program for input data that differ from those used for Figure 11 only in the scan time of the solid angle: for Figure 15, the scan time is increased by a factor of 5, from 15 s to 75 s.

A comparison of Figures 11 and 15 shows that an increase in the scan time also leads to a reduction in the detection range thresholds.

It should be noted that the curves of unconditional detection probabilities in Figures 15 and 12 are identical. Thus, increasing the target velocity or, equivalently, increasing the scan time by the same factor has the same effect on the unconditional probabilities of detection.

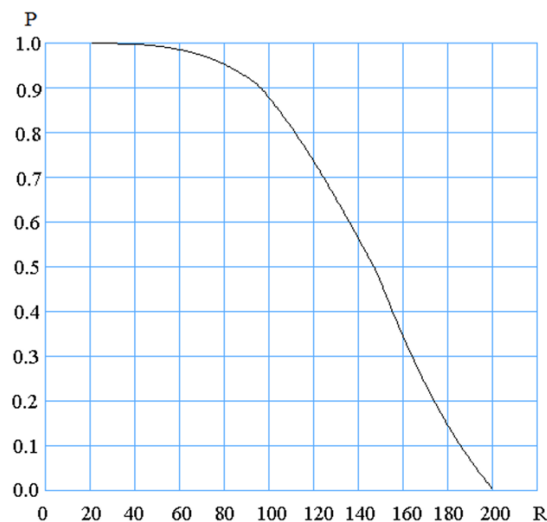


Fig. 15 – Unconditional probabilities of object detection over the radar operating range.
 Object speed $V = 700 \text{ m/s}$, scan time $T_{scan} = 75 \text{ s}$.

6. Conclusions

The present study developed a theoretical and computational framework for estimating both conditional and unconditional probabilities of target detection in surveillance radar systems employing scanning antenna beams.

At the first stage, the radar energy potential was determined using the radar equation under the Neyman–Pearson criterion for a specified probability of false alarm. This ensured the required conditional probability of correct detection at the maximum operational range. Based on this energy potential, conditional detection probabilities were calculated as functions of target range, confirming the expected monotonic increase in detection probability as the target approaches the radar.

At the second stage, a novel method for calculating unconditional detection probabilities was proposed. The method accounts for the temporal nature of radar operation, including cyclic beam scanning and target motion. By discretizing the target trajectory into segments corresponding to scan cycles and applying an iterative probabilistic approach, the cumulative detection probability was derived.

The scientific novelty of the work lies in the development of an iterative probabilistic framework that explicitly integrates antenna scanning periodicity with target motion, enabling the estimation of unconditional detection probability under realistic operational conditions. In contrast to traditional approaches focused primarily on single-scan or conditional detection models, the proposed method captures the cumulative effect of multiple observations over time.

Numerical experiments demonstrated that:

- the unconditional probability of detection significantly exceeds the conditional probability due to multiple observation opportunities;
- increasing target velocity leads to a reduction in effective detection range, as the number of observation opportunities decreases;
- increasing the radar scan time produces an equivalent effect to increasing target velocity, reducing detection performance;
- the combined influence of scan period and target dynamics is a critical factor in determining detection efficiency.

The results confirm that both target motion parameters and radar scanning characteristics play a decisive role in system-level detection performance. A key contribution of the study is the identification of the functional equivalence between scan time and target velocity in their impact on detection probability, which provides an important practical insight for radar system design and optimization.

The proposed method provides a practical alternative to costly experimental evaluations and can be used for performance prediction, parameter optimization, and system design of modern surveillance radar systems.

Future work may include extending the model to account for target maneuvering, non-uniform scanning strategies, correlated detection events, and the integration of modern data-driven detection techniques

REFERENCES

- [1] Barton D.K., *Radar System Analysis and Modeling*, Artech House, Boston, 2005, 549 p.
- [2] Blackman S., Popoli R., *Design and Analysis of Modern Tracking Systems*, 2nd ed., Artech House, 2021, 1232 p.
- [3] Guerri J.R., *Cognitive Radar: The Knowledge-Aided Fully Adaptive Approach*, 2nd ed., Artech House, 2023, 452 p.
- [4] Li W., Miao Q., Yuan Y., Tian Y., Yi W., The K.C., *Automotive Radar Multi-Frame Track-Before-Detect Algorithm Considering Self-Positioning Errors*, IEEE Press, New York, 2025, 32 p.
- [5] Mahafza B.R., *Radar Systems Analysis and Design Using MATLAB*, 4th ed., Chapman and Hall/CRC, Boca Raton, 2020, 672 p.
- [6] Park J., Kim Y., Kim H., *Deep Learning-Based Detection of LPI Radar Signals*, IEEE Access, 2023, Vol. 11, pp. 12345–12356.
- [7] Richards M.A., *Fundamentals of Radar Signal Processing*, 2nd ed., McGraw-Hill, New York, 2014, 1008 p.
- [8] Richards M.A., Scheer J.A., Holm W.A., *Principles of Modern Radar: Basic Principles*, SciTech Publishing, 2022, 945 p.
- [9] Ristic B., Vo B.N., Vo B.T., *Multi-Target Tracking and Data Fusion: Concepts and Applications*, 2nd ed., Artech House, 2020, 406 p.
- [10] Skolnik M.I., *Radar Handbook*, 3rd ed., McGraw-Hill, New York, 2008, 1352 p.
- [11] Swerling P., *Probability of Detection for Fluctuating Targets*, IRE Transactions on Information Theory, 1960, Vol. 6, No. 2, pp. 269–308.
- [12] Van Trees H.L., *Detection, Estimation, and Modulation Theory*, Part I, Wiley, New York, 2001, 1470 p.
- [13] Zhang Y., Liu Q., Wang X., *Deep Learning for Radar Signal Detection in Complex Environments*, Sensors, 2022, Vol. 22, No. 9, 3456.