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Detection of the Trajectories of Moving Rectilinearly Air Targets in the Secondary Processing of Radar Information

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Abstract

Introduction. The primary functions of secondary processing of radar information are to detect and maintain the trajectories of air targets (AT). The AT trajectory detection can be characterised by the probability of detecting trajectory and average autocapture time. When the target moves, its distance from the radar station changes, leading to a change in the signal/noise ratio and the probability of detecting AT.

Aim. To assess the impact of a change in the probability of detection of a straight and evenly moving target at consecutive time intervals of radar observation upon the characteristics of trajectory detection during secondary processing of radar information.

Methods and materials. The research aim was achieved using the methods of mathematical statistics, including verification of statistical hypotheses, assessment of distribution parameters and theory of perturbations by small parameters. The ratio of the distance travelled by the AT during the review period to the target range at the initial moment of its detection was chosen as a perturbation parameter.

Results. Analytical expressions were established for the probability of detecting a straight-moving AT and the probability of detecting the trajectory of its movement at interval multiples during the study period. The study illustrated the probability of detecting AT moving away from radar by means of consistent radar observations with reduced signal/noise ratios and angles between the velocity vector and the AT vector radius relative to the radar. The increase in AT speed which causes the z parameter to change from 0.01 to 0.07 reduces the probability of AT detection from 0.727 to 0.52 and leads to a corresponding change in the probability of detecting the trajectory. If the observation time is reduced by one time interval, the probability of detecting the trajectory is from 0.03 to 0.04...0.07 for signal/noise 40 ratio and from 0.06 to 0.08...0.11 for signal/noise 25 ratio (with the probability of false alarm 10^{-4}).

Conclusion. The resulting expressions allow for the calculation of directly moving AT trajectory detection, considering changes in the probability of detecting targets in successive time intervals of radar observations.

Key words: auto-trajectory, the average time of detection, dispersion, detection characteristics

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Оригинальная статья

Обнаружение траекторий движущихся прямолинейно воздушных целей при вторичной обработке радиолокационной информации

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Аннотация

Введение. Основными задачами вторичной обработки радиолокационной информации являются обнаружение и сопровождение траекторий движения воздушных целей (ВЦ). При этом процесс обнаружения траекторий движения ВЦ принято характеризовать вероятностями их обнаружения и средним временем их автозахвата. При движении цели ее дальность от радиолокационной станции (РЛС) изменяется, что приводит к изменению отношения сигнал/шум и вероятности обнаружения ВЦ.

Цель работы. Оценка влияния изменения вероятности обнаружения прямолинейно движущейся цели при радиолокационных наблюдениях на характеристики обнаружения траектории ее движения при вторичной обработке радиолокационной информации.

Методы. Используются методы математической статистики: проверка статистических гипотез, оценка параметров распределений и теория возмущений по малому параметру. В качестве возмущающего параметра выбрано отношение расстояния, проходимого ВЦ за период обзора, к дальности цели в начальный момент ее обнаружения.

Результаты. Получены аналитические выражения для вероятности обнаружения прямолинейно движущейся ВЦ и вероятности обнаружения траектории ее движения на интервалах, кратных периоду обзора. Проиллюстрировано уменьшение вероятности обнаружения ВЦ, удаляющейся от РЛС, при последовательных радиолокационных наблюдениях с уменьшением отношений сигнал/шум и угла между вектором скорости и радиусом-вектором ВЦ относительно РЛС. Увеличение скорости ВЦ, вызывающее изменение параметра z с 0.01 до 0.07, приводит к уменьшению вероятности обнаружения ВЦ с 0.727 до 0.52 и к соответствующему изменению вероятности обнаружения траектории. При сокращении времени наблюдения на один временной интервал уменьшение вероятности обнаружения траектории составляет от 0.03 до 0.04...0.07 для отношения сигнал/шум 40 и от 0.06 до 0.08...0.11 для отношения сигнал/шум 25 (при вероятности ложной тревоги 10^{-4}).

Заключение. Полученные выражения позволяют рассчитывать характеристики обнаружения траекторий воздушных целей, движущихся прямолинейно, с учетом изменений вероятностей обнаружения целей в последовательных временных интервалах обзора радиолокационных наблюдений.

Ключевые слова: автозахват траектории, среднее время обнаружения, дисперсия, характеристики обнаружения

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Introduction. One of the primary tasks solved by radar is the detection and tracking of moving air targets (ATs). This problem is solved as a result of primary and secondary processing of radar information (RI). Primary processing comprises the detection of a target at a certain point in time, while secondary processing consists in detecting and tracking the trajectory (sequential detection of the AT over several predefined scan intervals).

It is customary to evaluate the effectiveness of solving secondary processing problems in terms of the probability of detecting the AT trajectory, as well as the average time of its detection [1–9]. The indicated characteristics substantially depend on the probabilities of detecting an AT at each of the observation points, which are generally considered to be identical during secondary processing of radar data [3, 4, 9–12]. However, the distance of the AT relative to the radar can change significantly, causing a change in the signal-to-noise ratio for the received signals reflected from the target and, consequently, the probability of its detection. In addition to the average capture time, additional information about the detection of the AT trajectory is provided by a change in the probability of its detection at predefined time intervals [13, 14]. Therefore, studying the influence of changes in the probability of detecting an AT at the points of its sequential radar observation on the detection characteristics of the AT trajectories during secondary processing of radar data is of practical interest.

Thus, the purpose of this study is to assess the impact of changes in the probability of detection of a rectilinearly and evenly moving AT in successive time intervals of radar observation on the characteristics of the detection of the trajectory of its movement during the secondary processing of radar information.

Target detection methods. It can be assumed that the centre of motion moves with the velocity v along a rectilinear trajectory, which constitutes the angle θ at the initial moment of its detection with the radius vector R_0 of the location of the centre of rotation (Fig. 1). The

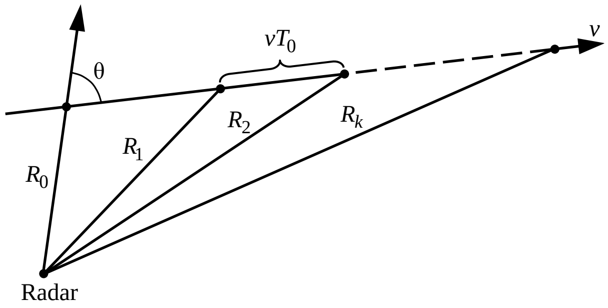

Fig. 1. Towards the calculation of the ranges of the targets in the observation points

target ranges at time intervals T_0, equal to the period of the radar, are defined as R_1, R_2, …, R_k.

In this case, the distances between the AT location points on the trajectory at the time of observation are vT_0. In this case, the AT range through k scan intervals is:

$$R_k = \sqrt{R_0^2 + (kvT_0)^2 + 2kvT_0R_0\cos\theta} = R_0\sqrt{1 + \left(\frac{kvT_0}{R_0}\right)^2 + 2\frac{kvT_0}{R_0}\cos\theta}. \qquad (1)$$

The power of the signal reflected from the target and received by the radar has the form [1, 2]

$$P_s = a^2 = \frac{P_{tr}G\sigma_t A_r}{(4\pi)^2 R^4},$$

where a – the effective value of the amplitude; P_{tr} – transmitter power; G – the antenna gain; σ_t – radar cross section; A_r – effective antenna surface; R – range to the target from the radar.

Signal strength received during initial observation is

$$P_{s0} = a_0^2 = \frac{P_{tr}G\sigma_t A_r}{(4\pi)^2 R_0^4}.$$

The ratio of the received signal powers at the initial and current observations has the form

$$P_s/P_{s0} = a^2/a_0^2 = (R_0/R)^4,$$

from which $a^2 = a_0^2 (R_0/R)^4$.

Then the signal-to-noise ratio for the signal reflected from the AT located in the k-th time interval of the scan and received by the radar receiver is

$$Q_k = \frac{2a^2E_1}{N_0} = \frac{2a_0^2E_1}{N_0}\left(\frac{R_0}{R_k}\right)^4 = Q_0\left(\frac{R_0}{R_k}\right)^4, \qquad (2)$$

where

$$E_1 = \frac{1}{2}\int_0^T U^2(t)\,dt$$

– signal energy at a unit amplitude; N_0 – two-way spectral noise density; Q_0 – the signal-to-noise ratio at the output of the radar receiver when receiving a signal reflected from the AT at the time of radar observation at a distance R_0 from the radar.

If the received signal has a random initial phase and amplitude, while the initial phase is evenly distributed over the interval $(-\pi;\ \pi)$, and the amplitude obeys the Rayleigh distribution:

$$\omega(a)=\left(a/\sigma_a^2\right)e^{-\left[a^2/\left(2\sigma_a^2\right)\right]},\ \ a\ge 0,$$

where σ_a^2 – the variance of fluctuations in the amplitude of the signal reflected from the target, then the signal-to-noise ratio takes the form $Q_0=2\sigma_a^2E_1/N_0$.

Taking into account the indicated distributions of the parameters of the received signal, one can substitute (1) in (2) and decompose the resulting expression in a series in a small value $z=vT_0/R_0$ – the ratio of the distance travelled by the AT during one scan period T_0 to the target distance at the initial moment of its detection. Then the signal-to-noise ratio for the signal reflected from the AT located at the point *k* of the trajectory and received by the radar receiver has the form

$$Q_k=Q_0\left(R_0/R_k\right)^4= =Q_0\left[1-4k\left(vT_0/R_0\right)\cos\theta+ +2\left(6\cos^2\theta-1\right)k^2\left(vT_0/R_0\right)\right]^2. \quad (3)$$

The probabilities of correct detection of AT at successive time intervals of radar observations are determined by the relation [9], [10]

$$D_k=F^{\left(1+Q_k\right)^{-1}}, \quad (4)$$

where *F* is the probability of false alarm.

Substituting (3) into (4) and expanding the last expression in a series in *z*, one can obtain an expression for the probability of correct detection of the AT at the point *k* of the trajectory:

$$D_k=D_0+A_1kz+A_2\left(kz\right)^{-2}, \quad (5)$$

where

$$A_1=D_0\frac{4Q_0\ln F\cos\theta}{\left(1+Q_0\right)^2};$$

$$A_2=D_0\left[\frac{8\left(\ln FQ_0\cos\theta\right)^2}{\left(1+Q_0\right)^4}+\right.$$
$$\left.+\frac{\ln F\left(4Q_0\cos\theta\right)^2}{\left(1+Q_0\right)^3}+\frac{2Q_0\ln F\left(1-6\cos^2\theta\right)}{\left(1+Q_0\right)^2}\right].$$

Fig. 2 shows the results of calculating the probability of correct detection D_k of an AT moving along a rectilinear trajectory as a function of the number of the observation interval multiple of the radar scan period T_0, . It is illustrated for the signal-to-noise ratio at the output of the radar receiver when receiving a signal reflected from a target at the time of radar observation at a range R_0 from the radar $Q_0=30$, at the ratio of the distance travelled by the AT during one radar scan to its range at the initial moment of observation $z=0.01$ and 0.07, the probability of false alarm *F* for various values of the angle θ between the AT movement trajectory and its radius vector at the starting point of observation.

From the curves given in Fig. 2 and relation (1), it follows that the probabilities of correct detection D_k decrease with an increase in the observation interval of the AT relative to the initial moment of its detection, as well as with a decrease in the angle θ between the direction of motion of the AT and the radius vector of its location at the initial moment of observation $(k=0)$. Indeed, a reduction in the angle leads to an increase in the range of the AT relative to the radar over the scan interval.

A comparison of the curves in Fig. 2, *a* and *c* shows that the decrease in the probability of detection D_k is also affected by an increase in the speed of the AT, causing an increase in the distance travelled by it during the time interval of the scan T_0,

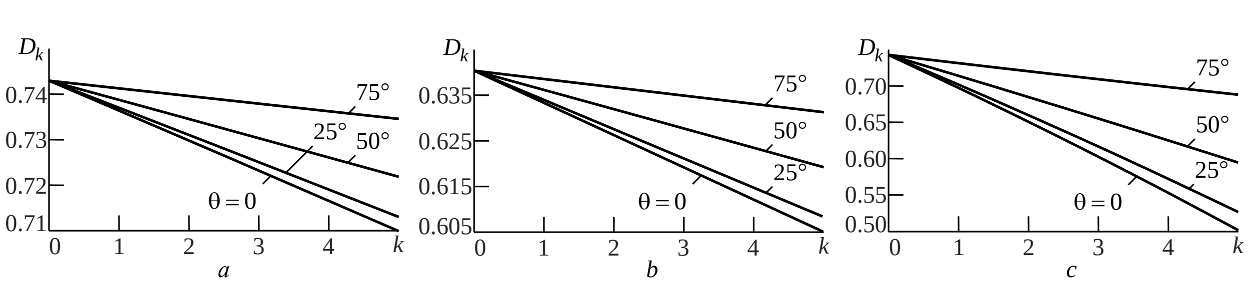

Fig. 2. Dependencies of the probability of correct detection on the number of radar coverage interval:
a – $z=0.01$; $F=10^{-4}$; *b* – $z=0.01$; $F=10^{-6}$; *c* – $z=0.07$; $F=10^{-4}$

and, accordingly, its distance from the radar, along with a decrease in the signal-to-noise ratio for the received signal reflected from the AT. So, for $\theta = 25°$ at $F = 10^{-4}$ and $Q_0 = 30$, an increase in the AT velocity causing a change in the parameter *z* from 0.01 to 0.07 leads to a decrease in D_3 from 0.727 to 0.52. A decrease in D_k is also caused by lowering the probability of false alarm *F*, caused by an increase in the threshold level of the decider of the signal detection receiver. As follows from the curves for $\theta = 25°$ in Fig. 2, *a* and *b*, a change in *F* from 10^{-4} to 10^{-6} ceteris paribus causes a decrease in the probability D_3 from 0.725 to 0.621.

Characteristics of the detection of the trajectory of the target. Trajectory detection is carried out in two stages. At the first stage, the sequential detection of a target at the first two radar scan periods (observation intervals), accompanied by the formation of tags in the secondary radar processing system, leads to the initiation of the trajectory (determination of the expected target trajectory at two points). Herein $P = P_0 P_1$, where $P_0 = D_0$, $P_1 = D_1$ are the probabilities of detection of the target at the initial moment of its observation and the next scan period. The detection of the trajectory of the target is carried out following its linking upon detection of the target (marking) at one of several subsequent intervals of radar observation [10].

Considering that the probabilities of correct detection of an AT at different periods of its observation are not the same, the probability of trajectory detection (the appearance of a mark in any of *k* subsequent scan intervals) is defined as

$$P_{\text{td}} = P_0 P_1 \sum_{k=2}^{n} P_k,$$

where

$$P_k = \begin{cases} D_2, \ k = 2; \\ D_k \prod_{i=2}^{k-1} (1 - D_i), \ k > 2 \end{cases} \qquad (6)$$

– the probability of detecting an AT at the *k*-th interval of its observation during trajectory auto-capture. Then the average time of detection of the trajectory of the AT (the appearance of the third mark) is

$$T_{\text{av}} = \frac{P_0 P_1 \sum_{k=2}^{n} T_0 (k+1) P_k}{P_0 P_1 \sum_{k=2}^{n} P_k} = \frac{\sum_{k=2}^{n} T_0 (k+1) P_k}{\sum_{k=2}^{n} P_k} = T_0 \left(1 + \frac{h_1}{h_0}\right),$$

where *n* is the number of time intervals for the radar scan necessary to detect the trajectories of the AT during the secondary processing of radar data;

$$h_1 = \sum_{k=2}^{n} k P_k; \ h_0 = \sum_{k=2}^{n} P_k.$$

Similarly, we can obtain the second moment of estimation of the detection time of the AT trajectory:

$$T_2 = \frac{T_0^2 \sum_{k=2}^{n} (k+1)^2 P_k}{\sum_{k=2}^{n} P_k} = \frac{h_2 + 2h_1 + h_0}{h_0},$$

where $h_2 = \sum_{k=2}^{n} k^2 P_k$.

Then the expression for the variance of the estimate of the detection time of the target trajectory is

$$\sigma^2 = T_2 - T_{\text{av}}^2 = T_0^2 \left(\frac{h_2}{h_0} - \frac{h_1^2}{h_0^2}\right).$$

In practice, it is customary to use the results of detecting an AT after linking the trajectory in four consecutive scan time intervals P_2, P_3, P_4, P_5 $(n = 5)$ at the stage of detecting the AT trajectory [10, 12].

Substituting (5) in (6) and after mathematical transformations, we can obtain:

$$h_0 = \sum_{k=2}^{5} P_k = h_{00} + h_{01} z + h_{02} z^2;$$

$$h_1 = \sum_{k=2}^{5} k P_k = h_{10} + h_{11} z + h_{12} z^2;$$

$$h_2 = \sum_{k=2}^{5} k^2 P_k = h_{20} + h_{21} z + h_{22} z^2,$$

where

$$h_{00} = 1 + q + q^2 + q^3; \ h_{01} = A_1 q \left(5q^2 - 5q - 2\right);$$

$$h_{02} = A_2 q \left(25q^2 - 13q - 4\right) + A_1^2 (6 - 45q);$$

$$h_{10} = 2 + 3q + 4q^2 + 5q^3;$$

$$h_{11} = A_1 \left(25q^3 - 29q^2 - 11q - 2\right);$$

$$h_{12} = A_2 q\left(125q^3 - 81q^2 - 25q - 4\right) + $$
$$+ A_1^2\left(6 + 50q - 225q^2\right);$$
$$h_{20} = 4 + 9q + 16q^2 + 25q^3;$$
$$h_{21} = A_1\left(125q^3 - 161q^2 - 53q - 10\right);$$
$$h_{22} = A_2 q\left(625q^3 - 469q^2 - 127q - 20\right) + $$
$$+ A_1^2\left(42 + 330q - 1125q^2\right),$$

moreover, $q = 1 - D_0$.

Then

$$T_{\text{av}} = \frac{T_0}{h_0}\left[h_{00} + h_{10} + \left(h_{01} + h_{11}\right)z + \left(h_{02} + h_{12}\right)z^2\right];$$

$$\sigma^2 = \frac{T_0^2}{h_0^2}\left[h_{00}h_{20} - h_{10}^2 + \right.$$
$$+ \left(h_{00}h_{21} + h_{01}h_{20} - 2h_{10}h_{11}\right)z +$$
$$\left. + \left(h_{00}h_{22} + h_{01}h_{21} + h_{02}h_{20} - 2h_{10}h_{12} - h_{11}^2\right)z^2\right].$$

Discussion of the results. Fig. 3 shows the dependencies of the average time of detection of the target trajectory normalised to T_0 on the ratio *z* with the probability of false alarm (F) 10^{-4} and 10^{-6}.

The curves in Fig. 3 show that the average detection time of the AT trajectory (T_{av}) increases with an increase in the parameter *z* (with an increase in the AT velocity and, correspondingly, its distance from the radar in one observation time interval). The most significant factor influencing T_{av} is the signal-to-noise ratio for the received signal at the initial moment of observation Q_0. Thus, a decrease in Q_0 from 40 to 25 with the probability of false alarm $F = 10^{-4}$ and an increase in the parameter *z* from 0 to 0.07 leads to an increase in the average detection time of the AT path from 0.15 to 0.17…0.22, and when $F = 10^{-6}$ – from 0.21 to 0.19…0.29. With a decrease in the probability of false alarm to $F = 10^{-6}$ (Fig. 3, *b*) this value increases at $Q_0 = 40$ from 0.13 to 0.15…0.2, and at $Q_0 = 25$ – from 0.19 to 0.17…0.27. Moreover, the increase in T_{av} with increasing *z* grows with a decrease in the angle θ between the direction of motion of the AT and its radius vector at the time of initial observation. The latter is explained by an increase in the AT distance over the time interval of the scan, which leads to a decrease in the power of the signal reflected from the AT, the signal-to-noise ratio and a decrease in the probability of detecting the AT.

Fig. 4 shows the dependencies of the root-mean-square deviation (RMS) σ with respect to the average time of detection of the target trajectory, normalised to T_0, the ratio *z* at the values of the probability of false alarm 10^{-4} and 10^{-6}.

It follows from the figure that RMS increases with an increase in the parameter *z*. This also depends on the signal-to-noise ratio for the received signal at the initial moment of observation Q_0 and the probability of false alarm *F*. Decreasing Q_0 from 40 to 25 with the probability of false alarm $F = 10^{-4}$ at the same time as increasing the parameter *z* (i.e., with increasing AT speed) from 0 to 0.07 leads to RMS increase from 0.14 to 0.15…0.18; at $F = 10^{-6}$, from 0.14 to 0.15…0.16. Moreover, the change in σ with increasing *z* increases with a decrease in the angle θ between the direction of motion of the AT and its radius vector at the time of initial observation. It is therefore that a decrease in the angle leads to an increase in the increment of the AT distance over the

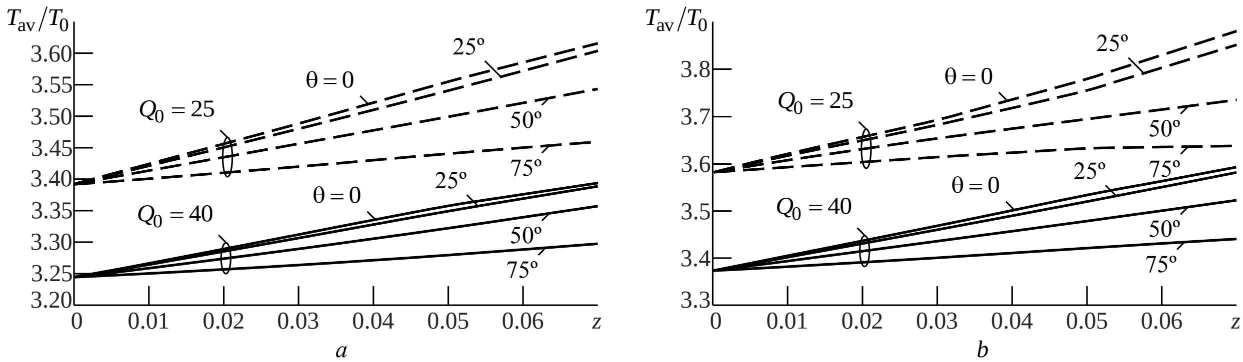

Fig. 3. Average time of detection of the trajectory of an air target:
a – $F = 10^{-4}$; *b* – $F = 10^{-6}$

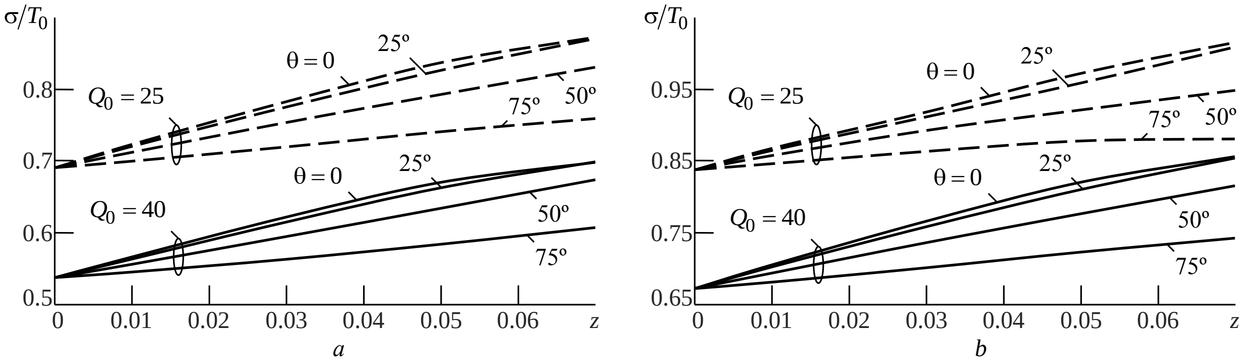

Fig. 4. Root mean square deviation of trajectory detection time relative to its average value:
$a - F = 10^{-4}$; $b - F = 10^{-6}$

time interval of the scan, as well as, accordingly, to a decrease in the power of the signal reflected from the AT and signal-to-noise ratios, thus reducing the likelihood of detecting the AT.

The moments of estimation of the detection time of the AT motion path (average detection time T_{av} and RMS σ) are integral characteristics, which whose derivation averaging is used that takes into account the probabilities of AT detection at the time intervals for viewing the motion paths allocated to detect the motion path. Along with the abovementioned points, additional information is provided by changes in the probability of detecting the AT trajectory at specific time intervals of radar observation (formation of the third mark) with respect to the probability of its detection at all time intervals allotted for this. These changes are characterised by the parameters

$$P_{23} = \frac{P_2 + P_3}{\sum_{k=2}^{5} P_k}; \quad P_{24} = \frac{P_2 + P_3 + P_4}{\sum_{k=2}^{5} P_k},$$

reflecting changes in probability during successive detection of the AT trajectory in the second and third – as well as in the second and fourth – time intervals of the scan, respectively.

Fig. 5 shows the dependencies of the P_{23}, P_{24} relationship change on the relationship $z = vT_0/R_0$ with the values of the probability of false alarm 10^{-4} and 10^{-6}.

As follows from the course of the curves, the dependencies of the change in the probabilities of detecting the trajectory of the targets moving along the rectilinear trajectory of the AT from the radar decrease with an increase in the parameter *z* (increasing the speed of the AT and, correspondingly, its distance from the location of the radar for one observation interval, leading to a decrease in the probability of AT detection). In this case, the time interval of its observation has a significant effect on the probability of detecting the AT trajectory. Indeed, the increase in P_{24} as compared with P_{23} at the probability of false alarm $F = 10^{-4}$, the signal-to-noise ratio during initial radar observation $Q_0 = 40$ and an increase in the parameter *z* from 0 to 0.07 is from 0.03 to 0.04…0.07, and at $Q_0 = 25$ – 0.06 to 0.08…0.11. With a decrease in the probability of false alarm to $F = 10^{-6}$, this change at $Q_0 = 40$ is from 0.06 to 0.07…0.11, while at $Q_0 = 25$ it is from 0.1 to 0.11…0.17. Moreover, the increase in the change in the probability of detecting the AT trajectory in the allotted scan time intervals with increasing *z* grows with a decreasing angle between the direction of the AT movement and its radius vector at the time of initial observation, which is associated with an increase in the AT distance over the time interval of the scan and, correspondingly, with a decrease in power reflected from the AT signal, the signal-to-noise ratio and a decrease in the probability of detecting the AT.

It should be noted that, for small observation intervals, the probability of detecting the AT trajectory at the allocated scan time intervals is significantly affected by the signal-to-noise ratio at the initial moment of observation, which depends on the range of the target and the probability of false alarm. As seen from Fig. 5, the change in probability P_{23}, corresponding to the second and third observation intervals, with $F = 10^{-4}$ and Q_0 from 25 to 40, increases on average by 0.04, while P_{24} changes by no more than 0.01…0.03.

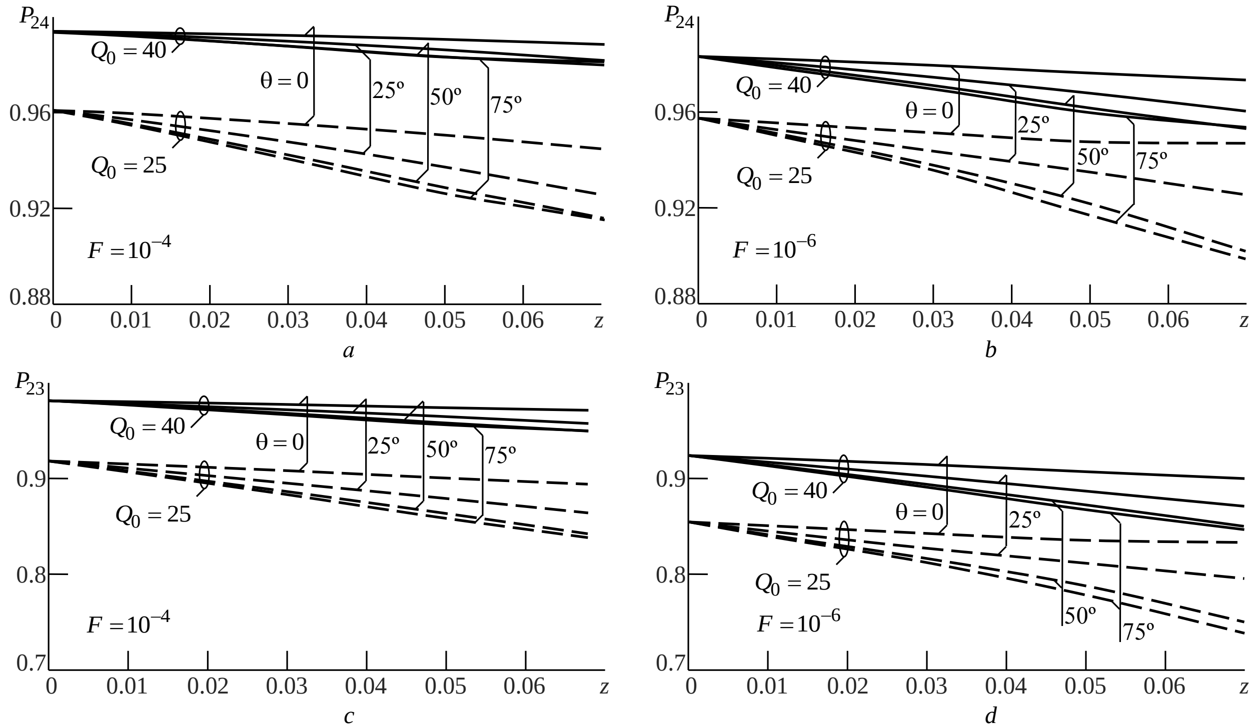

Fig. 5. The change in the probability of detecting the trajectory of an air target at two time intervals during the formation of the third mark:

$a - P_{24}$, $F = 10^{-4}$; $b - P_{24}$, $F = 10^{-6}$; $c - P_{23}$, $F = 10^{-4}$; $d - P_{23}$, $F = 10^{-6}$

Conclusion. Analytical relationships were obtained for the probabilities of detecting an AT with a rectilinear trajectory during its successive observations along with the probability of detecting the trajectory of the AT at the allotted scan time intervals during secondary processing of radar data. A decrease in the indicated probabilities is revealed when the ratio of the distance travelled by the target for the scan interval to the range of the target at the initial moment of its observation is changed along with the signal-to-noise ratio at the initial moment of observation and the time interval of observation. The expediency of taking into account changes in the probabilities of detecting rectilinear moving targets during their successive radar observations and the detection of their motion paths is demonstrated.

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