Radar and Navigation

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Strobing of Radar Marks for Trajectory Filtration in a Body-Fixed Frame

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Abstract

Introduction. Modern air targets, particularly drones, are becoming less noticeable, while their manoeuvrability continues to improve. Trajectory processing algorithms have also been improved in order to provide for effective tracking of highly manoeuvring targets. The accuracy of filtering trajectory parameters is largely determined by the reliability of radar information. This has also required an enhanced role for strobe algorithms and the need to increase the effectiveness of strobe radar marks.

Aim. To develop and investigate the efficiency of a trajectory strobe algorithm based on the target motion model in a high-speed coordinate system associated with the direction of the target motion and involving the formation of a strobe in the form of a truncated elliptical sector.

Materials and methods. The study considered the target motion model in the body-fixed frame. This model was taken as the basis for new trajectory filtering algorithms based on Kalman filtering. Existing methods for strobing radar marks of the target were considered and a new approach based on filtering in the body-fixed frame proposed. The new algorithm assumes the formation of a strobe in the form of a truncated elliptical sector. This form corresponds to the most probable location of the marks of the tracked target. The effectiveness of the proposed solutions is confirmed by the results of mathematical modelling carried out using MATLAB.

Results. The study produced analytical expressions for the motion model, recurrent filtering and strobe algorithm in the body-fixed frame. A comparative analysis of tracking effectiveness with the same dimensions of the elliptical and proposed strobes was performed. It was established that the algorithm with strobe formation in the form of a truncated elliptical sector provides for longer target tracking up to the time of the first loss of the mark for speed and highly manoeuvring targets, when compared to the elliptical strobe algorithm. In addition, the average duration of sector strobe tracking does not in practice depend on the initial speed of the target and provides greater accuracy for small measurement error values (less than 50 m) of the coordinates in comparison with the elliptical one.

Conclusion. The described results were achieved by the ability of the strobe in the body-fixed frame to adapt to the direction of motion and target manoeuvring, allowing high-quality target tracking within a larger speed range. Such strobe formation will also reduce the likelihood of skip-ping radar marks from the tracked target and will reduce the number of false marks and marks belonging to other trajectories inside the strobe.

Key words: ground speed; course; climb angle; body-fixed frame; trajectory filtration; extended Kalman filter; strobing

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Радиолокация и радионавигация

Оригинальная статья

Стробирование радиолокационных отметок при траекторной фильтрации в связанных координатах

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Аннотация

Введение. Современные воздушные цели, в особенности беспилотные, становятся менее заметными, а их маневренные возможности продолжают совершенствоваться. Для обеспечения эффективного сопровождения высокоманевренных целей актуализируются и алгоритмы траекторной обработки. Поскольку точность фильтрации траекторных параметров во многом определяется достоверностью радиолокационной информации, возрастает роль алгоритмов стробирования. В связи с этим возникает задача повышения эффективности стробирования радиолокационных отметок.

Цель работы. Разработка и исследование эффективности алгоритма траекторного стробирования, основанного на модели движения в скоростной связанной с направлением движения цели системе координат и предполагающего формирование строба в форме усеченного эллипсоидного сектора.

Методы и материалы. Рассмотрены модели движения целей в связанных координатах, которые положены в основу новых алгоритмов траекторного сопровождения, базирующихся на калмановской фильтрации. Рассмотрены существующие методы стробирования радиолокационных отметок от цели и предложен новый подход на основе фильтрации в связанных координатах. Новый алгоритм предполагает формирование строба в форме усеченного эллипсоидного сектора. Такая форма соответствует наиболее вероятному местоположению отметок от сопровождаемой цели. Эффективность предложенных решений подтверждается результатами математического моделирования, выполненного в среде MATLAB.

Результаты. Приведены аналитические выражения для модели движения, рекуррентной фильтрации и алгоритма стробирования в связанных координатах. Проведен сравнительный анализ эффективности сопровождения при одинаковых размерах эллиптического и предложенного стробов. Установлено, что для скоростных и высокоманевренных целей алгоритм с построением строба в форме усеченного эллипсоидного сектора обеспечивает до 30 % более длительное сопровождение до первой потери отметки от цели, чем алгоритм с эллиптическим стробированием. Кроме того, средняя продолжительность сопровождения для секторного строба практически не зависит от начальной скорости движения цели, а при значениях погрешностей измерения координат менее 50 м имеет большее значение, чем для эллиптического.

Заключение. Достигнутый результат обеспечивается способностью строба в связанных координатах подстраиваться под направление движения и маневрирование цели, что позволяет осуществлять качественное сопровождение объектов в большем диапазоне скоростей. Построение такого строба также позволит снизить вероятность пропуска радиолокационных отметок от сопровождаемой цели и обеспечит уменьшение числа ложных отметок и отметок, принадлежащих другим траекториям, внутри строба.

Ключевые слова: путевая скорость; курс; угол наклона траектории; связанная система координат; траекторная фильтрация; расширенный фильтр Калмана; стробирование

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Introduction. The creation of trajectory tracking algorithms [1–12] is based on the use of mathematical models, which can be used to accurately approximate the actual movement of a target and the process of its observation. The description of the motion trajectories should reflect the dynamic properties of various types of moving objects and provide the possibility to construct algorithms for processing observations in real time. These conditions are satisfied with the generally recognised representation of trajectories with the help of a wide class of vector Markov sequences. At the same time, the disadvantage of the known models is the binding of the object accelerations to the basic rectangular coordinate system 0*xyz*. It is clear that the direction of movement of a real target and its possible manoeuvres do not necessarily correlate with artificially entered coordinates.

In this connection, it was proposed in [13, 14] to use a body-fixed frame associated with the motion of a target to describe the trajectories. The analysis showed that in this case the efficiency of the trajectory filtering of manoeuvring targets can be increased [14, 15]. At the same time, the classical form of an elliptical strobe can be replaced by an elliptical sector, which corresponds to such coordinates, when filtering in body-fixed frame. In this regard, the purpose of this article is to solve the problem of constructing a strobe in the form of a truncated elliptical sector. The objectives of the study also include a comparative analysis of the effectiveness of the use of strobes of various forms.

Features of filtering in body-fixed frame. Let the rate of change in the position of an object be determined in a body-fixed frame. In this case, on the *i*-th measurement, it is necessary to set (Fig. 1) a possible change in the value of the ground speed v_i and two angles – the course θ_i, measured clockwise from the *x*-axis, and the angle of inclination of the trajectory (climb angle) $\varphi_i \in (-0.5\pi;\ 0.5\pi)$, counted from the projection of the velocity vector on the horizontal plane 0*xy*: $\varphi_i > 0$, если $v_{zi} > 0$ $(i = 1,\ 2, \ldots$ – is the measurement number).

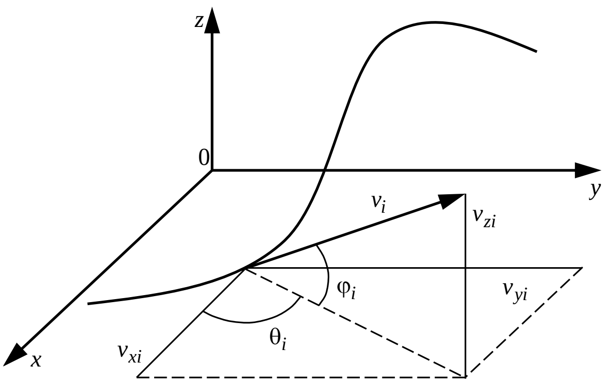

Fig. 1. The specifying of velocity in the body-fixed frame

The change in these parameters is set by the following autoregression equations:

$$v_i = v_{i-1} + \sigma_v t_i \xi_{vi};$$
$$\theta_i = \theta_{i-1} + \sigma_\theta t_i \xi_{\theta i};$$
$$\varphi_i = \varphi_{i-1} + \sigma_\varphi t_i \xi_{\varphi i},$$

where σ_v, σ_θ, σ_φ are the standard deviations (SDs) of the acceleration, the rate of change of course and the rate of change of the angle of inclination of the trajectory of the considered class of targets, respectively; t_i – time interval between adjacent measurements; ξ_{vi}, $\xi_{\theta i}$, $\xi_{\varphi i}$ – standard Gaussian independent random variables. These equations can be written in the vector form:

$$\mathbf{v}_{\mathrm{bf}\,i} = \mathbf{v}_{\mathrm{bf}(i-1)} + \vartheta_{\mathbf{v}i}\xi_i,$$

where

$$\mathbf{v}_{\mathrm{bf}i} = (v_i,\ \theta_i,\ \varphi_i)^{\mathrm{T}};$$
$$\vartheta_{\mathbf{v}i} = \mathrm{diag}(\sigma_v t_i,\ \sigma_\theta t_i,\ \sigma_\varphi t_i);$$
$$\xi_i = (\xi_{vi},\ \xi_{\theta i},\ \xi_{\varphi i})^{\mathrm{T}}.$$

After specifying the velocity vector, there are two possible approaches to the complete determination of target motion models for solving the problems of trajectory simulation, forecasting and filtering.

The first approach consists in the direct introduction of velocities and angles in body-fixed frame associated with the movement of the target into the state vector:

$$\mathbf{S}_{\mathrm{bf}i} = (x_i,\ y_i,\ z_i,\ v_i,\ \theta_i,\ \varphi_i)^{\mathrm{T}},$$

where

$$\begin{aligned} x_i &= x_{i-1} + t_i v_{xi}; \\ y_i &= y_{i-1} + t_i v_{yi}; \\ z_i &= z_{i-1} + t_i v_{zi}; \\ v_i &= v_{i-1} + \sigma_v t_i \xi_{vi}; \\ \theta_i &= \theta_{i-1} + \sigma_\theta t_i \xi_{\theta i}; \\ \varphi_i &= \varphi_{i-1} + v_\varphi t_i \xi_{\varphi i}, \end{aligned} \tag{1}$$

moreover, $v_{xi} = v_i \cos\theta_i \cos\varphi_i$; $v_{yi} = v_i \sin\theta_i \cos\varphi_i$; $v_{zi} = v_i \sin\varphi_i$ are projections of the velocity vector on the coordinate axes.

Fig. 2 shows typical implementations obtained using a body-fixed model with two sets of parameters. The analysis of many realisations shows the best resemblance to the real trajectories of the movement

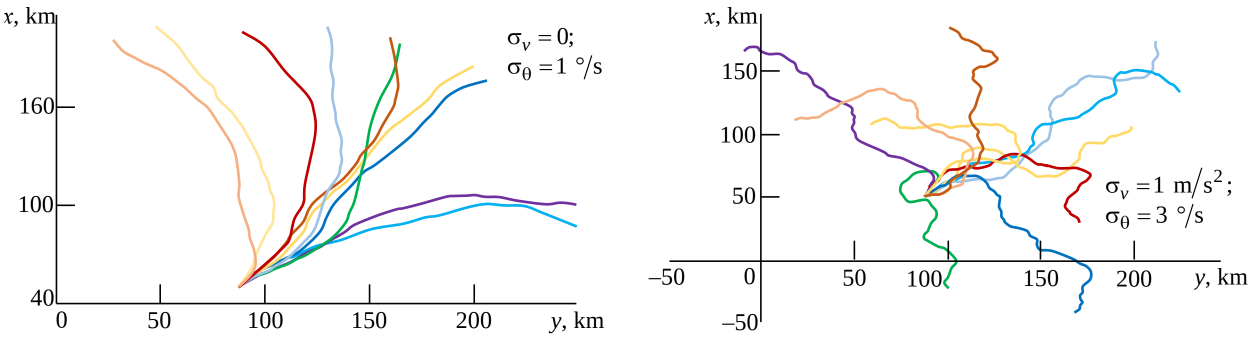

Fig. 2. Characteristic trajectories of the targets motion on the plane

of manoeuvring air targets. For the body-fixed model under consideration, it is very important to set the parameters σ_v, σ_θ, σ_φ, independent of the direction of the coordinate axes and determined only by the type of target.

The proposed model differs from the classical linear model has two significant ways. First of all, expressions (1) belong to the class of vector nonlinear stochastic difference equations:

$$\mathbf{S}_{\mathrm{bf}i} = \phi_i\left[\mathbf{S}_{\mathrm{bf}(i-1)}\right] + \vartheta_{\mathbf{v}i}\bar{\xi}_i;\ i = 1,\ 2,\ \ldots,$$

where $\phi_i\left[\mathbf{S}_{\mathrm{bf}(i-1)}\right]$ is the nonlinear vector function of the state vector $\mathbf{S}_{\mathrm{bf}(i-1)}$, defined by (1). Therefore, the forecast (extrapolation) of the state vector at the i-th observation step is determined by the formula

$$\hat{\mathbf{S}}_{\mathrm{bf.e}i} = \phi_i\left[\hat{\mathbf{S}}_{\mathrm{bf}(i-1)}\right],$$

and the covariance matrix of errors as

$$P_{\mathrm{e}i} = \phi_i'\left[\hat{\mathbf{S}}_{\mathrm{bf}(i-1)}\right]P_{(i-1)}\phi_i'^{\mathrm{T}}\left[\hat{\mathbf{S}}_{\mathrm{bf}(i-1)}\right] + \vartheta_{\mathbf{v}i}Q_i\vartheta_{\mathbf{v}i}^{\mathrm{T}}, \quad (2)$$

where

$$\phi_i'\left[\mathbf{S}_{\mathrm{bf}(i-1)}\right] = d\phi_i\left[\mathbf{S}_{\mathrm{bf}(i-1)}\right] / d\mathbf{S}_{\mathrm{bf}(i-1)};$$

$P_{i-1} = P_{\mathrm{e}(i-1)}\left[E + C^{\mathrm{T}}B_{i-1}^{-1}CP_{\mathrm{e}(i-1)}\right]^{-1}$ – the covariance matrix of estimation errors; $Q_i = \mathrm{M}\left\{\xi_i\xi_i^{\mathrm{T}}\right\}$, moreover, E is the identity matrix; C is the observation transformation matrix; M is the symbol of mean; the symbol "^" hereinafter marks the results of the evaluation of the corresponding quantities.

The estimation is performed according to the well-known expression for the Kalman filter [14, 15]:

$$\hat{\mathbf{S}}_{\mathrm{bf}\,i} = \hat{\mathbf{S}}_{\mathrm{bf.e}i} + P_iC^{\mathrm{T}}B_i^{-1}\left(\mathbf{z}_i - C\hat{\mathbf{S}}_{\mathrm{bf.e}i}\right),$$

where $\mathbf{z}_i$ is the observation model.

It is assumed that the observations are made within the Cartesian coordinate system. In this case, the observation model has the form: $\mathbf{z}_i = C\mathbf{S}_{\mathrm{bf}i} + \mathbf{n}_i$, where $\mathbf{n}_i = \left(n_{xi}\ \ n_{yi}\ \ n_{zi}\right)^{\mathrm{T}}$ is the additive noise with zero mean and covariance matrix

$$B_i = \begin{pmatrix} \sigma_{\mathrm{n}xi}^2 & b_{xyi} & b_{xzi} \\ b_{xyi} & \sigma_{\mathrm{n}yi}^2 & b_{yzi} \\ b_{xzi} & b_{yzi} & \sigma_{\mathrm{n}zi}^2 \end{pmatrix},$$

moreover, $\sigma_{\mathrm{n}xi}$, $\sigma_{\mathrm{n}yi}$, $\sigma_{\mathrm{n}zi}$ is the standard deviation of observations of the coordinates x, y, z respectively; b_{xyi}, b_{yzi}, b_{xzi} – covariance of the corresponding observations [15].

The transformation matrix in the Cartesian system has the form

$$C = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \end{pmatrix}.$$

Since during the operation of radar the position of the target is usually fixed in spherical coordinates, it is necessary to perform the corresponding transformations before starting the trajectory processing [15].

Based on the proposed motion description model, taking into account the observation model that depends on the type of radar, various algorithms for quasilinear recurrent estimation of changing target coordinates can be constructed. Examples of such algorithms and the results of their comparative analysis are given in [14, 15]. It was found that filtering in body-fixed frame leads to a gain in the accuracy of estimating the parameters of the target's movement.

Strobing algorithms. Within a Cartesian coordinate system, a strobe consists of an ellipsoid determined by the covariance matrices of observation errors and prediction errors of the target position [5, 7].

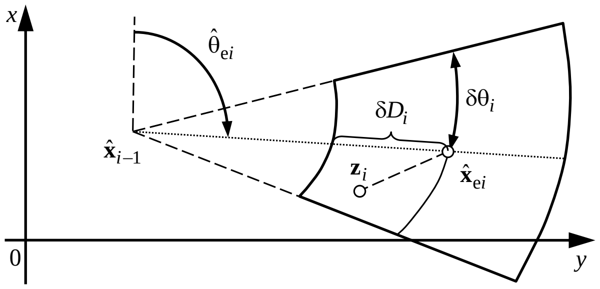

Fig. 3. Shape of the strobe in the body-fixed frame on the plane

Filtration in body-fixed frame [14, 15] involves the creation of a strobe in the form of a truncated elliptical sector (Fig. 3, for the case of two measurements). The dimensions of the strobe are determined by the level of permissible deviations $\Delta\mathbf{S}_{\text{fb}i} = \left(\Delta D_i,\ \Delta\theta_i,\ \Delta\varphi_i\right)^{\text{T}}$ in terms of range, course and angle of inclination of the trajectory, respectively.

The indicated deviations are calculated when determining the covariance matrix of forecasting errors (2). To obtain the necessary deviations from the composition of the obtained matrix, the covariances of coordinate prediction errors are selected:

$$P_{\text{ex}i} = \begin{pmatrix} p_{\text{e}11i} & p_{\text{e}12i} & p_{\text{e}13i} \\ p_{\text{e}21i} & p_{\text{e}22i} & p_{\text{e}23i} \\ p_{\text{e}31i} & p_{\text{e}32i} & p_{\text{e}33i} \end{pmatrix} = CP_{\text{e}i}C^{\text{T}}.$$

The covariance matrix of deviations of the radar marks from the extrapolated target coordinates in body-fixed frame is defined as

$$\begin{gathered} \text{M}\left\{\boldsymbol{\varepsilon}_{\text{fb}i}\boldsymbol{\varepsilon}_{\text{fb}i}^{\text{T}}\right\} = \\ = \text{M}\left\{T_i\left(\mathbf{z}_i - C\,\hat{\mathbf{S}}_{\text{fb.e}i}\right)\left(\mathbf{z}_i - C\,\hat{\mathbf{S}}_{\text{fb.e}i}\right)^{\text{T}} T_i^{\text{T}}\right\} = \\ = T_i\left(P_{\text{ex}i} + B_i\right)T_i^{\text{T}}, \end{gathered}$$

where $\boldsymbol{\varepsilon}_{\text{fb}i} = \left(\varepsilon_{Di},\ \varepsilon_{\theta i},\ \varepsilon_{\varphi i}\right)^{\text{T}}$ – the deviations in body-fixed axes;

$$T_i = \\ = \begin{pmatrix} \cos\hat{\theta}_{\text{e}i}\cos\hat{\varphi}_{\text{e}i} & -\sin\hat{\theta}_{\text{e}i}\cos\hat{\varphi}_{\text{e}i} & -\cos\hat{\theta}_{\text{e}i}\sin\hat{\varphi}_{\text{e}i} \\ \sin\hat{\theta}_{\text{e}i}\cos\hat{\varphi}_{\text{e}i} & \cos\hat{\theta}_{\text{e}i}\cos\hat{\varphi}_{\text{e}i} & -\sin\hat{\theta}_{\text{e}i}\sin\hat{\varphi}_{\text{e}i} \\ \sin\varphi_{\text{e}i} & 0 & \cos\hat{\varphi}_{\text{e}i} \end{pmatrix}$$

– matrix of rotation of coordinates.

Since the mutual covariance of observations is not taken into account in the algorithm, the covariance matrix of observation noise has the form

$$B_i = \begin{pmatrix} \sigma_{\text{n}xi} & 0 & 0 \\ 0 & \sigma_{\text{n}yi} & 0 \\ 0 & 0 & \sigma_{\text{n}zi} \end{pmatrix}.$$

The obtained values of forecasting errors in body-fixed frame $\left(\sigma_{Di},\ \sigma_{\theta i},\ \sigma_{\varphi i}\right)$ determine the linear dimensions of the strobe:

$$\delta_{Di} = \gamma\sigma_{Di};\ \ \delta_{\theta i} = \gamma\sigma_{\theta i};\ \ \delta_{\varphi i} = \gamma\sigma_{\varphi i},$$

which are associated with allowable deviations as follows:

$$\begin{gathered} \delta_{Di} = \Delta D_i; \\ \delta_{\theta i} = \left|\left(\hat{\mathbf{S}}_{\text{fb.e}i} - \hat{\mathbf{S}}_{\text{fb}(i-1)}\right)\right|\Delta\theta_i; \\ \delta_{\varphi i} = \left|\left(\hat{\mathbf{S}}_{\text{fb.e}i} - \hat{\mathbf{S}}_{\text{fb}(i-1)}\right)\right|\Delta\varphi_i, \end{gathered}$$

moreover, the parameter γ is selected according to the given probability of skipping the mark from the target, as a rule, in the interval 2…3.

As a result, the obtained form and dimensions of the strobe correspond to the most probable target location at the next instant of observation time.

Comparative analysis of the effectiveness of strobing. The study of the proposed strobing algorithm (PSA) was carried out by mathematical modelling on a computer in the case of two measurements. The authors studied the effectiveness of PSA in comparison with the well-known strobing algorithm (ISA) with the same area of the sector and elliptical strobes, which provides equal probabilities of getting false marks in them.

To estimate the effectiveness of the application of ISA and PSA in the MATLAB environment, a mathematical model was constructed that makes it possible to:

– simulate various trajectories of airborne objects;

– simulate observations from radars with specified accuracy characteristics;

– perform trajectory filtering of the observations using a simple linear Kalman filter and a linear Kalman filter with adjustment in body-fixed frame;

– form strobes in the form of an ellipse and a truncated sector and evaluate the position of the mark from the target relative to the borders of the strobes;

– display the original trajectory of the target, the observations received from the simulated radar, and the results of the processing of radar information;

– display the dependence of the average tracking time on the size of the strobe for ISA and PSA.

In addition, a program has been developed for visualising the results in Qt Creator in C++ using algorithms from the model implemented in MATLAB for the:

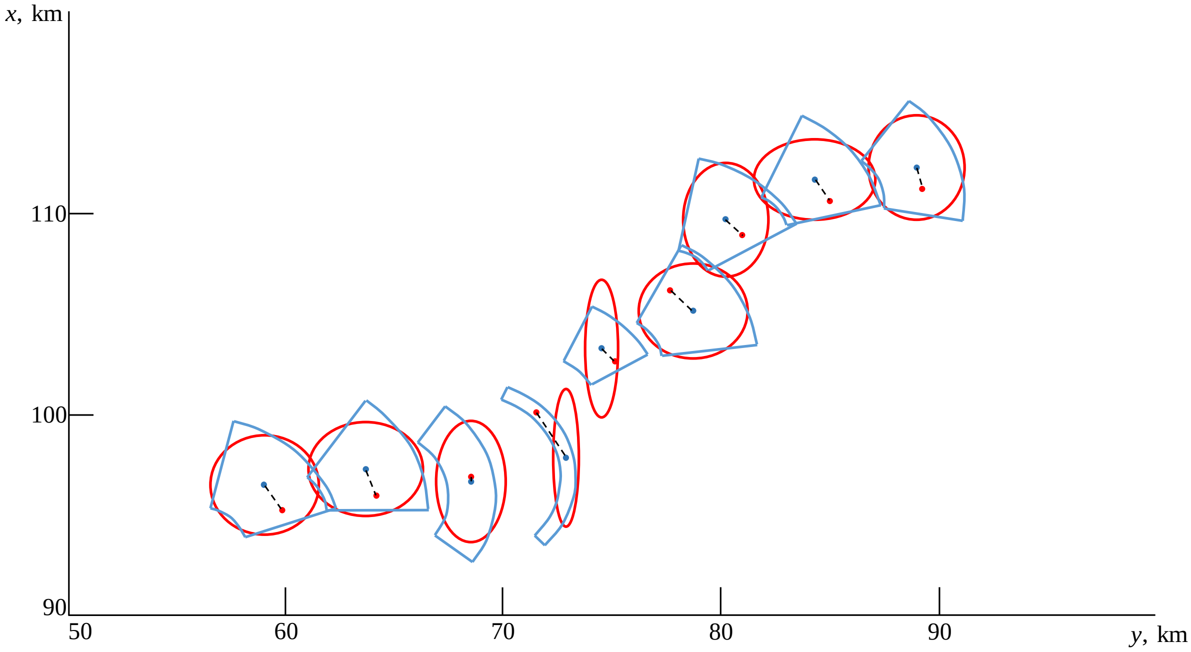

Fig. 4. Position and shape of strobes for maneuvering target.
Blue lines limit the strobes of the proposed algorithm; red lines limit the strobes of the known algorithm.
Blue markers is the strobes centers; red markers is the position of the target

– imitation and graphic construction of various trajectories of movement of airborne objects;

– imitation and graphical construction of observations from radars with specified accuracy characteristics;

– trajectory filtering of the obtained observations and graphical construction of the restored trajectories and predicted elevations;

– graphical construction of calculated strobes in the form of an ellipse and a truncated sector.

Modelling of the marks was carried out in Cartesian coordinates with a standard deviation of 10 m for each coordinate. The radar was located at the origin. The target moved with a course of $45°$ at an initial speed 300 m/s, acceleration of 1 m/s^2 and rate of change of course 3 °/s. In order to carry out trajectory filtering, a filter with separate estimation in body-fixed frame [15] was used; this was configured to track an object moving with the specified motion parameters.

Fig. 4 shows that the object performs manoeuvring on the course and at the moment of rotation the elliptical strobe of the ISA loses the mark from the target. This effect is explained by the dynamics of the object at the moment of strobing.

Average target tracking time to the first mark loss T_{ac1} for the ISA and PSA strobes of the same size was estimated to evaluate the effectiveness of the strobing algorithms during the simulation. Both filters are configured to track the target with the previously specified motion parameters.

Fig. 5 presents the results obtained by simulating the movement of the target with parameters that match the settings of the filters. With a small strobe size $(\gamma \le 2)$, the algorithms have close values of the average tracking duration until the first loss of the mark from the target. As the value of the coefficient increases, accompanied by an increase in the size of the strobes, the average PSA tracking time more and more exceeds that of the ISA.

Fig. 6 shows the results obtained at $\gamma = 2.5$ for a target moving at an initial speed 300 m/s for various values of the error in the measurement of coordinates (the measurement errors of both coordinates are set to be equal). The obtained results show that the PSA has an advantage with the values $\sigma_x < 50$ m. For larger coordinate measurement error values, both algorithms have a close average tracking time, with this value decreasing with an increase in the error.

Fig. 7 shows the graphs obtained at $\gamma = 2.5$ for the target moving with different initial speeds and coordinate measurement error of 10 m. It can be seen that with a speed less than 100 m/s, the ISA has an advantage, but with increasing speed, the average tracking time tends to a steady-state value. Moreover, the average PSA time is practically independent of

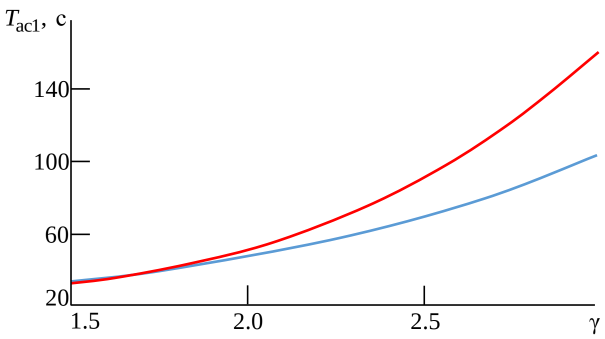

Fig. 5 Dependence of the average object tracking time on the value of the coefficient γ for the proposed algorism (red line) and known algorism (blue line)

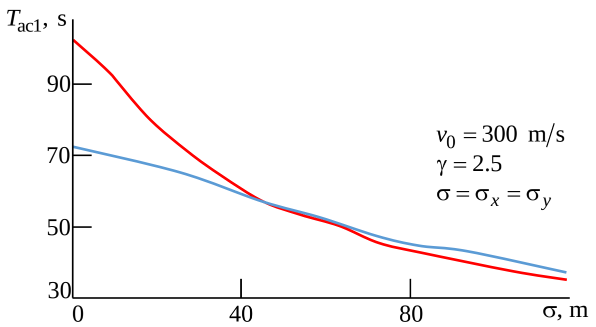

Fig. 6. Dependence of the average object tracking time on the measurement error of coordinates for the proposed algorism (red line) and known algorism (blue line)

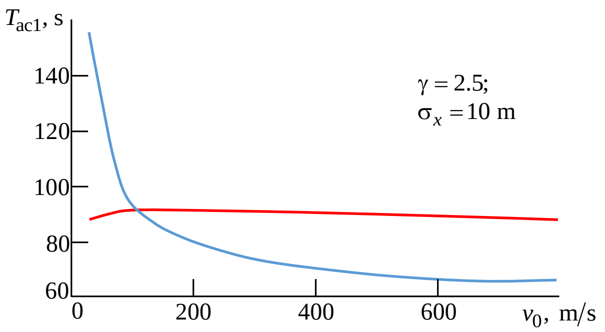

Fig. 7. Dependence of average object tracking time on initial speed for the proposed algorism (red line) and known algorism (blue line)

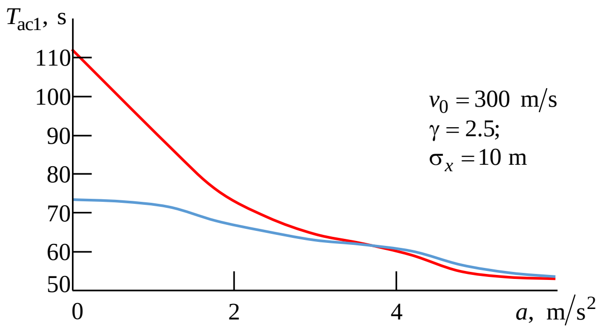

Fig. 8. Dependence of average object tracking time on acceleration for the proposed algorism (red line) and known algorism (blue line)

the initial speed and exceeds (on average by 20 s) the steady-state value of the ISA.

Fig. 8 shows the dependencies $T_{ac1}(a)$ for movement with different acceleration, obtained at a fixed value of the initial speed $v_0 = 300$ м/с; $\gamma = 2.5$ and $\sigma_x = 10$ м. From the obtained graphs, it can be concluded that with increasing dynamics of the movement, the value of the average tracking time decreases for both algorithms, while the PSA is inferior to the ISA.

Conclusion. It has been established that for fast and highly manoeuvrable targets, the PSA implemented in the body-fixed frame with the construction of a strobe in the form of a truncated elliptical sector provides longer tracking until the first loss of the mark from the target than the ISA with an elliptical strobe. ISA has an advantage in the average length of the tracking time only when monitoring low-speed objects, the nature of which is relatively straightforward. It has also been established that, for PSA, the average tracking time, which is only slightly dependent on the initial speed of the target, is more important for small errors in the measurement of coordinates than for ISA. Such results are explained by the fact that the size and form of the strobe in the PSA are adjusted depending on the nature of the movement: with intensive manoeuvring, the sector strobe extends along the course, while with rectilinear movement with acceleration, it stretches along the trajectory. As a result, such a strobe covers the region of the most probable target location better than the ISA ellipsoid, allowing for high-quality tracking of objects within a wider range of speeds.

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