[15] Methods and criteria for individual (separate) identification of mobile objects, moving in the group by the passive digital optical locators

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Abstract

Article is devoted to the development of methods and criteria for identification of multiple moving objects observed by passive optical digital locator. Approaches to the development of methods of identification of multiple moving objects are examined. Mathematical model of the promising measuring system and some results of practical research are provided. The developed model can be used in various measurement and control systems, real-time observation for the separate estimation of motion of objects in the group.

Keywords: *digital optical passive locator, identification, group of moving objects, trajectory measurements.*

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Introduction

The passive digital optical locator is a complex of spaced-apart digital theodolites with a single spatial-time software [1]. The system of two and more digital theodolites allows us to estimate such motion parameters of an aircraft as coordinates in a specified central coordinate system, velocities and accelerations.

Let us consider the case when a group of aircrafts moving with high velocity on the same course have entered the field of view of the passive digital optical locator, and it is required to separately estimate motion parameters for each aircraft.

As shown in paper [1], processing of trajectory information using the passive optical digital locator can be conventionally divided into two stages: preprocessing and reprocessing, which has been implemented in practice.

The preprocessing involves the measuring angular coordinates of observed objects according to logged data from each of the theodolites.

The reprocessing involves the joint processing of data from several theodolites and determining motion parameters of each of the objects observed in space.

All known preprocessing and reprocessing techniques usually involve estimation of motion parameters of the objects observed at the stage of operator-assisted after-session processing. However, due to the distribution of digital vision channels based on CCD-matrices and with the development of computers, it became possible now to use optical means to locate objects in real time.

The paper [2] shows that fundamental problems of passive optical location include also the problem of object identification. The authors propose to identify group targets according to spatial compatibility features of measurement pairs. However, identification procedures are performed with no regard to motion parameters of the objects observed in local coordinate systems of measuring stations. This can result to rapid increase of the number of computational procedures with increase of the number of objects come in the field of view and to situations resulting in the necessary use of three and more measuring stations to make a clear solution.

Mathematical model of trajectory measurements with identification opportunities

The foregoing approach may be summarized by the following fundamental mathematical model:

$$\left(X_k^*(i), Y_k^*(i), Z_k^*(i),\right)^T = P_{rep} \times \times \left[P_{id} \left[\bigcup_{l=1}^{L} P_{pre} \left[X_{Ck,l}(i), Y_{Ck,l}(i), \alpha_{0l}(i), \beta_{0l}(i) \right], v \right] \right] \quad (1)$$

where P_{pre} – is a preprocessing operator of trajectory information; P_{rep} – is a reprocessing operator of trajectory information; P_{id} – is a generalized identification operator of the observed objects; L – is the number of measuring stations; K – is the number of aircrafts in the group; $l \in [1; L]$ – is the measuring station number; $k \in [1; K]$ – is the aircraft number i – is the number of a real time reading t_i; $X^{ù}_{ù}(i), Y\ \ (i), Z\ \ (i)$ – are the aircraft coordinate estimates with the k –number in the Cartesian coordinate system based on the results of trajectory measurements at a time instant i; ν – is the coordinate vector for binding theodolites; $X_{Ck,l}(i), Y_{Ck,l}(i)$ – are the aircraft coordinates with the k-number in the CCD-matrix coordinate system; $\alpha_{0l}(i), \beta_{0l}(i)$ – are the readings of angular position sensors on the measuring station with the l -number at a given instant t_i.

In practical tasks the object coordinates on the CCD-matrix $X_{Ck,l}(i)$, $Y_{Ck,l}(i)$ are estimated according to the input image $I_i(x, y)$ by applying thereto the detection operators for moving objects P_{detect} and the center-of-coordinate evaluation operators P_{center}:

$$\left(X_{Ck,l}(i), Y_{Ck,l}(i)\right)^T = P_{center}\left[P_{detect}\left[I_i(x, y)\right]\right] \tag{2}$$

Whereas the input image can be represented as follows [3]:

$$\begin{aligned} &I_i(x, y) = b_i(x, y) g_i(x, y) + \\ &+ f_i(x, y)(1 - g_i(x, y)) + \xi_i(x, y) \end{aligned} \tag{3}$$

where $I_i(x, y)$ – is the observed image, $b_i(x, y)$ and $f_i(x, y)$ – are the intensities of pixels belonging to a background and the object, respectively, $g_i(x, y)$ – is a binary mask characterizing the fact that the pixel belongs to the moving object, $\xi(x, y, i)$ – is the additive noise of a photodetector. It is assumed that value of a noise component does not correlate to values of image details and their spatial coordinates and noise impact on the original image is described by the additive model; respectively, the most convenient recovery method is the spatial filtering which, along with binarization, reduces the impact of this effect.

The object detection operator solves the problem of determination of a designated location of the object observed in frame.

The center-of-coordinate evaluation operator shall estimate coordinates of the object center based on pixel intensities.

A particular type of operators P_{detect} and P_{center} depends on the type of the sensor and specific features of the problem to be solved.

The problem of object detection and localization in images is considered as a whole in paper [3].

The method of fast-moving object detection based on the improved frame-to-frame difference method using the digital optical locator of tracking type is proposed in paper [4].

Methods of calculating center coordinates in case of point object observation, as well as problems of dependence of computational errors of object center coordinates to the size of object projection on CCD-matrix plane are discussed in paper [5].

The preprocessing operator generally displays coordinates of the objects observed in the device CCD-matrix coordinate system into the measuring-station coordinate system with regard to readings of the remote position indicator:

$$\begin{aligned} &P_{pre} : (f \quad Y_{Ck,l}(i) \quad X_{Ck,l}(i))^T \to \\ &\to (\alpha_{Ck,l}(i) \quad \beta_{Ck,l}(i)) \end{aligned} \tag{4}$$

where $X_{Ck,l}(i)$ and $Y_{Ck,l}(i)$ – are the object (“target”) coordinates in the image from the device CCD-matrix; f – is a lens focal length; $\alpha_{Ck,l}(i)$ and $\beta_{Ck,l}(i)$ – are, respectively, azimuth and the object position angle in the local coordinate system of the measuring station; l – is the measuring station number; k – is the object number in frame; i – is the number of current time reading t_i. It can be constructed in various options depending on type of the measuring device.

The reprocessing operator is constructed on the basis of the known technique given in paper [1]. It generally displays a set of angular measurements of the object obtained from the measuring station to the central coordinate system (usually rectangular):

$$\begin{aligned} &P_{rep} : ((\alpha_{Ck,1}(i) \quad \beta_{Ck,1}(i))^T, \ldots, (\alpha_{Ck,L}(i) \quad \beta_{Ck,L}(i))^T) \to \\ &\to \left(X_k^*(i) \quad Y_k^*(i) \quad Z_k^*(i)\right); \end{aligned} \tag{5}$$

where $X^*_k(i), Y^*_k(i), Z^*_k(i)$ – are the estimates of aircraft coordinates in the Cartesian coordinate system; $\alpha_{Ck,l}(i)$ and $\beta_{Ck,l}(i)$ – are azimuth and the object position angle in the local coordinate system of the measuring station; l – is the measuring station number; k– is the object number in frame; i – is the number of current time reading.

When the group of objects comes into view of theodolites, the problem of determining object numbers jointly involved into the processing comes up. In order for this problem to be solved, we shall introduce to the model (2) the identification operator for the observed objects P_{id}. It performs identification of preprocessing results in accordance with selected identification criteria.

Identification criteria for observation objects

The solution for the identification problem generally reduces to constructing a likelihood function for all possible options of measurements distribution according to trajectories and searching its maximum as shown in [6].

In practice, the problem can be solved by computing a distance matrix between identified dimensions ac-

cording to some certain metric and subsequent selection of measurement combinations, which correspond to its minimal elements.
The identification problem is herewith divided into two sub-problems – spatial and time-dependent.
The spatial identification means the identity of measurements logged by different measuring stations at the same moment of time, whereas the time-dependent identification means the identity of measurements logged at different moments of time.
Let us consider the spatial identification. The problem geometry is shown in Fig. 1 [2].

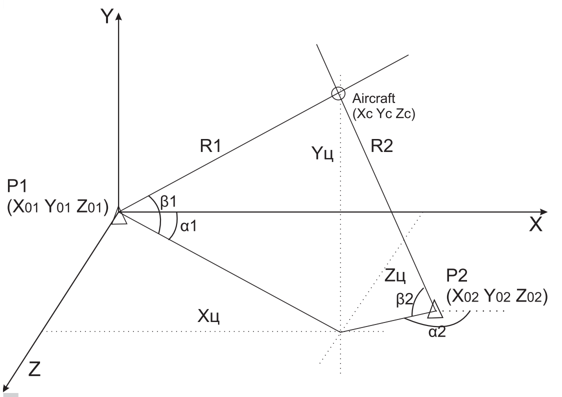

Fig.1. Geometry of the spatial identification problem: P1, P2 - are the measuring stations 1 and 2; α_1, β_1 - are the object coordinates in the coordinate system of the measuring station 1; α_2, β_2 - are the object coordinates in the coordinate system of the measuring station 2; X_C, Y_C, Z_C - are the aircratt coordinates in the Cartesian coordinate system; X_{O2}, Y_{O2}, Z_{O2} - are the binding coordinates of the measuring station 2 relating to the measuring station 1.

In radiolocation the spatial identification problem is solved by the cross-bearing method [7]. The similar cross-bearing criterion can be formulated with regard to the passive digital optical locator as follows [2]:

$$\begin{bmatrix} R_1 \\ R_2 \end{bmatrix} = A_1^{-1} \begin{bmatrix} X_0 \\ Y_0 \end{bmatrix} = A_2^{-1} \begin{bmatrix} X_0 \\ Z_0 \end{bmatrix} = A_3^{-1} \begin{bmatrix} Y_0 \\ Z_0 \end{bmatrix}; \qquad (6)$$

where X_0, Y_0, Z_0 are the binding coordinates of the second measuring station related to the first one; A_1, A_2, A_3 – are the matrices of coordinates transformation.
If the bearings are not crossed, the solutions solved in different ways shall give different results, and the condition is not fulfilled. We can't observe in practice this condition to be strictly fulfilled, because the measurements are performed with errors. Therefore some allowable limits are to be introduced for the distance differences ΔR^1_{ij} and ΔR^2_{ij}, the values of which are selected according to an arrangement plan for measuring devices and their measurement errors of angular coordinates.

Furthermore, let us consider the time-dependent identification. The identification criterion for measurements logged in neighboring moments of time is specified on the basis of a moving aircraft pattern to be detected.
Firstly, in accordance with class of the problems being solved, the criterion can be constructed on the basis of the known pattern of rectilinear motion of the aircraft given in [7]:

$$S_{i+1} = A_i S_i + \mu_i, \qquad (7)$$

where $S_i = \left(X_{k,i} \quad Y_{k,i} \quad Z_{k,i} \quad V_{X,k,i} \quad V_{Y,k,i} \quad V_{Z,k,i} \right)^T$ – is the aircraft state vector at the time instant t_i (in this case we consider the coordinates in three-dimensional space);

$$A_i = \begin{pmatrix} E_3 & E_3\tau_i \\ O_3 & E_3 \end{pmatrix}$$

– is a composite forecast matrix, where E_3 – is an identity 3x3 matrix, O_3 – is a zero 3x3 matrix, $\tau_i = t_i - t_{i-1}$ – is a time interval between measurements; μ_i – is the vector of normally distributed random variables with zero mathematical expectation. The vector μ_i may be represented as follows: $\mu_i = U_i v_i$, where $v_i = (v_x \quad v_y \quad v_z)$ – is the aircraft acceleration vector,

$$U_i = \begin{pmatrix} (\tau_i^2 / 2) E_3 \\ \tau_k E_3 \end{pmatrix}$$

– is the matrix 6x3 in size characterizing the effect of accelerations on components of the aircraft state vector.
The criterion of membership of the next set of measurements S_i to the same object which contains the previously logged sets of measurements S_{i-1} and S_{i-2} shall be specified as follows:

$$\begin{cases} v_x < \upsilon_x; \\ v_y < \upsilon_y; \\ v_z < \upsilon_z; \end{cases} \qquad (8)$$

where $\upsilon_x, \upsilon_y, \upsilon_z$ – are the specified limits of aircraft acceleration along each of the coordinate axes.
In some particular problems, when a linear change model of aircraft parameters can be applied not only to its coordinates, but also to some other observed features (e.g. brightness, dimension, etc.), the features and their change velocities may also be included in the aircraft state vector S_i. If the time-dependent identification is needed in angular coordinates of the measuring station (by results of preprocessing with no information to be brought from other measuring stations), the aircraft state vector will consist of angular coordinates and angular velocities of the object in the local coordinate system of the measuring station that will be discussed below.
Secondly, the time-dependent identification criterion can be based on the assumption that the

observed aircrafts may execute a group motion on the same course, and thus the deviation of a random aircraft with the state vector $S_{k,i}$ from the group center may insignificantly change in the process of time.

Mathematical expectation [8] of coordinates of the observed objects at the moment of time t_i is assumed as the center coordinates of the object group and has the following form:

$$S_i^0 = M(X_{k,i}, Y_{k,i}, Z_{k,i})^T = \left(\frac{\grave{u}}{\grave{u}} \sum_{\grave{u}-\grave{u}}^{\grave{u}} X_{k,i} \quad -\sum Y_{k,i} \quad -\sum Z_{k,i} \right)^T \quad (9)$$

Coordinates of some certain aircraft with regard to the group center shall be written as follows:

$$S_{k,i}^c = S_{k,i} - S_i^0 \quad (10)$$

In case of directed motions of the group of objects the following ratio is proposed:

$$S_{k,i+1}^c = S_{k,i}^c + \mu_{k,i} \quad (11)$$

where $\mu_{k,i} = \left(\Delta X_{k,i} \quad \Delta Y_{k,i} \quad \Delta Z_{k,i} \right)^T$ – is the vector of normally distributed random variables with zero mathematical expectation characterizing random motions of the aircraft in the coordinate system associated with the center of the group.

Then the criteria of membership $S_{n,i+1}$ and $S_{k,i}$ to the same aircraft in case of group motions in 3D space can generally be formulated as follows:

$$\begin{cases} \left| \Delta X_{k,i} \right| < d_v \sigma_x \\ \left| \Delta Y_{k,i} \right| < d_v \sigma_y \\ \left| \Delta Z_{k,i} \right| < d_v \sigma_z \end{cases}, \quad (12)$$

where $\sigma_x, \sigma_y, \sigma_z$ – are the mean square deviations of components of the vector $\mu_{k,i}$; d_v – is the confidential interval width [8]. These parameters are predefined, for example, based on results of the statistical analysis of the previously logged data.

Search reduction at the stage of spatial identification

If K-number of objects has come in view of L-number of measuring stations (i.e. it is necessary to produce K-number of coordinate sets of L-pairs per each), the maximum number of verified hypotheses of spatial identification will amount to K^L. The number of hypotheses grows with increase of the number of objects come in the field of view; besides, according to [2] they have to be verified prior to the time of each frame. The identification hypothesis shall hereinafter mean the set of L-number of measurements (one from each measuring station), for which it is assumed that they belong to the same object. It is easy to calculate that in order to verify only one identification hypothesis we shall need at least L-1-number of operations of criterion verification (6).

In multilevel radiolocation (provided that each measuring station measures three coordinates), the problem of search reduction in spatial identification is usually solved by spatial strobing based on the readings of one of the measuring stations and the subsequent identification of measurements within a strobe as shown in [7].

Application of the similar approach in the passive digital optical locator is meaningless due to the absence of direct range measurements, and other optimization techniques must be used herewith.

One of the possible methods involves the preliminary time-dependent object identification at the stage of preprocessing.

If the aircraft state vector S_i includes the aircraft angular coordinates and velocities, the time-dependent identification criteria (8) based on the linear motion model shall take the following form:

$$\begin{cases} v_\beta < \upsilon_\beta \\ v_\alpha < \upsilon_\alpha \end{cases}, \quad (13)$$

where $\upsilon_\beta, \upsilon_\alpha$ – are the specified limits of the angular accelerations according to the position angle and azimuth, respectively. The criterion shall be written in the following form which is convenient for practical implementation:

$$\begin{cases} \left| (F)^2 (\beta_{i,q} - 2\beta_{i-1,l} + \beta_{i-2,k}) \right| < \upsilon_\beta \\ \left| (F)^2 (\alpha_{i,q} - 2\alpha_{i-1,l} + \alpha_{i-2,k}) \right| < \upsilon_\alpha \end{cases}; \quad (14)$$

where F – is a frame frequency, α_i and β_i – are azimuth and the position angle of the observation object at the given moment of tiem i.

The algorithm of frame-to-frame identification based on this criterion and focused on the application in measuring stations of tracking type has been proposed in paper [9].

Similarly to the case, where the target group motion is considered in matrix plane and when it is required to verify whether the object image $(x_{Cn,l,i}, y_{Cn,l,i})$ belongs to the same aircraft or not, which involves $(x_{Ck,l,i-1}, y_{Ck,l,i-1})$, the identification criterion (12) shall have the following form:

$$\begin{cases} \left| x_{Cn,l,i} - (X_i^o + C_x (x_{Ck,l,i} - X_{i-1}^o)) \right| < d_v \sigma_x \\ \left| y_{Cn,l,i} - (Y_i^o + C_y (y_{Ck,l,i} - Y_{i-1}^o)) \right| < d_v \sigma_y \end{cases}; \quad (15)$$

where $X_i^o = \frac{1}{K} \sum_{k=1}^{K} x_{Ck,l,i}$, $Y_i^o = \frac{1}{K} \sum_{k=1}^{K} y_{Ck,l,i}$ – are the estimates of mathematical expectations of the observed object coordinates in the CCD-matrix coordinate system;

$C_x = \frac{a_{i,x}}{a_{i-1,x}}$ and $C_y = \frac{a_{i,y}}{a_{i-1,y}}$ –

are the coefficients providing scale-invariance, where $a_{i,x}, a_{i-1,x}, a_{i,y}, a_{i-1,y}$ – are the mean linear deviations of the corresponding coordinates for current and previous frames [8]:

$$a_{i,x} = \frac{1}{K}\sum_{k=1}^{K}\left|x_{Ck,l,i} - X_i^0\right|;\ a_{i,y} = \frac{1}{K}\sum_{k=1}^{K}\left|y_{Ck,l,i} - Y_i^0\right|. \qquad (16)$$

In practice, the identification criteria (14) and (15) may be used together.

Since the angular coordinates of the observation objects are not required to verify the proposed criterion of time-dependent identification in the above form (15), it can directly be applied to the coordinates of the observation objects in CCD-matrix space to be defined by the above formula (2). Nevertheless, this criterion is applicable to measuring devices both of patrol– and tracking-types. When using a multiprocessor computer in the measuring station, the algorithm, which verifies this criterion, can be performed parallel to the algorithm of trajectory information preprocessing.

Suppose g_i – is the number of measurements logged in some certain measuring station in frame with i-number. When the process of criterion verification has been completed (15), the number of dimensions from i-1 frame, for which we were able to find the corresponding measurements from i-frame, will come to be known. Let us denote this value by p_i . It will enable to evaluate the identification quality of measurements within the group:

$$Q_i = \frac{p_i}{g_i} \qquad (17)$$

The condition $Q_i = 1$ means that for all objects logged in one of the frames being considered and belonging to the group G_i, we could find a pair of those registered in the second frame, which means the successful identification of all dimensions according to the proposed criterion.

The measurements from the current frame for which we could not find identifications shall form the set $S_i \in C_i$. They must be identified by another algorithm, e.g. based on the above criterion (14). The reality is that the above criterion (15) provides the high quality of identification under the conditions when the number of objects in frame does not change, and the observed aircrafts move on the same course. When some new objects appear or some old objects disappear in the field of view, the value Q_i decreases and a new criterion shall be involved for identification (14).

After the time-dependent identification has been completed in the measuring station, the angular coordinates of the selected objects and the trajectory numbers assigned thereto shall be transmitted to a central office, where the reprocessing is performed. Consequently, in the process of spatial identification in the central computer, the exhaustive search technique of all possible measurement pairs can be replaced by a pseudooptimal technique, when we shall first compare the measurements received the trajectory numbers which have previously been regarded to be compatible.

Experimental results

Experiment 1. We compared the number of computational procedures while verifying the cross-bearing criterion at the stage of spatial identification using the exhaustive search technique and having regard to the results of the preliminary time-dependent (interframe) identification in the angular coordinates. The results are given in Fig. 2.

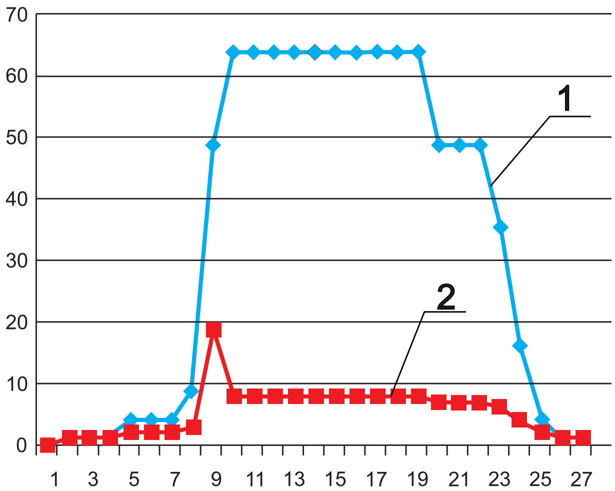

Fig. 2. The number of verifications of the cross-bearing criterion in a passive optical measuring complex consisting of two measuring stations: 1 – for the exhaustive search method; 2 – for the method that takes into account the results of time-dependent identification.

We simulated a situation when the group of 10 objects was coming in view of the passive digital optical locator from two measuring stations; it was steadily being observed for some time and then was leaving the field of view. In accordance with the actual situation, the objects can appear in the field of view and disappear therefrom not simultaneously, but in succession.

The reason for productivity advantage in spatial identification is that in the case of preliminary interframe identification the input data happen to be grouped according to trajectory membership criteria, and the search is required only for new objects which have come in view of the theodolite at the given moment of time.

Experiment 2. We investigated the effectiveness of identification algorithms jointly operating according to the previously proposed scheme. We considered the possibility to use two measuring stations.

Errors of angular coordinate estimates were simulated by normally distributed random variables with zero mathematical expectation [8] and the root-mean-square-deviation corresponding to typical situations when using real hardware. Displacement of the group consisting of 20 aircrafts fling with a velocity of 200 m/s was simulated during a login session of 500 frames at frequency of 50 frames per second.

We separately calculated the number of identification errors corresponding to the following cases:

1. False identification with true results of time-dependent identification at least in one measuring station.
2. Simultaneous false time-dependent identification in both measuring stations.

It must be emphasized that occurrence of single errors of false detection or a object acquisition error in a particular measuring station does not yet mean a false result of complex performance as a whole, since false measurements are eliminated at the stage of reprocessing while verifying the cross-bearing criterion. The same goes for false time-dependent identification. Let us consider the measuring station 1. If, in the process of time-dependent identification following the verification results of the criterion (12) or (13), some certain measurement $A_{i,P1}$, logged at the i-moment of time and actually belonging to the object, which was previously assigned with the trajectory number $j_{1,P1}$, will mistakenly be referred to as the trajectory with the number $j_{2,P1}$, then at the stage of spatial identification, in the process of comparing the measuring station 1 and the measuring station 2, the cross-bearing criterion (4) won't indicate the coincidence between the measurement $A_{i,P1}$ and the measurement $B_{i,P2}$ from the measuring station 2, which, during time-dependent identification, received the trajectory number $j_{2,P2}$, which, in turn, was previously assigned to measurements from the measuring station 2, which were indentified with measurements from the measuring station 1 having the trajectory number $j_{2,P1}$. For that purpose, in the set of non-identified measurements from the measuring station 2, based on the cross-bearing criterion (4), we will find the measurement $A_{i,P2}$, which is compared with the measurement $A_{i,P1}$ and actually corresponds to the same object. Thus, single errors of time-dependent identification shall be corrected at the stage of spatial identification.

Providing that the events "false time-dependent identification on the measuring station 1" and "false time-dependent identification on the measuring station 2" are to be considered as irrespective, the probability of their simultaneous occurrence can be estimated by the probabilities multiplication formula [8].

The obtained parameters of identification quality for different values of the root-mean-square deviation of measurement errors of the angular coordinates are given in Table 1.

Table 1. Simulation experiment results.

No.	Root-mean-square deviation of measurement errors of the angular coordinates, second of angle		Number of false identification cases, %		Number of correctly identified objects, %
	$\sigma_{azimuth}$	σ_{aop}	Caused by bearing false identification	Caused by simultaneous false measurement identification in both measuring stations or by object acquisition failure	
1	1	1	0.01	0.02	99.9
2	5	5	0.52	0.1	99.4
3	10	10	2.11	0.58	97.3
4	20	20	8.3	2.08	89.6
5	30	30	16	4.6	81.4

Conclusion

1. The proposed model provides a proper solution to the problem of identification when processing trajectory information in a distributed computing system and the possibility of combining the methods of identification with acceptable results obtained using only two measuring stations.

2. The developed algorithms provide a reduced number of computational procedures at the stage of spatial identification, which allows us to extend the scope of the passive digital optical locator, for example, for monitoring of air space and operational evaluation of field test results, and they can also be used in other areas where identification is required for fast-moving group objects.

3. One of the promising directions for further development of passive optical trajectory measurement complexes is to introduce the identification operators based on shape-, size– and brightness parameters, to the mathematical model, along with the coordinate feature identification operators discussed herein, that will enable to improve the identification quality in some special cases and to significantly expand the scopes of application of such systems.

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