The variability of shooting conditions affects the quality of images of Solar System objects in a series of frames. Identification of a frame with the corresponding part of the sky becomes difficult if the quality is poor. Because of this fact, the detection quality indicators and estimation of the position of Solar System objects are significantly reduced when using already known methods and international astronomical catalogs. To solve this problem, the procedure of full identification of measurements of objects on digital frames was devised.

This procedure is based on the formation of triplets (triangles) of primary identification from the side of the digital frame and the astronomical catalog. Positional coordinates on the frame and ideal tangential coordinates from the catalog were used. Owing to this, a comparison of the primary identification triplets was carried out by comparing the calculated angles of the triangle vertices. The identity of the hypothesis was determined by comparison with the acceptable deviation.

The use of the developed full identification procedure makes it possible to reduce the number of false detections and improve identification with reference astronomical objects. The study showed that when identifying frames, astrometry has better accuracy of reference to the starry sky. In addition, the standard deviation of frame identification errors in this case is 6–9 times less than without using the devised procedure.

The procedure developed for complete identification was practically tested within the framework of the CoLiTec project. It was implemented in the Lemur software for automated detection of new and tracking of known objects. Owing to the use of Lemur software and the proposed computational procedure implemented in it, more than 700,000 measurements of various astronomical objects under study were successfully identified

Keywords: image processing, parameter estimation, measurement identification, series of frames, catalog form

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IMPROVING THE ACCURACY OF IDENTIFYING OBJECTS IN DIGITAL FRAMES USING A PROCEDURE OF FULL IDENTIFICATION OF MEASUREMENTS

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1. Introduction

The potential for asteroid-comet hazard [1] is growing and becoming an urgent problem for humankind. Therefore, to solve it, the improvement of various methods of astrometry [2] and photometry [3] has become the leading direction. The results of asteroid/comet/satellite surveys are received as input data for automated processing. Astronomical/photometric catalogs and archival big data [4] make it possible to accumulate, obtain knowledge [5], explore, and analyze accumulated data (measurements, series of frames) that are publicly available [6]. Most often, they are acquired over the entire period of observation of various celestial Solar System objects (SSO) [7] (for example, comets or asteroids [8]), as well as artificial Earth satellites (AES) [9]. Such an analysis includes the calculation of the position, orbits, period, and shape of rotation of such SSOs [10].

The instability of shooting conditions greatly affects the quality of SSO images in frames generated by a charge-coupled device (CCD) [11]. This applies to both freshly generated images and archival footage. The instability of shooting conditions leads to the fact that the typical image shape [12] becomes inhomogeneous. And this, in turn, makes it difficult to identify both the entire frame with the corresponding part of the sky, and selective SSOs with catalog objects. This fact significantly reduces the accuracy of identifying SSOs and estimating their positions when using already known computational methods [13] and astronomical catalogs.

Therefore, it is relevant to devise a procedure for completely identifying the measurements of objects on digital frames. This procedure will make it possible to more accurately estimate the positional coordinates of the center of the frame [14], which will enable identification of the frame with a specific part of the starry sky. This procedure will also increase the conditional probability of correct detection (CPCD) of real objects [15].

2. Literature review and problem statement

Various changes in shooting conditions during the formation of each frame of the series can lead to the appearance of heterogeneity in the typical shape of the image of objects. This can significantly impact the accuracy of image processing and computer vision techniques.

For example, in the methods of parameter estimation [16] and object image recognition [17], only those pixels that potentially belong to the object under study are analyzed. Their disadvantage is that if the typical image shape differs from frame to frame, it is much more difficult to determine specific pixels belonging to the object. Therefore, it is also difficult to reject pixels that have an intensity exceeding the established limit value [18].

Paper [19] proposed the use of automatic reference point selection as part of pre-calibration. Namely, a selection is made of several reference points available in the field of view of the telescope. The disadvantage of this implementation is that such a choice of reference points is useful only for the selection of calibration frames, and not for identification with real SSOs in the sky.

Works [20, 21] consider segmentation and pixelization of only single images of objects. These methods have an important drawback due to the inability to accurately process SSO images with ambiguous brightness peak due to the diversity of the typical image shape.

Another implementation is described in [22], where an additional procedure for brightness equalization was added to the general algorithm. It is designed to avoid the internal coma of the telescope's secondary mirror. However, there is an approach that is more improved in accuracy and quality using an inverse median filter [23]. It includes taking into account the combination of calibration master frames (Bias, Dark, Flat) at the preliminary stage of brightness equalization. However, such implementations also have a common disadvantage. Namely, poor accuracy of positional coordinate estimates during the identification process between frames of the same series.

There is also a matched filtering method [24], based on an image correlator. The main disadvantage of this method is that it only uses an analytical image model, which can be inaccurate if frames are blurred. This means that without defining a clear typical image shape, this method will not work accurately enough. In the case when the typical image of an object in different frames of a series is different and does not have clear boundaries, then the methods of frame filtering [25] and computer vision [26] will also be ineffective. The disadvantage of these methods is the low CPCD of objects at further stages of processing.

Therefore, it is necessary to solve the problem of increasing the accuracy of identifying object measurements on digital frames. At the stages of preliminary and intra-frame processing, positional measurements of SSO are formed in the coordinate system (CS) of frames. But to use this data, astronomers need to convert these positional measurements from a Cartesian flat CS to an equatorial spherical CS. Only after this will it be possible to identify these measurements with the forms of the astronomical catalogs used.

And it is precisely in the case when the positional coordinates of the center of the frame or the pointing coordinates of the telescope during the observation program are not specified that difficulties arise in identifying SSO. In this case, it is necessary to find an initial approximation of the parameters of pairwise correspondence (matching) between sets of star catalog forms and frame measurements. From the above it follows that there is the need to devise a procedure for completely identifying the measurements of objects on digital frames.

3. The aim and objectives of the study

The purpose of this study is to increase the accuracy of identifying measurements of objects on digital frames with already known SSOs based on data from astronomical catalogs through the complete identification procedure.

To achieve the goal, the following tasks were set:

– to determine the linear constants of plates;

– to form and sort the sets of dimensions as triples of primary identification from the side of the frame and catalog;

– to compare the primary identification triples from the frame and catalog side;

– to develop an architecture for a procedure for completely identifying object measurements on digital frames;

– to verify the procedure for complete identification of object measurements on digital frames.

4. The study materials and methods

The object of our study is images of stars on a digital frame to perform identification with star catalogs. To test the devised procedure, initial data were generated in the form of a series of frames from telescopes installed at observatories in Ukraine and around the world. Namely, the ISON-NM observatory, the SANTEL-400AN telescope (New Mexico, USA); Vihorlat Observatory, VNT telescope (Humenne, Slovakia) [23]; Odesa-Mayaky observatory, OMT-800 telescope (Mayaki, Ukraine) [27]; Cerro Tololo observatory, PROMPT-8 telescope (La Serena, Chile) [28].

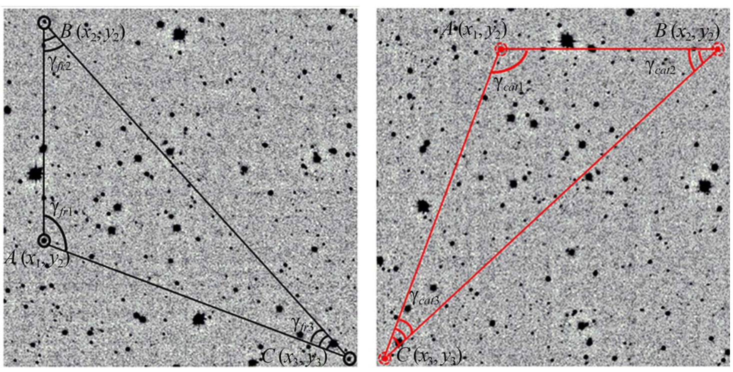
The study obtained 30,391 measurements of stars after successful identification and identification with international star catalogs. The UCAC 4.0 catalog [29], which contains more than 113 million stars with a magnitude of up to 16, was used as an astrometric catalog.

Our research results, as well as the devised procedure for complete identification of measurements, were converted into program code using the C++ programming language. This code was implemented at the stage of intra-frame processing of the Lemur software package (Ukraine) [30] for the automated detection of new and observance of known objects within the CoLiTec project [31]. The Lemur software package (Ukraine) was used during the successful identification of more than 700,000 different SSOs. Their measurements were also successfully identified with known star catalogs. With this fact, the method of complete identification of object measurements on digital frames has confirmed its practical significance.

5. Results of investigating the procedure for complete identification of object measurements on digital frames

5. 1. Determination of linear constants of plate

For the initial identification of a digital frame with an astronomical catalog, it is necessary to calculate six parameters of the linear constants of plate [32]. The initial data for their calculation are the positions $A(x_1,y_1)$, $B(x_2,y_2)$, $C(x_3,y_3)$ of three statically unchanged objects (stars) from the side of the identified frame in its own SC (Fig. 1, *a*). As well as the ideal coordinates $A(\xi_1,\eta_1)$, $B(\xi_2,\eta_2)$, $C(\xi_3,\eta_3)$ of the corresponding stars from the astronomical catalog (Fig. 1, *b*). To obtain them from equatorial coordinates, it is necessary to have an approximation of the equatorial coordinates of the optical center of the digital frame itself.



a *b*

Fig. 1. Formation of triplets (vertices of a triangle) of primary identification: *a* – from the side of the frame; *b* – from the side of the star catalog

The ideal coordinates of the object under study are connected by the following reduction equation [33] with its coordinates in the digital frame SC:

$$\begin{bmatrix} a_0 \\ a_1 \\ a_2 \end{bmatrix} = \begin{bmatrix} 1 & x_1 & y_1 \\ 1 & x_2 & y_2 \\ 1 & x_3 & y_3 \end{bmatrix}^{-1} \begin{bmatrix} \xi_1 \\ \xi_2 \\ \xi_3 \end{bmatrix}, \quad (1)$$

$$\begin{bmatrix} b_0 \\ b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} 1 & x_1 & y_1 \\ 1 & x_2 & y_2 \\ 1 & x_3 & y_3 \end{bmatrix}^{-1} \begin{bmatrix} \eta_1 \\ \eta_2 \\ \eta_3 \end{bmatrix}. \quad (2)$$

In this way, a relationship is formed between the stars on the frame (positional measurements in the frame's SC) and the astronomical catalog forms (spherical coordinates). This matching is termed a primary identification triple.

5. 2. Formation and enumeration of multiple dimensions as primary identification triples from the side of the frame and catalog

To form primary identification triples on the frame side, a set of Ω_{bl50} candidates is used, consisting of N_{bl50} frame measurements with the highest brightness. An additional set of Ω_{bl100} frame measurements with the highest brightness is also introduced, which are used to form the weight of the hypothesis about the correspondence of the frame and catalog triplets (confirming the primary identification hypotheses). Similarly, from the side of the astronomical catalog, a set of $\Omega_{star100}$ catalog entries and an additional set $\Omega_{star200}$ are formed, taking into account the uniform distribution of star entries in the studied area of the sky.

The selection of the first dimension of any triple from the generated sets is performed randomly. In order for the triple of measurements with coordinates $(x_{1(k)};y_{1(k)})$, $(x_{2(k)};y_{2(k)})$, $(x_{3(k)};y_{3(k)})$ to form a triangle in the digital frame SC, then for the other two dimensions of the triple certain conditions are introduced. For example, the second dimension of the triple must be no closer than k_h angular size R_{CCD} of the RCCD frame from the first dimension:

$$r_{(1)(2)} = \\ = \sqrt{\left(y_{2(k)} - y_{1(k)}\right)^2 + \left(x_{1(k)} - x_{2(k)}\right)^2} \geq 0.5\, k_h \begin{pmatrix} R_{CCD(x)} + \\ + R_{CCD(y)} \end{pmatrix}. \quad (3)$$

The choice of the third dimension is based on the condition that it is possible to lower the perpendicular r_{trian} [34] from it onto a straight line passing through the first and second dimensions of the primary identification triple:

$$r_{trian} = \left| x_{1(k)} y_{2(k)} - x_{2(k)} y_{1(k)} \right|. \quad (4)$$

In this way, triples of primary identification are formed from the side of the digital frame and the astronomical catalog. In order to compare the formed triangles (primary identification triplets), it is necessary to calculate the angles (vertices) of each triangle. This can be done using the sines and cosines of angles γ_1, γ_2, γ_3 [35]:

$$\sin\gamma_1 = \left(\frac{x_{2(k)} y_{3(k)} - y_{2(k)} x_{3(k)}}{\sqrt{x_{2(k)}^2 + y_{2(k)}^2} \cdot \sqrt{x_{3(k)}^2 + y_{3(k)}^2}} \right), \quad (5)$$

$$\cos\gamma_1 = \left(\frac{x_{2(k)} x_{3(k)} + y_{2(k)} y_{3(k)}}{\sqrt{x_{2(k)}^2 + y_{2(k)}^2} \cdot \sqrt{x_{3(k)}^2 + y_{3(k)}^2}} \right), \quad (6)$$

$$\sin\gamma_2 = \left(\frac{x_{1(k)} y_{3(k)} - y_{1(k)} x_{3(k)}}{\sqrt{x_{1(k)}^2 + y_{1(k)1}^2} \cdot \sqrt{x_{3(k)}^2 + y_{3(k)}^2}} \right), \quad (7)$$

$$\cos\gamma_2 = \left(\frac{x_{1(k)} x_{3(k)} + y_{1(k)} y_{3(k)}}{\sqrt{x_{1(k)}^2 + y_{1(k)}^2} \cdot \sqrt{x_{3(k)}^2 + y_{3(k)}^2}} \right), \quad (8)$$

$$\sin\gamma_3 = \left(\frac{x_{1(k)} y_{2(k)} - y_{1(k)} x_{2(k)}}{\sqrt{x_{1(k)}^2 + y_{1(k)}^2} \cdot \sqrt{x_{2(k)}^2 + y_{2(k)}^2}} \right), \quad (9)$$

$$\cos\gamma_3 = \left(\frac{x_{1(k)} x_{2(k)} + y_{1(k)} y_{2(k)}}{\sqrt{x_{1(k)}^2 + y_{1(k)}^2} \cdot \sqrt{x_{2(k)}^2 + y_{2(k)}^2}} \right). \quad (10)$$

Knowing the values of the equatorial coordinates (α_0, δ_0) of the optical center of the frame, it is possible to determine the tangential (ideal) coordinates of the stars of the astronomical catalog according to the following expressions [36]:

$$\xi_{j(k)} = = \frac{\cos\delta_{j(k)} \cdot \sin\left(\alpha_{j(k)} - \alpha_0\right)}{\cos\delta_0 \cdot \cos\delta_{j(k)} \cdot \cos\left(\alpha_{j(k)} - \alpha_0\right) + \sin\delta_0 \cdot \sin\delta_{j(k)}}; \quad (11)$$

$$\eta_{j(k)} = = \frac{\cos\delta_0 \cdot \cos\left(\alpha_{j(k)} - \alpha_0\right)}{\cos\delta_0 \cdot \cos\delta_{j(k)} \cdot \cos\left(\alpha_{j(k)} - \alpha_0\right) + \sin\delta_0 \cdot \sin\delta_{j(k)}}; \quad (12)$$

where $\alpha_{j(k)}$, $\delta_{j(k)}$ are the angular coordinates of the $j(k)$th object in the astronomical catalog.

Based on the obtained tangential (ideal) coordinates, by analogy with expressions (5) to (10), the angles of the triangle (triple) of primary identification from the side of the astronomical catalog are determined.

5. 3. Comparison of primary identification triples from the frame and catalog side

The two generated primary identification triples are checked for the identity of the angles (each with each) of their corresponding triangles. The stars of two triplets (frame and catalog) are considered preliminary identical if the deviations in the values of the corresponding angles in these triangles do not exceed the permissible deviation of the angle values $\Delta\gamma$:

$$\left|\gamma_{1fr} - \gamma_{1cat}\right| < \Delta\gamma, \quad (13)$$

$$\left|\gamma_{2fr} - \gamma_{2cat}\right| < \Delta\gamma, \quad (14)$$

$$\left|\gamma_{3fr} - \gamma_{3cat}\right| < \Delta\gamma, \quad (15)$$

where γ_{ifr}, γ_{icat} are the angles of triangles that correspond to the triple of primary identification from the side of the frame and the astronomical catalogue.

The parameter $\Delta\gamma$ determines the computational costs of the procedure for completely identifying measurements of objects on digital frames with significant uncertainty in their parameters.

5. 4. Development of an architecture for a procedure for complete identification of object measurements on digital frames

The architecture of the procedure for complete identification of object measurements on digital frames includes the following sequence of operations (Fig. 2) [14]:

1. For multiple frame measurements, when generating primary identification triples, the following actions are performed.

1. 1. Formation of a set Ω_{bl50} of the brightest measurements of the frame consisting of N_{bl50} candidates when choosing triples of primary identification. In order to ensure stability of identification results, the frame is divided into $M_{reg} \times M_{reg} = M_{reg}^2$ parts. The specified number of frame measurements N_{bl50} is divided by the number of frame fragments, and in each such fragment the brightest frame measurements N_{bl50} / M_{reg}^2, are selected.

1. 2. Formation of an additional set Ω_{bl100} of the brightest measurements of the frame, consisting of N_{bl100} elements evenly distributed on the frame (by analogy with Step 1. 1). A set of measurements Ω_{bl100} is used to confirm the primary identification hypotheses (forming the weight of the next hypothesis about the correspondence of frame and catalog triplets).

2. For a set of catalog forms, when generating primary identification triples, the following actions are performed.

2. 1. Formation of a set $\Omega_{star100}$ of catalog entries, taking into account the uniform distribution of star entries in the studied area of the starry sky.

2. 2. Formation of an additional set $\Omega_{star200}$ of catalog entries consisting of $N_{star200}$ elements (taking into account the uniform distribution of the used star entries in the studied area of the starry sky), which is used to confirm the hypotheses of the primary identification (forming the weight of the next hypothesis about the correspondence of the frame triple and the catalog).

3. Sorting out and confirmation of hypotheses of primary identification.

3. 1. Sorting through measurements of set Ω_{bl50} as elements of primary identification triples. The measurements that make up the primary identification triplets must satisfy conditions (3) and (4).

3. 2. Sorting through the set $\Omega_{star100}$ of catalog entries as elements of primary identification triples from the catalog side.

3. 3. Comparison of primary identification triples from the side of frame measurements and from the side of catalog forms based on the corresponding angles of the triangles, the values of which are calculated according to expressions (5) to (10).

3. 4. Confirmation of the hypothesis about the parameters of identification of frame and catalog, which corresponds to the considered triples of primary identification (from the catalog and frame). The hypothesis is recognized as true if, in the process of identifying the sets Ω_{bl100} and $\Omega_{star200}$, part of the generated admissible pairs exceeds the previously specified value of parameter $v_{\min\_ident}$. When the identification hypothesis is confirmed, further search stops.

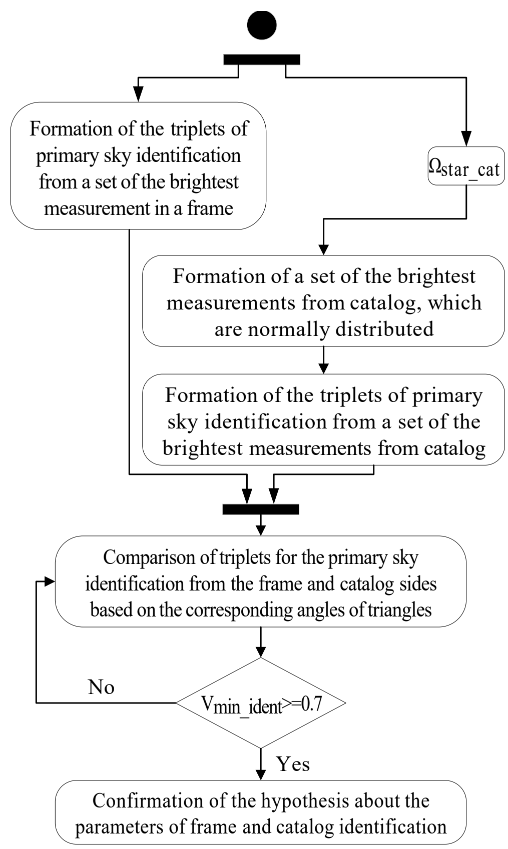


Fig. 2. Architecture of the procedure for complete identification of object measurements on digital frames

5. 5. Verification of the procedure for complete identification of object measurements on digital frames

To verify the devised procedure for complete identification of object measurements on digital frames, testing was carried out on a series of frames containing 30,391 measurements.

The following statistical [37] indicators of the accuracy of reference star measurements were studied: estimates of the average deviation of estimates of equatorial coordinates $\overline{\Delta}_\alpha$, $\overline{\Delta}_\delta$ and estimates of brightness $\overline{\Delta}_m$ between the catalog and measured values:

$$\hat{\overline{\Delta}}_\alpha = \sum_{i=1}^{N_{mea}} \Delta_{ai} / N_{mea}; \quad (16)$$

$$\hat{\overline{\Delta}}_\delta = \sum_{i=1}^{N_{mea}} \Delta_{\delta i} / N_{mea}; \quad (17)$$

$$\hat{\overline{\Delta}}_m = \sum_{i=1}^{N_{mea}} \Delta_{mi} / N_{mea}, \quad (18)$$

where N_{mea} is the number of measurements of the i-th object in the series.

As well as estimates of standard deviation (RMS) σ_α, σ_δ, σ_m [38]:

$$\hat{\sigma}_\alpha = \sqrt{\sum_{i=1}^{N_{mea}} \left(\Delta_{\alpha i} - \hat{\overline{\Delta}}_\alpha\right)^2 / \left(N_{mea} - 1\right)}; \quad (19)$$

$$\hat{\sigma}_\delta = \sqrt{\sum_{i=1}^{N_{mea}} \left(\Delta_{\delta i} - \hat{\overline{\Delta}}_\delta\right)^2 / \left(N_{mea} - 1\right)}; \quad (20)$$

$$\hat{\sigma}_m = \sqrt{\sum_{i=1}^{N_{mea}} \left(\Delta_{mi} - \hat{\overline{\Delta}}_m\right)^2 / \left(N_{mea} - 1\right)}. \quad (21)$$

The study implied calculating the accuracy indicators listed above before and after applying the developed full identification procedure. The results of our study are given in Table 1.

Table 1

Statistical indicators of the accuracy of reference star measurements

Statistical indicator	Value before	Value after
Average deviation RA, arc. sec.	0.013	0.003
Average deviation DE, arc. sec.	0.015	0.002
Average deviations brightness, sv.vel.	0.34	0.03
Max. deviation module RA, ang. sec.	0.98	0.13
Max. deviation module DE, ang. sec.	0.84	0.12
Min. gloss deviation modulus, sv.vel.	0.002	0.001
Max. gloss deviation modulus, sv.vel.	3.34	0.42
Standard deviation of deviations according to RA, ang. sec.	0.55	0.07
Standard deviation of deviations according to DE, ang. sec.	0.47	0.08
RMS deviations in brightness, s.vel.	0.73	0.37

The indicators given in Table 1 testify to the successful application of the devised procedure. When identifying frames, the fitting provides better accuracy of reference to the starry sky. The standard deviation of frame identification errors in this case is 6–9 times less than without using the developed procedure.

6. Discussion of results of investigating the procedure for complete identification of object measurements on digital frames

A study was carried out on the accuracy of identifying measurements of objects on digital frames with already known SSOs based on data from astronomical catalogs. For this purpose, a procedure was devised for completely identifying the measurements of objects on digital frames. Known methods of computer vision and image processing were also analyzed. However, the accuracy of processing using known methods directly depended on the homogeneity and constancy of the typical image of objects in each frame of the series. Therefore, to develop a procedure for completely identifying object measurements, it was proposed to use only the brightest measurements in the frame and from catalog forms. A uniform distribution of identified measurements throughout the frame was also applied to ensure stability of identification.

As part of the CoLiTec project, research was carried out on the application of the devised procedure for the complete identification of object measurements on digital frames. Based on certain conditions (3) and (4), triplets of primary identification were formed. Owing to sine and cosine, it became possible to determine the angles of each vertex of such a triangle (triple) using expressions (5) to (10). In addition, by converting the equatorial coordinates of the optical center into ideal tangential ones and using the calculation of the resulting angles, it became possible to form primary identification triplets from the astronomical catalog.

When conducting research, the following values of the parameters of the developed procedure were assumed. The number of frame measurement candidates for primary identification from the frame side is N_{bl50}=50. The number of elements of the set of frame measurements to confirm the hypotheses is Ω_{bl100}=100. The number of fragments into which the frame is divided M_{reg}=4. The number of candidate stars for primary identification from the astrometric catalog is $N_{star100}$=200. The number of elements of the set of form stars to confirm the hypotheses is $\Omega_{star200}$=200. The minimum permissible distance between the first and second points of the primary identification triple is k_h=0.1. The permissible deviation of the angle values of the formed primary identification triangles is $\Delta\gamma$=60'. The maximum distance between elements of an identified valid pair is Δr_{ident}=10 pixels. The minimum acceptable ratio of the number of pairs to the size of the set Ω_{bl100} is $\upsilon_{\min\_ident}$=0.7. The parameters of the computational procedure listed above were obtained empirically.

The study (Table 1) showed that the use of the procedure reduces the identification errors of images and cataloged (reference) objects by 6–9 times. This significantly affects the quality and accuracy of a number of data acquisition tasks [39] and detection of object trajectories [40].

The results from Table 1 are determined by increasing resistance to various types of destabilizing factors by taking into account the formation of false measurements based on frames of the entire series. This indicator clearly indicates that the assigned tasks have been successfully completed.

A limitation of this study is the uniformity of the input frames of the series, their sizes, as well as the same shooting conditions. Another limitation is the computing power of the equipment on which the processing will take place. The issue of frame security, namely the encryption of input data, is also important. In this case, an additional decryption algorithm will be required. In addition, to use data from astronomical catalogs, you need increased storage capacity or stable access to the Internet for uninterrupted access to catalog data.

The disadvantage of the study is the impossibility of applying the devised procedure without the availability of forms from existing astrometric star catalogs. This implies the need to use a layer to obtain data from these directories before using it in the procedure. This leads to delays in the processing pipeline and downtime of computing power.

Further research may be aimed at applying the developed procedure for complete identification of measurements to identify SSOs in astronomical star catalogs. This can be realized by introducing into the astronomical image processing pipeline with appropriate methods for sampling services/modules [41]. It is also necessary to evaluate the impact on other motion detection methods that will be used subsequently. To this end, one can use machine learning, Wavelet analysis, time series analysis, or a forecasting method to calculate quality indicators.

7. Conclusions

1. For the initial identification of the digital frame with the astronomical catalog, six parameters of the linear constants of plate were calculated. The calculations were based on the positions of three statically unchanged objects (stars) from the side of the identified frame and the ideal coordinates of the corresponding stars from the side of the astronomical catalog. Owing to the reduction equation, the ideal coordinates of the object were related to its coordinates in the digital frame. In this way, a matching was formed, called the triple of primary identification.

2. Triples of primary identification were formed from the side of the frame and from the side of the astronomical catalog. The triplets included measurements on the frame and catalog forms with the highest brightness from the formed sets. In addition, owing to the formation of additional sets, it became possible to confirm the hypotheses of the primary identification, namely the formation of the weight of the hypothesis about the correspondence of frame and catalog triplets. Sorting out candidates from sets and certain formation conditions made it possible to form more accurate triplets of primary identification. After this, the angle values of each vertex of the formed triangle were calculated through sine and cosine. In addition, owing to the conversion of equatorial coordinates into ideal tangential coordinates, it became possible to calculate the angles of the vertices of triangles from the side of the astronomical catalog.

3. The generated primary identification triples were checked for the identity of the angles (each with each) of the corresponding triangles from the side of the frame and the astronomical catalog. Taking into account the permissible deviation of the values of angles $\Delta\gamma$ in comparison with the obtained deviations in the values of the corresponding angles in the triangles (triples) of the primary identification, the hypothesis of their identity was accepted.

4. Owing to preliminary calculations, an architecture for a procedure for completely identifying object measurements on digital frames was designed. The key point is the formation of additional sets Ω_{bl100} of the brightest measurements of the frame and $\Omega_{star200}$ of catalog forms to take into account the uniform distribution of the objects under study in the frame and the sky area, respectively. An approach was also used to determine the truth of the hypotheses by counting the excesses of the maximum permissible value $v_{\min\_ident}$ by the formed pairs in the process of identifying the Ω_{bl100} and $\Omega_{star200}$ sets.

5. The procedure for complete identification of object measurements on digital frames containing 30,391 measurements was verified. Statistical indicators of the accuracy of measurements of guide stars after their successful identification were studied. The use of the devised procedure reduces the identification errors of images of cataloged (reference) objects by 6–9 times.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

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