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IMPROVING THE ACCURACY OF IDENTIFYING OBJECTS IN DIGITAL FRAMES OF ONE SERIES THROUGH THE PROCEDURE OF PRELIMINARY IDENTIFICATION OF MEASUREMENTS

The object of this study is images of various objects of the Solar System on a series of digital frames. The variety and quality of shooting conditions make it difficult to identify a frame with the corresponding part of the sky. This fact significantly reduces the quality indicators of detection and estimation of the position of objects of the Solar System using already known computational methods and international astronomical astrometric and photometric catalogs. To solve this problem, a procedure for preliminary identification of measurements of digital frames of one series was devised.

This procedure is based on the determination of the shift parameters between the dimensions of a frame and the forms of a catalog or another frame. Also, taking into account the possibility of forming false measurements has made it possible to increase the accuracy of identification and resistance to various kinds of destabilizing factors. Based on this, the final estimation of the shift parameters between frames was performed. Due to these features, the use of the devised preliminary identification procedure makes it possible to improve identification with reference astronomical objects and reduce the number of false detections. The study showed that when identifying frames, the fitting gives the best accuracy of binding to the starry sky. Also, the standard deviation of frame identification errors in this case is 7–10 times less than without using the devised procedure.

The procedure developed for preliminary identification of measurements of digital frames of one series was tested in practice within the framework of the CoLiTec project. It has been incorporated into the Lemur software for automated detection of new and tracking of known objects. Owing to the use of the Lemur software and the proposed 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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1. Introduction

The issue of potential asteroid-comet hazard [1] has become the leading area for the use of various methods of astrometry [2] and photometry [3]. The results of asteroid/comet/satellite surveys are used as initial data for automated processing. Huge astronomical catalogs and archival big data [4] make it possible to accumulate, obtain knowledge [5], and analyze the accumulated publicly available data and measurements [6]. Most often, they were obtained for the entire period of observation of specific celestial objects of the Solar System (SSO) [7] (for example, asteroids [8] or comets), as well as artificial satellites [9]. Such an analysis may even include the calculation of the period and shape of rotations of similar SSOs [10].

However, a variety of shooting conditions significantly affects the quality of SSO images on frames that are formed by a charge-coupled device (CCD) [11]. This applies to both

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archival images and freshly formed frames. The quality of the shooting conditions leads to the fact that it is difficult to identify the frame with the corresponding part of the sky. This fact significantly reduces the quality indicators of SSO detection and estimation of their position using already known computational methods and international astronomical catalogs.

Therefore, it is relevant to devise a procedure for preliminary identification of measurements of digital frames of one series. This method could make it possible to more accurately estimate the positional coordinates of both the center of the frame and objects [12], which will allow them to be identified with those already known from the cataloged list [4]. Also, this method would increase the conditional probability of correct detection (CPCD) of actual objects [13].

2. Literature review and problem statement

Under different shooting conditions during the formation of a series, each frame can have a different shift in the positional coordinates of the frame center. This leads to the formation of a heterogeneous typical form of the image of objects [14]. And this fact affects the accuracy of performing various tasks of image processing and machine vision [15]. Namely, the accuracy of detection and recognition of images of objects [16], the performance of parameter estimation [17]. These methods are based on the analysis of only those pixels that potentially belong to the object under study. Their disadvantage is that, with a variety of typical image shapes, it is completely impossible to initially determine specific pixels and reject those whose intensity exceeds a given limit value [18].

In [19], the authors propose to use the automatic selection of the reference point as part of the calibration. For example, several such reference points are selected in the field of view, but they can only be useful for selecting calibration frames. The disadvantage of this approach is that, due to image artifacts, there may be falsely detected objects that do not correspond to real SSOs with fixed positional coordinates.

Works [20, 21] consider pixelization and segmentation of only single images of objects. The disadvantage of these methods is the impossibility of accurate processing of images of objects with an ambiguous number of brightness peaks due to the variety of typical image shapes. This diversity also affects various methods for analyzing large datasets, namely Wavelet transform (analysis) [22] and time series analysis [23]. The disadvantage of these methods is that they are adapted to work only with "pure" measurements, so the heterogeneity of images will spoil the overall indicator very much.

Another suggestion is presented in [24] in the form of an additional leveling procedure to avoid the internal coma of the telescope's secondary mirror. However, there is an approach that is more improved in terms of accuracy and quality of brightness equalization using an inverse median filter [25]. It preliminarily uses a combination of calibration master frames (Bias, Dark, Flat). But the disadvantage of these approaches is the poor accuracy of positional coordinate estimates during the process of identification between frames of the same series.

The matched filtering method [26] is also known, but it uses an analytical image model. The main disadvantage of this method is the fact that the method will not work correctly if the typical image of the object on different frames of the series is different. The disadvantage of the frame addition methods [27] and machine vision [28] is the impossibility of application when the image of the object under study does not have clear boundaries on all CCD frames of the series.

Thus, the various image processing methods listed above, including images of astronomical objects, do not allow one to accurately identify the measurements. The main reason is the significant uncertainty of the typical form of the images themselves and the unexpressed peak. Also, these methods do not imply rejection of false measurements and do not take into account the parameters of shifts between frames. Because of this, the accuracy of identifying the measurements of objects on the frame is significantly reduced, which leads to a drop in the CPCD of objects at further stages of processing.

Therefore, it is necessary to solve the problem of increasing the accuracy of identifying measurements of objects on digital frames, as well as to increase resistance to destabilizing factors and take into account common features of measurement formation. This implies the need to devise a procedure for preliminary identification of measurements of digital frames of one series. In this case, the positional coordinates of a single astronomical object based on its image in the digital frame plane are considered as measurements.

The preliminary identification procedure will take into account the features of the formation of both series of digital frames and measurements of specific objects with various typical shapes and exclude false measurements from consideration. Such false measurements have image positional coordinates that do not correspond to a real astronomical object (for example, image artifact, flare, etc.). If such false measurements are not taken into account, then the set of measurements formed from the entire series of frames for the same object will contain such anomalous measurements and cannot be used in more accurate calculations.

Thus, the exclusion of false measurements will lead to an increase in resistance to destabilizing factors and, accordingly, the accuracy of identification.

3. The aim and objectives of the study

The aim of this study is to improve the accuracy of identifying object measurements on digital frames with already known SSOs based on astronomical catalog data.

To achieve the goal, the following tasks were set:

– to exclude false measurements from consideration;

– to devise a procedure for preliminary identification of measurements of digital frames of one series;

– to verify the procedure for preliminary identification of measurements of digital frames of one series.

4. The study materials and methods

The object of our study is the images of various SSOs on a series of digital frames. As part of the preliminary identification, the main hypothesis is the hypothesis that the measurements of different frames belong to the same object. The initial data are a series of digital CCD frames formed under various shooting conditions. The initial series for the study were obtained from a variety of telescopes installed at observatories in Ukraine and around the world. Namely, the ISON-NM observatory, the SANTEL-400AN telescope (New Mexico, USA); Odesa-Mayaky observatory, OMT-800 telescope (Mayaky, Ukraine) [29]; Vihorlat Observatory, VNT telescope (Humenne, Slovakia) [25]; Cerro Tololo observatory, PROMPT-8 telescope (La Serena, Chile) [30].

The total number of measurements obtained for the study corresponds to 28,872 SSO measurements after successful detection and identification with international astronomical catalogs. As part of the study, it was assumed that the measurements used to verify the measurement method belong to objects on frames with a shift parameter between frames of one series of no more than 1 angular degree.

The UCAC 4.0 catalog (USA) [31] was used as an astrometric catalog. Its "density" is 2000 stars per square degree. The catalog contains more than 113 million stars with magnitudes up to 16. The USNO B1.0 (USA) catalog [32] was used as a photometric catalog. The catalog contains the angular positional coordinates and brightness of more than one billion SSOs, formed on 3.6 billion measurements. As part of the study, a simplification was adopted that the series of frames used to verify the method were made on telescopes with a penetrating power no higher than the catalog one.

During the research, the following values of the parameters of the devised computational method were assumed. The radius of confirmation areas (strobes) is R_{rej}=20 pixels. The minimum allowable number of acknowledgments is N_{min_ack}=70 %. The number of areas of the same size into which the frame is divided is equal to $M_{reg}\times M_{reg}$=4×4. The number of the brightest measurements of the frame area is equal to $N_{mea\_reg}=N_{mea}/M_{reg}^2=3$. The parameters of the computational method listed above were obtained empirically.

Our research results, as well as the deised method of preliminary identification of measurements, were converted into a program code using the C++ programming language. This code was implemented at the stage of intraframe processing of the Lemur software package (Ukraine) [33] for automated detection of new and tracking of known objects within the CoLiTec project (Ukraine) [34].

The devised computational method, implemented in the Lemur software (Ukraine), was used during the successful identification of digital frames, on which there were a total of more than 700,000 different SSOs. Their measurements were also successfully identified with known astronomical catalogs. By this fact, the method of preliminary identification of measurements of digital frames of one series confirmed its practical significance.

5. Results of the study of identification accuracy based on the procedure for preliminary identification of measurements of digital frames of one series

5. 1. Exclusion of false measurements from consideration

There is a possibility that the measurement can be formed when an astronomical object enters the field of view of the telescope and subsequently the frame. In this case, the frequency of viewing the corresponding section of the starry sky affects the a priori probabilities of forming measurements of the i-th object. In this case, the a priori probabilities [35] of obtaining measurements from the objects of the astronomical catalog, the brightness of which is not lower than the penetrating value of the telescope itself, can rightly be considered equally probable.

If there are data in the star catalog only about astronomical objects, there is no need to impose any requirements on the probability of confusion between measurements between uncatalogued objects, data on which are not contained in the star catalog. All non-cataloged objects can be reduced to a conditionally called "null object". Also, the confusion of measurements between astronomical objects from the star catalog leads to a loss of accuracy in determining the position of the objects under study, for example, comets, asteroids. It is assumed that all astronomical objects of the star catalog are equally important and, accordingly, the requirements for the probability of mixing up measurements between them should also be the same.

Thus, the most common destabilizing factors are:

– confusion of measurements;

– false measurements obtained due to technical failures during the survey;

– false measurements obtained due to artifacts, noise, intraframe processing errors;

– false measurements caused by formation features;

– non-uniform shift parameters between frames.

To solve the problem set, it is necessary to find the initial approximation of the parameters of pairwise correspondence (matching) between two sets of measurements formed on two frames and corresponding to the same region of the celestial sphere. One of the cases of identification significant for practice is the case of mutual identification of frames of a series formed approximately at the same time on the same telescope by one CCD camera without changing the angle of its rotation. In this case, only the shift parameters (rotation parameters are near zero, and the scale is the same from frame to frame) distinguish the position of celestial objects on frames formed in this way. The shift parameters are common for all dimensions of two frames and characterize the mutual arrangement of frames relative to each other on the celestial sphere, being the desired matching parameters between two sets of dimensions. When preliminary identifying the measurements of digital frames of one series, it is advisable to avoid a global enumeration of matching measurements of these frames. To do this, it is necessary to take into account the invariability of the shift parameters from pair to pair. In this case, it is possible to solve the problem of preliminary identification by putting forward (sorting out) hypotheses about the belonging of the measurements of different frames to the same object.

Each such matching hypothesis corresponds to shift estimates conditional on the hypothesis of correspondence to the same astronomical object of the "measurement-measurement" pair for one measurement of each frame:

$$\Delta_{xi}=x_{1(i)}-x_{2(i)}, \quad (1)$$

$$\Delta_{yi}=y_{1(i)}-y_{2(i)}, \quad (2)$$

where $x_{1(i)}$, $y_{1(i)}$, $x_{2(i)}$, $y_{2(i)}$ are the measurement coordinates of the same i-th object (object coordinate estimates) on the first and second identified frames in the coordinate system of the base frame of the series.

When identifying frames of a series, measurements of stars that have zero apparent motion are used. Objects with non-zero apparent motion (for example, objects of the solar system, artificial satellites of the Earth) are considered false in this connection. Also, false measurements can correspond to image artifacts or image noise spikes and be formed due to errors in intraframe frame processing [36].

Under the assumption that there are no false measurements, it would be sufficient to test only the hypotheses about the correspondence of one measurement of the first frame to one measurement of the second. However, the frame measurement chosen for such a study may be false. The false measurement rate needs to be stabilized at a sufficiently low level. Therefore, the probability that two and even more so three false measurements of the first objects will be successively chosen for preliminary identification is negligible. When implementing the method, no more than three measurements of the first frame are used to search for the corresponding measurements of the second frame.

One of the requirements for the preliminary identification procedure is its resistance to various kinds of destabilizing factors. First of all, these include the possible presence on one of the frames of a bright track of an artificial earth satellite (AES) [9], the effect of charge flow. When a bright AES enters the frame, its image can illuminate the frame, forming a large number of false measurements on it (Fig. 1).

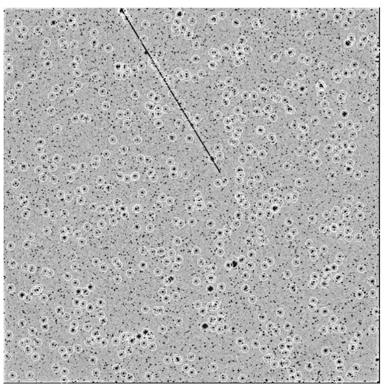

Fig. 1. An example of a frame with the presence of a satellite track and false measurements formed on it

The effect of charge leakage has the same consequences for preliminary identification. In addition, images of the brightest stars in the frame, as a rule, have a number of other features that lead to a decrease in the accuracy of estimating their position, which makes them undesirable candidates for reference stars (Fig. 2).

In order to ensure the stability of the results of the preliminary identification procedure, the frame is divided into a predetermined number of regions of the same size $M_{reg}\times M_{reg}$. In this case, stability is considered to be approximately the same accuracy based on the results of the procedure in any part of the frame, regardless of the presence of a different number of false measurements. To increase stability, it is better to process only qualitative measurements instead of processing everything, including false ones. From each such area, the same predetermined number of the brightest objects N_{mea_reg} is selected. Thus, the selected measurements will be evenly distributed over the frame, which will help minimize the likelihood of pre-identification errors.

Such a choice of measurements for preliminary identification will make it possible to exclude from consideration a large number of bright false measurements caused by the flow of the charge of a large star or a bright satellite track.

After taking into account the possibility of forming false measurements, as well as a uniform distribution of regions with the same size, to ensure stability, it is necessary to perform a final assessment of the shift parameters:

$$\bar{\Delta}_x = \sum_{i=1}^{N_{ident}} \Delta_{xi} / N_{ident}, \tag{3}$$

$$\bar{\Delta}_y = \sum_{i=1}^{N_{ident}} \Delta_{yi} / N_{ident}, \tag{4}$$

where N_{ident} is the number of pairs used in estimating frame shift parameters relative to each other.

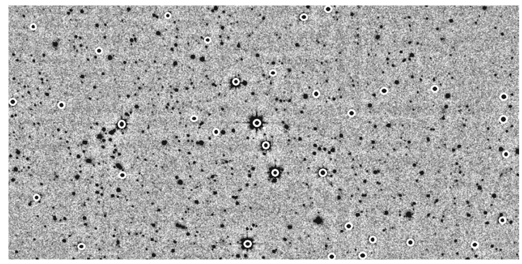

Fig. 2. An example of a frame with the effect of charge flow and false measurements formed on it

This evaluation is performed between frames as part of the preliminary identification of digital frames of the same series. Since the positions of objects on each frame are determined with errors, the frame shift parameters relative to each other can be determined more accurately by averaging the shift parameters in each individual pair of object images on two frames.

5. 2. Procedure for preliminary identification of measurements of digital frames of one series

It is necessary to devise a procedure that will allow carrying out a preliminary stage of identifying the measurements of digital frames of one series. This preliminary identification will improve the accuracy of identification due to greater resistance to the destabilizing factors listed above, as well as take into account the features of the formation of the measurements themselves.

The procedure for preliminary identification of measurements of digital frames of one series includes the following sequence of operations (Fig. 3):

1. The digital frame of the series is divided into a set $M_{reg}\times M_{reg}$ of equal areas (areas).

2. Sets of the brightest dimensions of the frame are formed. To this end, from each area, an equal predetermined number N_{mea_reg} of measurements with the highest estimates of the brightness of the hypothetical objects corresponding to them is selected.

3. A measurement is selected from a preselected set of the brightest measurements of the first frame (no more than three such measurements are selected).

4. The next measurement (a cycle is organized according to the studied measurements of the second frame) of the second frame from a preselected set of measurements of the second frame is put in correspondence with the measurement under study of the first frame. To this end, according to expressions (1) and (2), a conditional estimate of the shift parameters is preliminarily calculated according to the pair hypothesis.

5. For each selected pair, the weight of the next hypothesis about the correspondence of pairs of measurements of the first and second frame (measurement of the frame and the catalog form) to the same object is estimated. To do this, each measurement of the first frame is compared with each measurement of the second frame. First, the shift parameters (1) and (2) are

added to the measurement coordinates of the first frame. Based on the deviations between the measurements of the first and second frames, the fact that the measurements of the second frame fall into the confirmation area (strobes) is determined.

6. If a sufficient number of measurements of the second frame N_{ack} fell into the confirmation strobes, then it is considered that the hypothesis about the combination of pairs of measurements of the first and second frames is considered confirmed (proceed to step 7):

$$N_{ack} \geq N_{\min\_ack}, \tag{5}$$

where $N_{\min\_ack}$ is the minimum allowed number of acknowledgments.

If not, then the hypothesis about the shift parameters is considered false and a transition is made (to step 4) to the next dimension of the second frame. When the preselected set of measurements of the second frame is exhausted, a transition is made to the next measurement of the first frame (to point 3).

7. The final estimate of the shift parameters (3) and (4) is calculated.

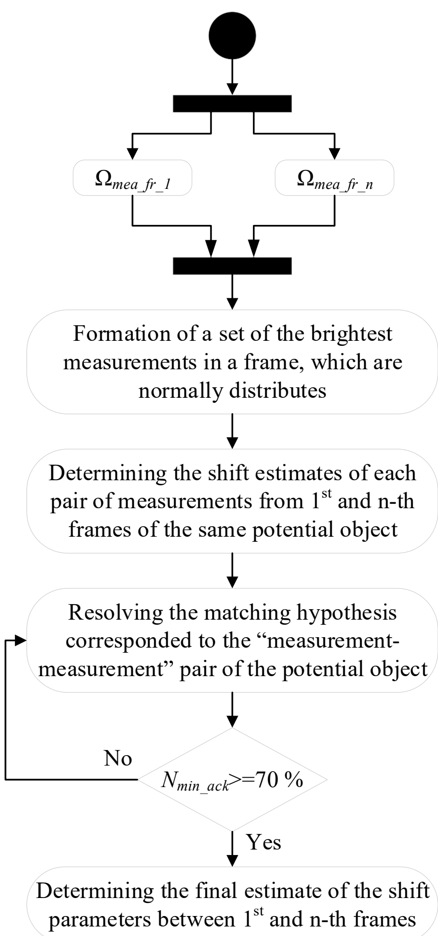

Fig. 3. Architecture of the procedure for preliminary identification of measurements of digital frames of one series

5. 3. Verification of the procedure for preliminary identification of measurements of digital frames of one series

To confirm the rationality of devising a procedure for preliminary identification of measurements of digital frames of one series, it is necessary to verify it. This verification should include the study of statistical indicators of accuracy, which will confirm the increase in resistance to destabilizing factors.

To verify the devised procedure for the preliminary identification of measurements of digital frames of one series, testing was carried out on a series of frames containing 28872 measurements. The series of frames tested were specially selected in such a way that they contained a variety of destabilizing factors (artifacts, flying AES, charge leakage, failure of the daily tracking of the telescope).

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

$$\hat{\bar{\Delta}}_\alpha = \sum_{i=1}^{N_{mea}} \Delta_{\alpha i} / N_{mea}; \tag{6}$$

$$\hat{\bar{\Delta}}_\delta = \sum_{i=1}^{N_{mea}} \Delta_{\delta i} / N_{mea}; \tag{7}$$

$$\hat{\bar{\Delta}}_m = \sum_{i=1}^{N_{mea}} \Delta_{mi} / N_{mea}, \tag{8}$$

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

As well as estimates of the standard deviation (RMSD) σ_α, σ_δ, σ_m:

$$\hat{\sigma}_\alpha = \sqrt{\sum_{i=1}^{N_{mea}} \left(\Delta_{\alpha i} - \hat{\bar{\Delta}}_\alpha \right)^2 / \left(N_{mea} - 1 \right)}; \tag{9}$$

$$\hat{\sigma}_\delta = \sqrt{\sum_{i=1}^{N_{mea}} \left(\Delta_{\delta i} - \hat{\bar{\Delta}}_\delta \right)^2 / \left(N_{mea} - 1 \right)}; \tag{10}$$

$$\hat{\sigma}_m = \sqrt{\sum_{i=1}^{N_{mea}} \left(\Delta_{mi} - \hat{\bar{\Delta}}_m \right)^2 / \left(N_{mea} - 1 \right)}, \tag{11}$$

where N_{mea} is the number of measurements of the object under study.

The study involved calculating the above statistical indicators of accuracy before and after applying the devised preliminary identification procedure. The results of the study are given in Table 1.

Table 1

Statistical indicators of the accuracy of measurements of reference stars

Statistical indicator	Value before	Value after
Average of deviations RA, arcsec	0.013	0.002
Average of deviations DE, arcsec	0.015	0.001
Average of brightness deviations, mag.	0.35	0.03
Max. deflection modulus RA, arcsec	0.97	0.15
Max. deflection modulus DE, arcsec	0.85	0.14
Min. brightness deflection modulus, mag.	0.001	0.001
Max. brightness deflection modulus, mag.	3.51	0.36
RMS of deviations in RA, arcsec	0.56	0.08
RMS of deviations in DE, arcsec	0.49	0.07
RMS of brightness deviations, mag.	0.71	0.38

The indicators in Table 1 point to the successful application of the devised procedure. When identifying frames, the fitting gives the best accuracy of binding to the starry sky. The standard deviation of frame identification errors in this case is 7–10 times less than without the application of the developed procedure.

6. Discussion of results of investigating the accuracy of identification based on the procedure for preliminary identification of measurements of digital frames of one series

A study was performed of the procedure for preliminary identification of measurements of digital frames of one series. Existing methods of basic image processing [27] and machine vision [15] were also analyzed. However, the accuracy of processing by existing methods directly depended on the features of the formation of a series of digital frames. The quality of processing also depends on the invariance of the most typical image of the object [14] on all frames of the series.

Therefore, in order to devise a procedure for preliminary identification of measurements, the problem of excluding false measurements from consideration was stated. This increased the resistance to destabilizing factors, taking into account the peculiarities of the formation of measurements. As part of this task, it was proposed to use the parameters of the shift between the dimensions of the frame and the forms of the catalog or another frame. Also, in order to avoid various kinds of destabilizing factors (false measurements, artifacts, glare, etc.), it was proposed to split the frame into a predetermined number of regions of the same size. Choosing the same number of the brightest objects from each such area makes it possible to get a normal distribution of measurements over the entire frame. This equalizes the chances for measurements of bright objects to be identified throughout the frame, and not just in some part of it. The steps described above, which were taken into account in the procedure, are fundamentally different from the steps in the already existing procedures for eliminating anomalous observational data.

The task of devising a procedure for preliminary identification of measurements of digital frames of one series was solved by determining the shift estimates (1) and (2) in two coordinates. Owing to this, hypotheses about matching were formulated, conditional on the correspondence to the same object. The possibility of forming false measurements was also taken into account, which made it possible to increase resistance to various kinds of destabilizing factors. The key step of the method devised is the final estimation of the shift parameters between frames (3) and (4). This has made it possible to reject false hypotheses about matching measurements.

Also, during the study, the devised procedure was empirically refined. Namely, if during the operation the procedure tries to select the fourth dimension, then it is necessary to make an emergency exit from it with the issuance of a message about identification failure. Practice says that this is usually associated with large errors in estimating the anchoring coordinates of the identified frame center. Another improvement during the study was the conclusion that if the set of measurements of the second frame is exhausted, then it is also necessary to perform an emergency exit from the procedure. It is also necessary to add a message about the impossibility of identifying the measurements of the first and second frames. This speeds up the operation of the method, and also prevents leakage of computing power with false measurements and matchings.

Within the framework of the CoLiTec project, the verification of the devised procedure for the preliminary identification of measurements of digital frames of one series was carried out. In the course of verification, various statistical indicators of the measurement accuracy of reference stars after their successful identification were used. The study (Table 1) showed that the application of the procedure reduces by 7–10 times the errors in identifying images of cataloged (reference) objects [17]. This significantly affects the quality and accuracy of performing a number of tasks for obtaining data [38] and detecting object motion trajectories [39]. The results given in Table 1 are predetermined by increasing the resistance to various kinds of destabilizing factors by taking into account the formation of false measurements based on the frames of the entire series.

The limitation of this study is the size of the received frames of the series, their uniformity, as well as the same shooting conditions for each frame of the series. The type of CCD-matrix affects the angular size and field of view, which leads to a varied number of SSOs on frames. Also, the limitation is the computing power of the equipment on which the processing will take place. The issue of security [40] of frames, namely the encryption of input data, is also important. In this case, an additional decryption algorithm is required.

The disadvantage of the study is the impossibility of applying the method devised immediately after receiving the first frame of the series. This is due to the fact that preliminary identification is performed between each frame of the series. Accordingly, the completion of the shooting of the entire series of frames is required. And this leads to a delay in the processing pipeline and to idle computing power.

Further research should be focused on the application of the developed procedure for the preliminary identification of measurements before identifying SSOs with astronomical catalogs, as well as detecting their movement within a series of frames. To that end, it is necessary to design a processing pipeline and corresponding methods for selecting services/modules [41]. It is also necessary to evaluate its impact on other motion detection methods [42], which will be used later. To do this, you can use Wavelet analysis [43], machine learning [44], time series analysis [45], or the forecasting method [46] to calculate qualitative indicators.

7. Conclusions

1. The key task of preliminary identification is to increase the accuracy of identification. This was achieved by eliminating false measurements and defining the shift parameters between frame measurements and catalog forms. Thus, the resistance to destabilizing factors was increased, taking into account the peculiarities of the formation of measurements. The most common such factors and conditions for the formation of measurements were investigated. The formation of false measurements was taken into account. Such measurements may correspond to image artifacts or image noise spikes and be generated due to intra-frame frame processing errors. Namely, getting rid of measurements with artifacts,

satellite tracks, or the effect of charge leakage, made it possible to more accurately perform preliminary identification. For this, an additional uniform distribution of regions with the same size $M_{reg}\times M_{reg}$ was performed. Next, to ensure greater accuracy, the final estimate of the shift parameters was determined, based on a refined set of measurements without false ones.

2. Owing to preliminary calculations, a procedure for preliminary identification of measurements of digital frames of one series was devised. The key point is the optimized enumeration of measurements of neighboring frames, taking into account pre-calculated shift parameters. Based on the deviations between the measurements of the first and second frames, the fact that the measurements of the second frame fall into the confirmation area (strobes) is determined. With a sufficient number of measurements of the second frame that fell into the gates, the hypothesis about the combination of pairs of measurements of the first and second frames is considered confirmed.

3. The procedure for preliminary identification of measurements of digital frames of one series containing 28872 measurements was verified. Statistical indicators of measurement accuracy of reference stars after their successful identification were studied. The application of the devised procedure reduces by 7–10 times the errors in identifying images of cataloged (reference) objects.

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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