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DEVELOPMENT OF A METHOD FOR DETERMINING THE APERTURE BRIGHTNESS OF AN OBJECT USING A TYPICAL FORM OF ITS IMAGE

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The object of this study is the aperture brightness of the image of the object, which has a variety of typical shapes in the frames of the series. It directly depends on the stability of the shooting conditions of the objects under study. Thus, determining the exact aperture brightness of an object in the frame becomes more difficult. For this purpose, a method was devised for determining the aperture brightness of an object using the typical shape of its image on a series of frames.

This method is based on the formation of a typical shape of a digital image of an object based on data from all frames of the series. The typical shape makes it possible to take into account the peculiarities of the formation of the image of the object on each frame of the series. Based on this, a more accurate estimate of the initial approximation of the parameters of all Gaussian images of the object is performed. In addition, the adaptation of the method to the standard shape makes it possible to perform a more accurate assessment of the aperture brightness of the object in comparison with the analytically defined profile. An estimate of the aperture brightness of the object was derived using the least squares method. Due to minimization using the Levenberg-Marquardt algorithm, the use of the method improved identification with reference objects and reduced the number of false positives. The study showed a decrease in the standard deviation of frame identification errors by 5–7 times when using a typical shape of a digital image.

The devised method for determining an object's aperture brightness using its image's typical shape was tested in practice within the framework of the CoLiTec project. It was implemented in the intra-frame processing unit of the CoLiTecVS software for the automated construction of brilliance curves of the studied variable stars. Owing to the use of the CoLiTecVS software and the proposed computational method implemented in it, more than 700,000 measurements of various objects under study were successfully processed and identified

Keywords: image processing, image typical shape, aperture brightness, parameter estimation

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1. Introduction

The modern methods of astrometry [1] and photometry [2] have been actively used for such a leading direction as asteroid-comet hazard [3]. Most often, photometry [4] includes automatic processing of the results of asteroid/cometary/satellite surveys, as well as the results of observations of variable stars [5]. Massive astro- and photometric catalogs [6], along with archival big data [7], make it possible to obtain knowledge [8] and analyze publicly available data and measurements [9] of celestial objects of the Solar System (OSS) [10].

A large number of frames generated by a charge-coupled device (CCD) [11] have different quality of shooting conditions. And this, in turn, significantly affects the quality of OSS images on CCD frames. This leads to the fact that the images of individual OSS or the entire frame as a whole can be heterogeneous. The consequence is the variety of typical shapes of single OSS images between frames in a series. This fact significantly reduces the quality of OSS detection and the estimation of their aperture brightness using already-known computational methods [12].

Therefore, it is a relevant task to devise a method for determining the aperture brightness of an object using the typical shape of its image on a series of frames. This method will make it possible to more accurately estimate the aperture brightness (brilliance) of OSS objects [2], which will allow their identification with those already known from the list of cataloged objects. In addition, this method will increase the conditional probability of correct detection (CPCD) [13] of real objects and build a more accurate brilliance curve.

2. Literature review and problem statement

The appearance of heterogeneity in a typical shape [14] of the image of objects is a consequence of various significant synchronous displacements over the entire exposure time. This fact affects the accuracy of various image processing and machine vision tasks [15]. For example, the detection and recognition of images of objects [16, 17], as well as the evaluation of their parameters [18]. The advantage of these methods is to analyze only those pixels that belong to a real object. However, their disadvantage is that with the heterogeneity of the typical shape of the image, it is completely impossible to primarily identify specific pixels and reject those whose intensity exceeds the specified limit value [19].

In [20, 21], the pixelation and segmentation of only single images of objects are considered. 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. Such diversity also affects various methods of analysis of large data sets, namely Wavelet transform (analysis) [22] and time series analysis [23]. The advantage of such methods is to obtain more accurate data based on a large data set. The disadvantage of these methods is that they need to use only «clean» measurements for work, and the heterogeneity of the images just spoils the overall indicator very much.

A method of matched filtering is known [24], which uses an analytical mathematical model of the image. The main disadvantage of this method is the incorrectness of calculations when distinguishing typical images of the same object in different frames of the series. There is also an improved method of consistent filtering [25] using the already typical image form. The disadvantage of these methods is the inability to estimate the aperture brightness of objects after consistent filtering of their images.

Methods for obtaining aperture brightness (PSF photometry) for point astronomical objects are also known [26, 27]. Their disadvantage is the inability to work with extended or blurry objects.

The disadvantage of the methods of adding frames [28] and machine vision [29] is the impossibility of their application when the image of the object under study does not have clear boundaries on all CCD frames of the series.

The main disadvantage of existing methods is the impossibility of isolating a specific peak of brightness in the image of an object, which would allow the most accurate assessment of its aperture brightness itself. Therefore, it is necessary to devise a method for determining the aperture brightness of an object using the typical shape of its image on a series of frames.

3. The aim and objectives of the study

The aim of our study is to devise a method for determining the aperture brightness of an object using the typical shape of its image. It is the preliminary formation of the typical shape of the image of the object on the basis of the frames of the entire series that makes it possible to perform a more accurate assessment of the aperture brightness of the object.

To accomplish the aim, the following tasks have been set:

– to form a typical shape of the image of an object;

– to determine the number of Gaussians of a typical image of an object and estimate the initial approximation;

– to propose the architecture of the method for determining the aperture brightness of an object using the typical shape of its image;

– to verify the method for determining the aperture brightness of an object using the typical shape of its image.

4. The study materials and methods

The object of this study is digital images of various objects on CCD frames. Within the framework of the current study, the basic hypothesis was put forward assuming that the use of a typical image shape of an object could significantly increase its CPCD. In addition, the devised method would increase the accuracy of estimating the aperture brightness of objects during further photometry and the construction of a brilliance curve by already known methods [4]. The initial data is a CCD frame A_{in} the size of $N_{CCDx} \times N_{CCDy}$. The image of the j-th single object is indeed present in the frame and is also in the intra-frame processing area (IFPA), which is a set of Ω_{Nobj} pixels. The obtained research results, as well as the devised method for determining the aperture brightness of an object, were converted into a program code using the C++ programming language. This code was used at the stage of intra-frame processing of the CoLiTecVS software (Ukraine) [30] for automated construction of brilliance curves of the studied variable stars within the framework of the CoLiTec project [10].

As initial data, information obtained from various telescopes installed at observatories in Ukraine and the world was used. Namely, the ISON-Uzhhorod observatory (Uzhhorod, Ukraine) [31], the telescopes AZT8 (Dunaivtsi, Ukraine) and Takahashi BRC-250M (Uzhhorod, Ukraine); Mayaki Astronomical Observatory (Mayaki, Ukraine), OMT-800 telescope [32]; Vihorlat Observatory (Humenné, Slovakia) [4]. Table 1 gives the main characteristics of the telescopes and CCD cameras that were used in our study.

Table 1

Specifications of telescopes and CCD cameras

Telescope	CCD Camera	Resolution	Pixel size, μm	Exposure-time, s
OMT-800	Sony ICX429ALL	795×596	12	150
AZT8	FLI PL09000	3056×3056	12	150
Takahashi BRC-250M	Apogee Alta U9	3072×2048	9	180

The observation conditions were specially selected so that the CCD frames contained a variety of typical shapes of images of the studied variable stars [5].

The devised computational method was used during the successful identification of more than 700,000 different OSS using the CoLiTecVS software (Ukraine) [2]. Given this, the method for determining the aperture brightness of an object using a standard shape confirmed its practical significance within the framework of the main hypothesis put forward.

5. Results of investigating the method for determining the aperture brightness of an object using the typical shape of its image

5. 1. Construction of the typical shape of an object image

On each CCD frame, there are single images of objects, which can take a variety of shapes of the image of the object from frame to frame in the series. The typical shape of an image of an object is considered to be the average of all images of the same object on all CCD frames of the series [14]. The typical shape on a CCD frame is estimated from the N_{sel} pre-selected single images. For each m-th single image of the object, the aperture (total) brightness of the pixels is determined using the following expression:

$$A^{*}_{\Sigma m}=\sum_{l=1}^{Nsm}\left(A^{*}_{l(i,k)m}-C_{fm}\right), \tag{1}$$

where $A^{*}_{l(i,k)m}$ is the brightness of the $l(i, k)$-th pixel of the m-th single image;

$l(i, k)$ is the number of the pixel l in the set Ω_{Sm}, which is a function of the numbers of the ik-th pixel on the frame;

C_{fm} is the average brightness of the background substrate of the CCD frame.

Next, a list of single images with aperture brightness of the pixels of the images of objects (1) is formed, which satisfies the following condition:

$$A^{*}_{\Sigma m}\geq(10\div 20)\sigma_{noise}, \tag{2}$$

where σ_{noise} is the root mean square deviation (RMS) of the brightness of the background of the frame.

The typical shape of an object is based on the eccentricity ε_m and the length L_m of a single image [33]. The eccentricity ε_m is calculated by:

$$\varepsilon_m=\frac{m_{20}+m_{02}-\sqrt{m_{20}-m_{02}+4m_{11}^2}}{m_{20}+m_{02}+\sqrt{m_{20}-m_{02}+4m_{11}^2}}, \tag{3}$$

where

$$m_{20}=\sum_{l=1}^{Nsm}\left(A^{*}_{l(i,k)m}-C_{fm}\right)\left(x_{l(i,k)m}-X_0\right)^2, \tag{4}$$

$$m_{02}=\sum_{l=1}^{Nsm}\left(A^{*}_{l(i,k)m}-C_{fm}\right)\left(y_{l(i,k)m}-Y_0\right)^2, \tag{5}$$

$$m_{11}=\sum_{l=1}^{Nsm}\left(A^{*}_{l(i,k)m}-C_{fm}\right)\left(y_{l(i,k)m}-Y_0\right)\left(x_{l(i,k)m}-X_0\right), \tag{6}$$

$$X_0=\frac{\sum_{l=1}^{Nsm}\left(A^{*}_{l(i,k)m}-C_{fm}\right)x_{l(i,k)m}}{A^{*}_{\Sigma m}}, \tag{7}$$

$$Y_0=\frac{\sum_{l=1}^{Nsm}\left(A^{*}_{l(i,k)m}-C_{fm}\right)y_{l(i,k)m}}{A^{*}_{\Sigma m}}, \tag{8}$$

where m_{20}, m_{02}, m_{11} are the second-order moments;

X_0 and Y_0 are the first-order moments;

$x_{l(I,k)m}, y_{l(I,k)m}$ are the coordinates of the $l(i, k)$-th pixel of the m-th single image.

The length L_m of a single image of an object is calculated by the following expression [34]:

$$L_m=\sqrt{\left(x_{m\max}-x_{m\min}\right)^2+\left(y_{m\max}-y_{m\min}\right)^2}, \tag{9}$$

where $x_{m\max}$, $y_{m\max}$, $x_{m\min}$, $y_{m\min}$ are the minimum and maximum values of the abscissa and ordinate of the m-th IFPA.

After that, single images of objects are rejected based on the eccentricity ε_m values (3) and length L_m (9) and the following conditions:

$$\varepsilon_m>\gamma_\varepsilon, \tag{10}$$

$$\frac{\left|L_m-L_{1/2}\right|}{L_{1/2}}<\gamma_L, \tag{11}$$

where γ_ε=0.6 is the boundary permissible value of eccentricity;

$L_{1/2}$ is the median value of the length of bright images of objects;

γ_L=0.1 is the permissible deviation of the length of the image of objects.

5. 2. Determining the number of Gaussians of a typical image and estimating the initial approximation

The resulting single image of the j-th object can be divided into a number of Gaussians, which are evaluated separately from the Levenberg-Marquardt algorithm (ALM) [35]. The desired number of Gaussians N_{Gj} is selected from the range of values $\overline{N_{Gfirstj},N_{Gendj}}$. To this end, we determine the number of segments N_{segm} using the following expression:

$$N_{segm}=\frac{L_m}{\Delta x_{seg}}. \tag{12}$$

The pixels of a single image from the set $\Omega_{segm\ell}$ are considered to belong to the ℓ-th segment if the following condition is satisfied:

$$\ell\Delta x_{seg}\leq x_{l(i,k)m}<(\ell+1)\Delta x_{seg}. \tag{13}$$

Next, the initial approximation of the Gaussian form parameter σ_{Gj0} is calculated using the expression below:

$$\sigma_{Gj0}=\frac{1}{N_{segj}}\sum_{m=0}^{N_{segj}-1}\sigma_{Gjm}, \tag{14}$$

where σ_{Gjm} is an estimate of the initial approximation of the Gaussian form parameter.

The initial number of Gaussians N_{Gjmin} of a single image of the j-th object corresponds to that at which the sum of the squared deviations $F_{\Delta A\tau}\left(\Theta^{over}_{\tau jn}\right)$ is minimal. Therefore, it is necessary to estimate the initial approximation of the parameters of the Gaussian forms from the vector of the estimated parameters. To this end, the sum of the squares of the deviations between the experimental A^{*}_{ikj} and model $A_{Sikmj}(\Theta_{\sigma m})$ brightness of the pixels of the m-th segment of a single image of the j-th object is imposed on the ALM procedure:

$$F_{\Delta A\sigma}\left(\Theta_{\sigma m}\right)=\sum_{k=\Omega_{segjm}}\left(A^{*}_{ikj}-A_{Sikmj}\left(\Theta_{\sigma m}\right)\right)^{2}\underset{\Theta_{\sigma m}}{\rightarrow}\min, \qquad (15)$$

where $\Theta_{\sigma m}=(\sigma_{Gjm}, A_{Gjm}, y_{0jm})$ is the vector of the estimated parameters of the m-th segment;

$A_{Sikmj}\left(\Theta_{\sigma m}\right)=A_{Gjm}\exp\left\{-\frac{1}{2\sigma^{2}_{Gjm}}\left[\left(y_{kj}-y_{0jm}\right)^{2}\right]\right\}$ – model brightness of the pixels of the m-th segment of a single image of the j-th object;

A_{Gjm} is the model amplitude of the Gaussian in the m-th segment;

y_{kj} – estimation of the coordinate of the k-th pixel of the j-th object along the ordinate axis;

y_{0jm} is the coordinate of the Gaussian anchor center in the m-th segment along the ordinate axis.

The final refinement of the typical shape of the image of the j-th object is performed after determining the number of Gaussians N_{Gjmin} (15) and the initial approximation of the Gaussian form parameter σ_{Gj0} (14).

5. 3. Architecture of the method for determining the aperture brightness of an object using the typical shape of its image

The following sequence of actions is proposed, which makes up the architecture of the method:

1. Compile a list of N_{sel} single images with the aperture brightness of pixel images of objects (1).

2. Reject 10÷20 % of single images of objects with the aperture brightness of pixels exceeding the RMS estimate of the brightness of the frame background (2).

3. Derive the eccentricity value ε_m (3) for every single image of the object based on calculations of the moments of the second (4) to (6) and first (7), (8) orders.

4. Derive the length L_m (9) for each single image of the object.

5. Reject single images of objects in accordance with conditions (10) and (11) based on the obtained values of eccentricity ε_m (3) and length L_m (9).

6. Calculate the number of Gaussians N_{Gj} from the range of values $\overline{N_{Gfirstj},N_{Gendj}}$ and the initial approximation of the Gaussian form parameter σ_{Gj0} (14) for every single image using the ALM procedure (15).

7. Determine the size of rectangular IFPA, into which the pixels of the single image of the object under study fall [5].

8. Determine the model brightness $A_{ik\tau j}\left(x_{ij},y_{ij},\Theta^{over}_{\tau j}\right)$ of the ik-th pixel for the studied single image of the j-th object using the following expression:

$$A_{ik\tau j}\left(x_{ij},y_{ij},\Theta^{over}_{\tau j}\right)=C_{j}+\frac{A_{Gj}}{2\pi\sigma^{2}_{Gj}}\times$$
$$\times\sum_{n=0}^{N_{Gj}-1}\exp\left\{-\frac{1}{2\sigma^{2}_{Gj}}\left[\begin{array}{l}\left(\begin{array}{l}x_{ij}-x_{\tau j}\left(\Theta^{over}_{\tau j}\right)-\\-\ell_{nj}\cos\omega_{j}\end{array}\right)^{2}+\\+\left(\begin{array}{l}y_{ij}-y_{\tau j}\left(\Theta^{over}_{\tau j}\right)-\\-\ell_{nj}\sin\omega_{j}\end{array}\right)^{2}\end{array}\right]\right\}, \qquad (16)$$

where C_j is the average value of the brightness of the background substrate of the single image of the j-th object under study;

x_{ij}, y_{ij} – coordinates of the ik-th pixel of the single image of the j-th object under study;

A_{Gj} is the model amplitude of the Gaussians corresponding to the studied single image of the j-th object;

ℓ_{nj} is the position of the n-th Gaussian from N_{Gj} used to approximate the single image of the j-th objects under study.

9. To eliminate differences in the aperture (PSF) brightness of object images, normalization is performed when calculating the mean or median of selected single images. The brightness of the pixels of the normalized single image of the object of the m-th IFPA is calculated using the following expression:

$$A^{n}_{l(i,k)m}=\frac{A^{*}_{l(i,k)m}-C_{fm}}{A^{*}_{\Sigma m}}, \qquad (17)$$

where $A^{n}_{l(i,k)m}$ is the normalized brightness of the $l(i,k)$-th pixel of the m-th IFPA.

5. 4. Verification of the method for determining the aperture brightness of an object using the typical shape of its image

Our studies into the effectiveness of using a typical image of an object in determining aperture brightness were carried out on the frames from the OMT-800 (Mayaki, Ukraine), AZT8 (Dunaivtsi, Ukraine), and Takahashi BRC-250M (Uzhhorod, Ukraine) telescopes. As an efficiency criterion, the RMS $\sigma_{\Delta Aj}$ of the difference between the experimental and model brightness of the pixels of the image of the j-th of a single object in the frame was calculated:

$$\sigma_{\Delta Aj}=\sqrt{\frac{1}{N_{j}}\sum_{i=1}^{N_{j}}\left(A^{*}_{i}-A_{i}\right)^{2}}, \qquad (18)$$

where A^{*}_{i} and A_i is the experimental and model brightness of the i-th pixel of the image of a single object;

N_j is the number of pixels of the image of the j-th single object in the frame.

RMS of the brightness difference $\sigma_{\Delta Aj}$ of the image of the j-th single object was calculated for two model values of the brightness of the image pixels. In the first case, the model brightness was calculated from the generated typical image of the object based on frames in the series, in the second – from the analytical model of the image of the object.

Table 2 gives the statistical [36] characteristics of the RMS $\sigma_{\Delta Aj}$ difference between the experimental and model brightness of the pixels of all images of single objects on the frame. Namely, the average value of the RMS $\sigma_{\Delta A}$ of difference in brightness $M\sigma_{\Delta A}$ on the frame; the value of the median $M_{1/2}\sigma_{\Delta}A$ on the frame; maximum $\max\sigma_{\Delta A}$ and the minimum $\min\sigma_{\Delta A}$ value of the RMS of the brightness difference on the frame.

Below, Fig. 1 shows an example of a brilliance curve constructed using the CoLiTecVS software (Ukraine) [2] for the automated construction of brilliance curves of the variable stars under study. The object «GZAnd», observed on the OMT-800 telescope (Mayaki, Ukraine), was chosen as the examined object. The brilliance curve was constructed on the basis of the data obtained from a series consisting of 107 frames. Each photometric measurement was obtained using the method devised.

Table 2

Characteristics of RMS of model and experimental brightness on the frame

Telescope	Number of single objects	Model brightness	$M\sigma_{\Delta A}$, ADU	$M_{½}\sigma_{\Delta}A$, ADU	$\max\sigma_{\Delta A}$, ADU	$\min\sigma_{\Delta A}$, ADU
OMT-800	91	Typical image	4.39	2.35	19.24	0.34
		Analytical model	7.86	4.52	30.43	0.71
AZT8	214	Typical image	24.35	3.17	1345.42	0.21
		Analytical model	67.37	5.76	1612.73	0.47
Takahashi BRC-250M	524	Typical image	12.01	3.17	239.71	0.31
		Analytical model	14.46	3.85	1112.35	1.28

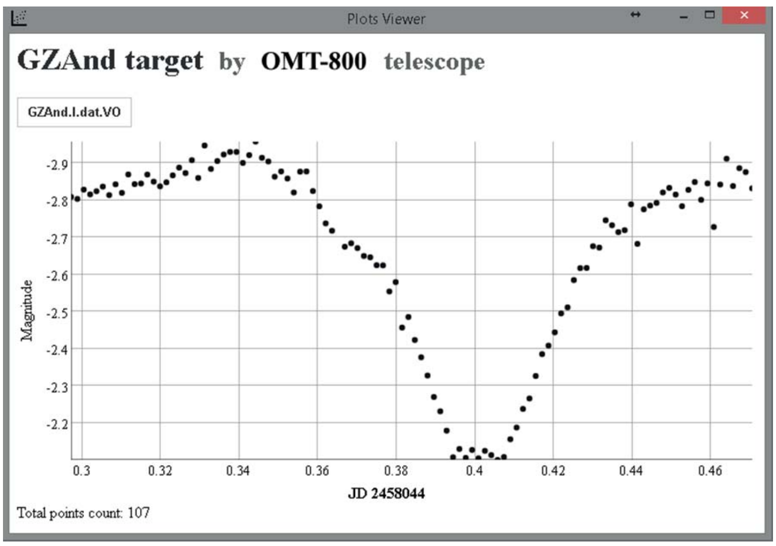

Fig. 1. Brilliance curve of the object «GZAnd»

Based on the output statistics (the average value of RMS of the brightness difference $M\sigma_{\Delta A}$ and the value of medians $M_{½}\sigma_{\Delta}A$ on the frame) in Table 2, we can draw the following conclusion. The efficiency of the devised method for determining the aperture brightness of an object using the typical shape of its image is much higher (up to 38 %) in relation to the use of an analytical image model. In addition, the RMS errors of frame identification when using a typical shape are 5–7 times less than those with an analytical model.

6. Discussion of results of investigating the method for determining the aperture brightness of an object using the typical shape of its image

The possibility of using the typical shape of a digital image of an object for the subsequent determination of its aperture brightness was investigated. Existing methods of basic image processing [12] and machine vision [15] were also analyzed. However, the accuracy of processing by existing methods directly depended on the quality of the original image of the object and the invariability of its typical image on a series of frames. Therefore, to construct a method for determining the aperture brightness of an object, it was proposed to use the automated construction of a typical image shape instead of the classical application of the analytical form [14].

Within the framework of the CoLiTec project [37], studies were carried out on the application of the devised method for determining the aperture brightness of an object using the typical shape of its image. By determining the eccentricity (1) and length (7) of a single image, its preliminary typical shape was derived. In addition, after determining the number of Gaussians (15) and the initial approximation of the form parameter of Gaussians (14), the typical shape of the image has been clarified. By calculating the model brightness (16) of each pixel of a single image, the aperture brightness (17) of the image of the object was calculated, which made it possible to construct a brilliance curve.

The study results (Table 2) showed that the application of the method reduces the RMS errors of identification of images of cataloged objects by 5–7 times [6]. This significantly affects the quality and accuracy (up to 38 % improvement) of performing a number of tasks for detecting the movement of objects and constructing brilliance curves (Fig. 1) based on data acquisition [38]. In addition, the use of the devised method makes it possible to reduce the number of false detections due to the construction of a clearer typical shape of the image of the object. This indicator clearly indicates that the tasks set have been successfully solved. The results given in Table 2 are determined by the construction and refinement of the typical shape of an image of the object based on the frames of the entire series.

The limitation of this study is the variety of typical shapes of images of objects in a series of frames. In addition, the constraint is the computing power of the equipment on which the processing will take place. The issue of the security [39] of frames, namely the encryption of input data, is also important. In this case, an additional decryption algorithm will be required before using the devised method.

The disadvantage of the study is the impossibility of applying our method immediately after obtaining the first frame of the series. The construction of a typical image shape of an object requires data from all its images on each frame of the series. This makes it impossible to obtain measurements in the brilliance curve immediately after processing the frame. It also leads to a delay in the processing pipeline with a microservice architecture [40].

It is advisable to focus further research on the application of the devised method for determining the aperture brightness of an object before detecting its motion to obtain the brilliance curves of moving objects. Therefore, it is necessary to evaluate the impact of the devised method on other methods of motion detection [12], which will be used later. To that end, one can use machine learning [18], wavelet analysis [41], time series analysis [23], and the method of forecasting [42] for the calculation of qualitative indicators.

7. Conclusions

1. On a series of CCD frames, a sample with single images of objects with a variety of typical shapes was determined. For each image, the eccentricity ε_m and the length L_m were calculated. Based on these values and selection criteria, single images of objects were rejected.

2. Each resulting single image of the object was divided into a certain number of Gaussians. Based on this, the initial approximation of the Gaussian form parameter σ_{Gj0} for a single image of the j-th object was calculated. This made it possible to refine the typical shape of a single image of an object after minimization by the ALM procedure.

3. Owing to preliminary calculations, the architecture of the method for determining the aperture brightness of an object using the typical shape of its image was built. Determination of the model brightness $A_{ik\tau j}\left(x_{ij}, y_{ij}, \Theta_{\tau j}^{over}\right)$ of each pixel of a single image of the j-th object made it possible to obtain the aperture brightness of the image of the object itself. Normalization was also performed to eliminate differences in the aperture brightness of the images of objects when calculating the mean or median.

4. The results of testing the devised method showed that the application of our method for a variety of typical image shapes reduces the RMS of errors in identifying the images of cataloged objects by 5–7 times. This improves the accuracy of estimating the brightness of an object by up to 38 % compared to using an analytical image model to plot a brilliance curve.

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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