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Registration of star transits on semiconductor matrix in real time

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In this paper, we consider the problem of using CMOS matrices to record the transit of stars on a transit instrument. Reasoning is given that indicates the relevance of this task, as well as a project for the modernization of a transit instrument and the current results of work on the development of technologies for creating a modernized transit instrument. The paper also considers the problem of specific image artifacts and proposes a method for calibrating images that removes these artifacts.

Keywords: image calibration, fixed-pattern noise correction.

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Until the 1980s of the last century, observations on a passage instrument were the main way to determine Universal Time, the right ascensions of stars, as well as the longitudes of points. Inasmuch as the 1980s, regular observations with ultra-long baseline radio interferometers (ULBRI) have begun, which in the 1990s completely replaced observations with passage instruments from widespread astronomical practice. At present ULBRI is the only way to determine Universal Time and the difference between Universal and Coordinated Universal Time. Such a situation gives rise to potential problems — the tasks of coordinate-time and navigation support (CTNS) are now being solved in conjunction with two technologies: ULBRI, which provides a fundamental base, and global navigation satellite systems (GNSS), which have almost completely captured applied problems and some problems of fundamental science. However, there are still tasks in which optical observations are important. In the field of applied science, the azimuth of a local object from optical observations is obtained faster and less laborious than the azimuth from the processing of GNSS observations. In addition, it is necessary to consider the fact that measurements made in the radio range and in optics give slightly different coordinates: in the case of radio observations, we are talking about geodetic latitude and longitude, while optical observations give astronomical latitude and longitude, the difference between which makes it possible to determine the deviation of the plumb line, which is an important scientific task in its own right. Determination of plumb line deviation based on the comparison of astronomical and geodetic coordinates is the fastest and cheapest in terms of financial costs. Thus, the improvement of classical astronomical optical instruments in order to increase their accuracy and ease of use is an important task. One of the key areas of this work is the automation of image registration and processing, which will make it possible to obtain definable parameters in real time. At present, the Department of Astronomy of St. Petersburg State University (SPbU) is working on the development of observation techniques on a passage instrument equipped with a CMOS matrix. For this purpose, a passage instrument manufactured by Bamberg, installed at the astronomical observation site St. Petersburg State University, is used. For this purpose, a passage instrument manufactured by Bamberg, installed at the astronomical observation site St. Petersburg State University, is used. For astronomical imaging, the ZWO ASI-120MM-S camera with a resolution of 1280×960 pixels is used. The camera is secured using a 3D printed adapter. The CMOS technology for the photosensitive element was chosen primarily because, unlike CCDs, it allows for real-time detection of the moment of illumination of each pixel by a star image with a deterministic delay. However, currently, the use of CMOS arrays in astrometry is not generally accepted, and the use of semiconductor array radiation recorders for the purposes of CTNS did not take place due to the fact that the development of this technology coincided with the time when ULBRI and GNSS replaced classical optical observation technologies. Therefore, it is necessary to adapt observational methods to the capabilities of CMOS matrices. The purpose of this work is, firstly, to measure the time delay in registering the moments of pixel illumination under different modes of matrix operation and exposure time. Secondly, you need a digital noise filtering algorithm that ensures reliable identification of each star in the field of view, and, finally, an algorithm for finding the center of brightness of the star image in the frame.

The first task — measuring the time delay of registration — turned out to be very complex and was separated into a separate paper, the results of which will be published later.

In the course of the first test observations on the CMOS array, the problem of the appearance of CMOS

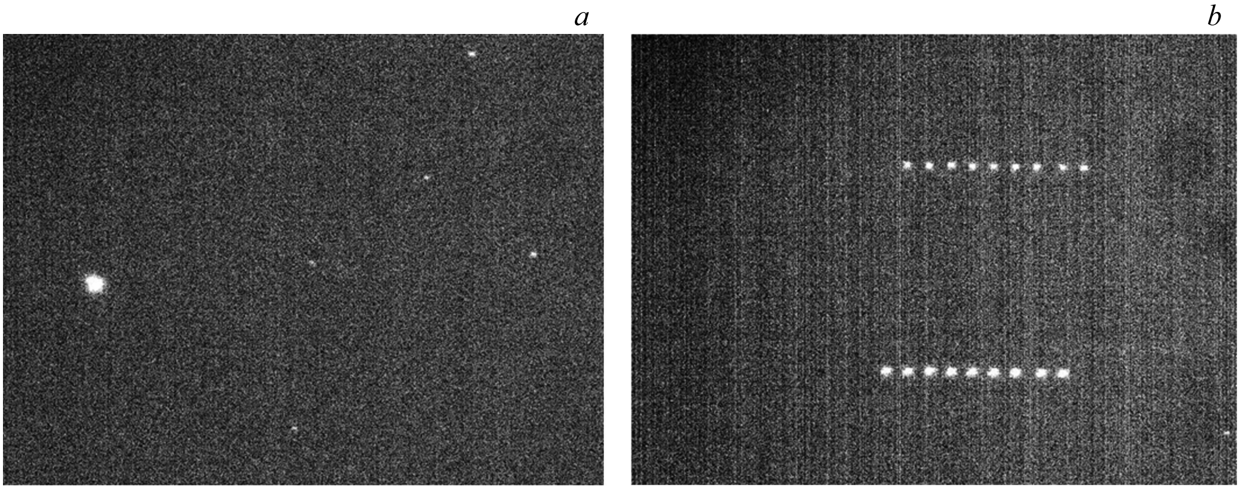

Figure 1. *a* — single shot; *b* — the sum of nine frames obtained using a CMOS matrix.

array-specific image artifacts was revealed, namely the linear structure that changes over time, also called fixed distribution noise.

Such noise has already been described and illustrated in [1]. Here is an example of the images obtained in the course of our observations. In a single image (Fig. 1, *a*) the bar structure of the background is not very noticeable, but when several frames are summed up (Fig. 1, *b*), the linear structure of the background is clearly distinguished. This can be a significant problem, as these background lines can be identified as star tracks in the automated selection of star images.

This phenomenon can be detected in the frame by analyzing the median intensity as a function of the column number (Fig. 2). From the graph in Fig. 2, it can be seen that the values of the median intensity are not evenly distributed in a certain range, but occupy a few selected values. Such deviations cannot be explained by the inclusion of light sources, i.e. stars, in a part of the columns due to the fact that the total extent of such objects along the column cannot be half of it due to their sparseness on the studied frames. After a considerable time or with a significant change in the illuminance created on the light-sensitive matrix, the absolute values of such brightness deviations change, so the traditional method of calibration by subtracting „bias“, „darks“ and „flats“, described in [2], did not show the proper efficiency.

It is not possible to name the exact physical cause of the formation of such noise, since the details of the implementation of each individual CMOS sensor are not disseminated due to the fact that they constitute a trade secret. But it is suggested that the physical reason for this behavior lies in the mechanism of signal digitization. As the most probable explanation of the physical nature of these artifacts, the paper [2] showed that there are minimal differences in the set of columnar signal amplifiers in the matrices of the type under consideration, each of which amplifies the signal coming from certain columns of the matrix. Due to the fact that they can't do it exactly the same way (due to manufacturing error), we see intensity jumps along the horizontal axis and fairly high uniformity along the vertical axis. Inasmuch as the noise is not random, when summing up several shots, the repetitive noise structure will be amplified, while moving objects will not be amplified due to the change in their position on the sensor. When a small number of frames are summed up, about 10, the intensity of the noise becomes comparable to the intensity of weak objects in the frame. It should be noted that the noise pattern is not constant and changes over time.

Also in the article [3] was a classification of methods for compensating for such heterogeneity of images by the type of methods underlying them, followed by a comparison of their effectiveness. There are other papers [4,5] that describe the problem of this noise. However, all the methods identified by the authors as effective, with the exception of the classical subtraction of calibration frames, to a greater or lesser extent contain anti-aliasing, which adversely affects the accuracy of determining the subpixel coordinates of the stars in the frame, and therefore the accuracy of the determined parameters (Universal Time, Longitude, etc.).

In view of the above, it was decided to develop an alternative method for getting rid of the vertical linear structure of frames created with CMOS matrices. In the course of the study of this phenomenon, it became clear that the linear structure changes very little from frame to frame within the same series. Thus, by subtracting from a frame a frame that was taken a few exposures ago, or by averaging several such frames without any visible deterioration in the images of stars that have time to move significantly across the frame, you can get rid of the „bands“ without resorting to smoothing or other blurring of the original image. In general, the image taken with a CMOS camera can be represented as

$$Y = U + S + N,$$

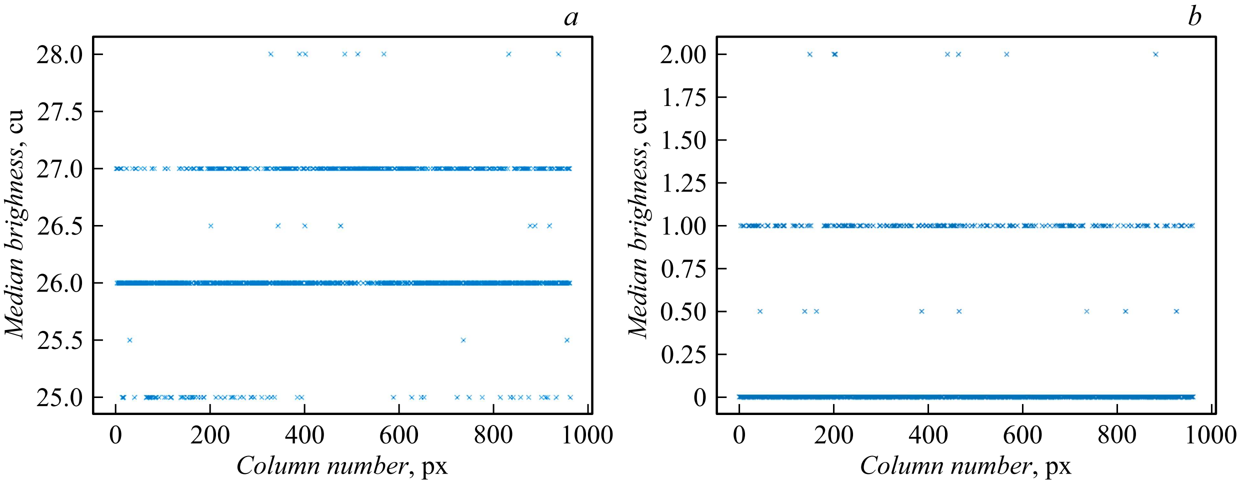

Figure 2. Dependence of median intensity on column number: *a* — dependence of median intensity in conventional units of pixel illumination on column number for a single frame; *b* — for the difference between two frames separated by multiple exposures.

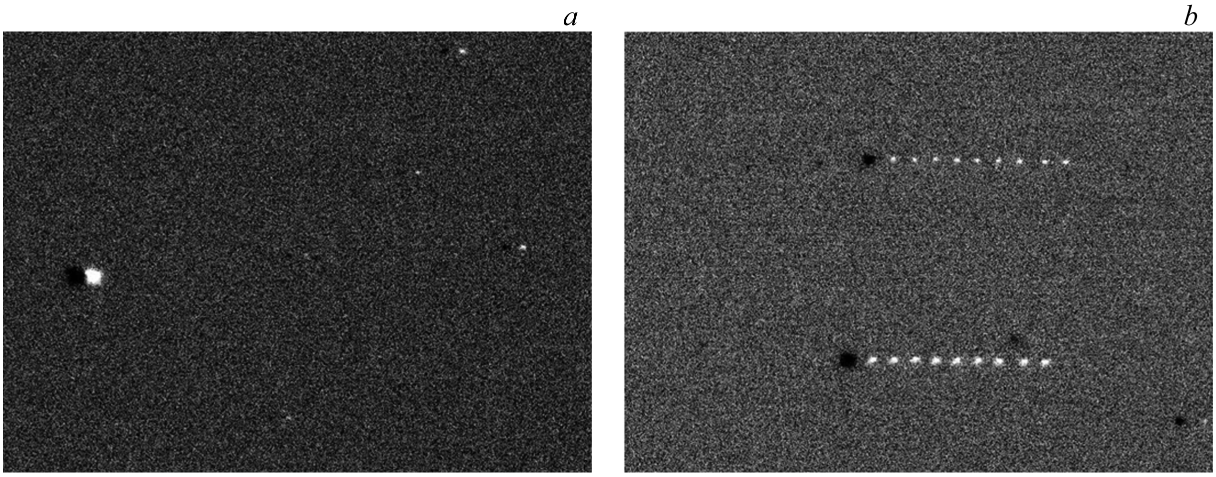

Figure 3. *a* — single image after calibration; *b* — sum of multiple frames after calibration.

where Y — is the final image, U — is the useful signal, S — is the systematic linear structure, N — is random noise. On short time intervals (about 15 min [3–5], which is longer than the time a typical star is in the frame), we can assume

$$S = \text{const}.$$

In such a case, given that the difference between the two random noises will produce a random noise, the frame difference can be described as

$$Y_2 - Y_1 = (U_2 - U_1) + (N_2 - N_1) = (U_2 - U_1) + N.$$

A peculiarity of astronomical observations by the method of passage is that, as a rule, we observe point objects moving at a constant known speed. The position of the object in the next frame is not the same as the position of the object in the previous frame if they are separated by a sufficient amount of time. The illumination of a pixel is written as an integer, from 0 to 255 (with 8-bit encryption), i.e. when considering the difference between the second and first frames, it turns out that we subtract the background from the star in the second frame, and we subtract the star from the background in the second frame. To ensure that subtracting a star from the background does not result in negative illumination values, we reset the values of such pixels to zero. In fact, when we reset the negative values to zero, we get

$$Y_2 - Y_1 = U_2 + N.$$

In the final image, we get images of the stars in the second frame, dark areas in place of the stars in the first frame, and the inevitable random noise. The image obtained in this way is more suitable for further processing of astronomical images by standard means; The stars of the second frame stand out on it without any problems.

Let us draw some examples of images calibrated using the proposed method. (Fig. 3, *a*), shows a is a single image. (Fig. 3, *b*) shows an image obtained by summing up several frames that have been calibrated by the proposed method.

In both images, you can clearly see the disappearance of the characteristic linear background present on (Fig. 1, *b*). The effect of calibration is clearly visible in the graph shown in (Fig. 2, *b*), when the typical values of the median illumination intensity of the column do not exceed 2, while before calibration we can speak of a typical value of the median illumination of the column around 26 or 27, so the background illumination is drastically reduced. The time interval on which the images presented in Fig. 1 and Fig. 3 were obtained is about 100 s.

This calibration technique also reduces the false positive source selection rate with SExtractor. The procedure is simple, but it is optimized for pass-through observations (the instrument is stationary while a star or other object moves in the field of view). Another important advantage of the method is that it does not require a change in the observation program, since only the previous images of the series are used. Thus, the proposed technique can be used in real time for the automation of observations and subsequent processing.

In the course of work on the adaptation of observation methods on the passage instrument to new means of recording, such as the CMOS matrix, a new method of image calibration was proposed as part of the work on the modernization of the passage instrument. This technique removes the noise of fixed distribution specific to CMOS arrays, unlike traditional calibration methods developed for CCD sensors, it does not require the formation of special calibration images at the beginning and end of observations, it works only with a sequence of working images. The existing technique is applicable only for observations by the passage method, implemented only on the passage instrument. In the future, it is planned to continue the work, installing CMOS arrays on other instruments, such as the zenith telescope or the universal astronomical instrument. Accordingly, it is planned to test and adapt the developed technique to other instruments of classical astronomy.

Conflict of interest

The authors declare that they have no conflict of interest.

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