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Automatic CCD photometer

V.R. Amirkhanyan[a], N.A. Vikul'ev[b], V.V. Vlasyuk[b], D.A. Stepanian[b]

[a] Sternberg Astronomical Institute of Moscow State University, Universitetskij prospect, 13, 119899, Moscow
[b] Special Astrophysical Observatory of the Russian AS, Nizhnij Arkhyz 369167, Russia

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Abstract. At the end of 1997 development and manufacture of a new photometer of unique design for small telescopes were finished. The photometer is equipped with a CCD matrix of 1050 × 1170 pixels, a set of filtres providing a Johnson–Cousins BVRI system, a shutter and an automatic guide. The weight of the photometer is 9.5 kg, the diameter is 350 mm, the height is 110 mm. All the units of the photometer are controlled by a computer of class 386 and above. The software combines a telescope, the photometer and the computer in a photometric complex and renders photometric observations completely automatic. On the telescope Zeiss-600 an average detection thresholdof objects of 22–22.5 magnitudes is attained with 15–20-minute exposures.

Key words: telescopes — instrumentation: photometer

In late 1997 the authors finished designing of a new photometer "TAZIK-1", manufactured and put it into regular observation. The aim of the project was to make a device for mass-scale photometric observations with the small telescopes of SAO RAS. When developing the photometer, the authors were guided by the following principal ideas:
1. The photometer should be equipped with a shutter, an automatic guide, and operate in the standard BVRI system. A CCD matrix should be used as the light detector.
2. The photometer should have minimum overall dimensions and as few communication as possible, should be easily mountable on the telescope. Besides, all the members incorporated should be readily accessible.
3. Control of the photometer is executed by a computer of PC class. The software should completely exclude attendance of an operator in observations.

1. Design

The performance data of the photometer: reliability and stability of operation of its components, possibility of prompt modification of an observational mode, mounting of the device on the telescope, its maintainability depends directly on the design. It is for this reason that considerable attention was paid to design matters. In connection with the fact that observations with the small telescopes are made at the secondary focus and the filling neck of the cryostat looks down, measures have to be taken against draining nitrogen from the matrix cryostat. For this purpose, a flat mirror reflects the image to the CCD camera mounted at a right angle to the telescope axis. The demerits of this approach are evident: an extra mirror whose quality and adjustment affect the image, an essential complication of the design necessity for changing the position angle of the photometer when changing the position of the telescope, which complicates the processing of the image and automation of observations. A radical solution of the problem is the use of a CCD camera with an unspillable cryostat. At our request the cryostat was made at the laboratory headed by S.V. Markelov.

When developing the turret of changeable filters, we abandoned the classical design. Since the CCD chip is a rectangle of 16.8×18.72 mm, the working part of the filters is a square of 30 mm on side. Allowance for the size is made on the assumption of possible use of a light detector of a larger dimension. The thickness of all the filters is 4 mm. The filters are rimless. A tail piece is clued to the face of each filter, which is fixed to the turret by a screw. The small weight and overall dimensions made it possible to mount the turret on the axis of a compact step motor without intermediate transmission mechanisms. The desired filter is set up by feeding to the motor an appropriate number of clock pulses reckoned from the limit switch. This circuit provides high repetition of setting filters, which makes it possible to remove dust traces and filter inhomogeneities from the images. The turret is capable of holding four filters and, when assembled, looks like a flower. The filters, with the CCD frequency characteristic being taken into account, provide a Johnson-Cousins system (Fig. 1).

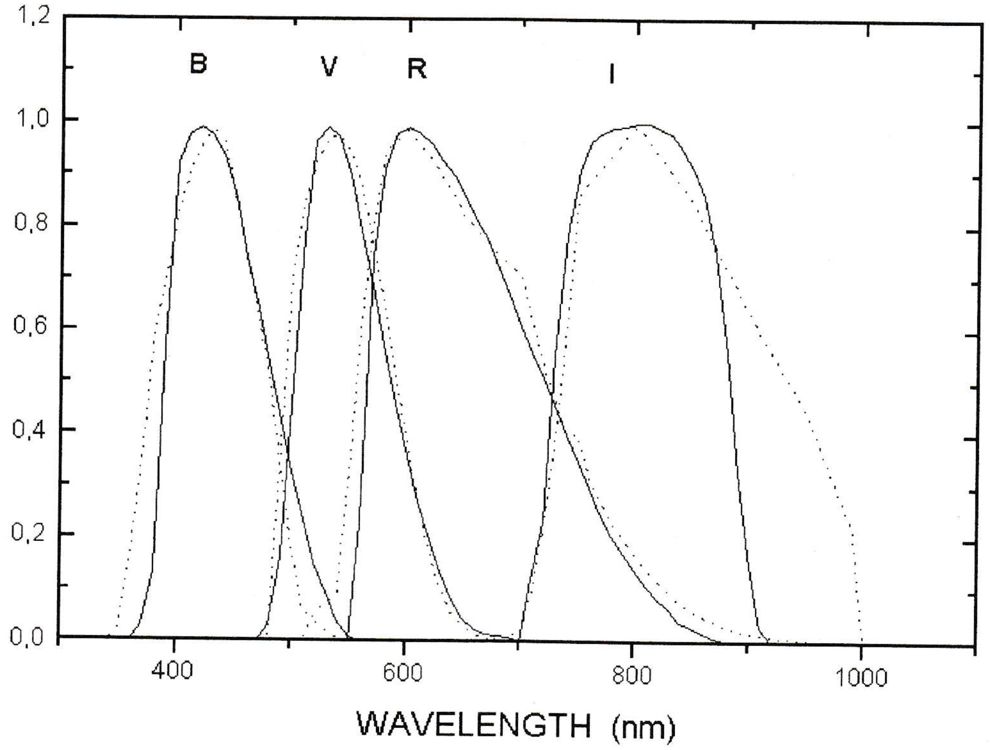

Figure 1: *Bandpasses of the photometer. Standard — the solid line, calculated — dots.*

The shutter is made of two overlapping blades which are actuated by solenoids. The speed of the shutter is not lower than 0.1 s.

In designing the guiding unit we took account of the necessity for automation not only of the process of guiding but also of displacement of the light detector of the guide to the point of location of a reference star. Allowing for the limited sensitivity of the light detector of the guide, for warranted finding of a guide star of sufficient brightness, it is necessary to ensure its movement over the whole field of view of the telescope. Having considered several alternatives of two-coordinate travels, we chose the design operating in the polar coordinate system. In this case the light detector moves in radius and angle. The rotation axis of the system is coincident with the optical axis of the telescope. Such a scheme has no dead zone, enables transport of the light detector of the guide to any point of the telescope field of view and has the overall dimensions not exceeding the size of the telescope flange. The disadvantage of the polar coordinate system is that the position angle of the image depends on the position angle of a reference star in the telescope field of view. This is of no consequence in automatic guiding. When changing to manual guiding, the programme must turn the image in the guide through an angle convenient for the operator. The range of angles of slewing of the light detector is 0–360 degrees with a step of 0.064 degree and that of radial displacement is 25–75 mm with a step of 0.06 mm. The displacement is performed by two step motors. The system TANDEM VS56, designed by the domestic firm IPC Videoscan ltd., is used as the light detector of the guide. The assembly consists of a compact CCD camera, an interface mounted in the computer in the standard way, a coupling cable and software. The matrix of the camera has 512×576 pixels 8.8×8.8 microns in size. Electronical shutter of the camera operates in a range of exposures from 0.0001 s to 5 min. The sensitivity of the camera is sufficient for operation with objects to 12 stellar magnitude with a mirror of 600 mm. The image is projected onto the matrix of the guide through a reflecting prism and a diminishing lens with a change of the scale of 3.0 times. The field of view of the guide is more than 5 arcmin at the telescope Zeiss-600 and 3.5 arcmin at Zeiss-1000. The base of the structure of the photometer is an aluminium plate 10 mm thick and 300 mm in diameter. One side of the plate holds the shutter, the turret of filters, a mounting for the CCD matrix, and a circuit of control of the photometer. An automatic guiding unit is located on the other side. The plate is attached to the standard flange by racks (Fig.2).

Control of all the units of the photometer and its state is executed by the computer through serial port via a three-wire communication line. The control circuit is housed in the same case as the power package, which is attached on the exterior part of the photometer. Zeiss-600 and Zeiss-1000 were equipped with identical communication lines, which enabled prompt transport of the photometer from one telescope to the other. Filling of the cryostat with nitrogen without dismounting the CCD camera turned out to be a serious problem. As was mentioned, in observations the filling neck of the cryostat is directed downward. The solution to the problem was found by A. Pritychenko who made a mug preventing spilling of nitrogen when filling the cryostat. The weight of the photometer together with the control circuit and power unit is 9.5 kg (without the CCD camera). The dimensions: maximum diameter — 350 mm, height — 110 mm.

Along with the development of the photometer, the authors modernized the mechanical part and the electric circuit of the "fine" drives of the telescope Zeiss-600, which was necessary for operation in the mode of automatic guiding. To correct the telescope position in right ascension a low-power direct-current high-speed motor was switched to the main motor through a planetary gear. Its speed of rotation provides displacement of the telescope by 1–3″ per a second. For control of the telescope in declination a small-sized step motor having 200 steps per revolution of the shaft was coupled to the manual correction device by means of an electric clutch and an additional reducer. This drive also provides displacement of the telescope by $1'' - 3''$ per a second. To exclude malfunctions of the computer and CCD system caused by relay jamming, the system of control of the correcting motors is assembled from contactless components. Commands for correction of the telescope position come through the parallel port of the computer to the control circuit and then to the motors. The circuit implemented preserved both "pushbutton" and mechanical correction control. The telescope Zeiss-600 has no fast drives, and its pointing to the object is accomplished manually. This is why, for ease of control a digital indicator of the current hour angle was put in the dome. The angle is permanrntly calculated by the computer.

1.1. Software

The software is to unite the telescope, the photometer and the computer in an observational complex which, in the ideal case, needs the operator only at the stage of preparing the job.

The developed software performs consecutively all the operations of an observing cycle:

- pointing of the telescope;
- selection and capture of the reference star;
- setting of a specified filter;
- triggering of exposure;
- guiding;
- readout of the image from the CCD.

This process can go into cycle with the necessary changes in observing conditions.

When preparing for observations, samples of stars from the GSC and DSS catalogues in the areas of the celestial sphere where the observations are to be carried out are entered into the computer memory. The programme uses this information for pointing of the telescope and selection of the reference object. Besides, these fields can be used as identification charts. The pointing programme chooses from the catalogue the coordinates of the object to be studied and computes its apparent position and needed telescope setting. Then from the stars of the field near the object the programme selects a reference star optimum in location and brightness for the guide. Its coordinates are transferred to the guiding programme which computes the position of the guide slide and places the light detector of the guide in the calculated position. If the reference star falls within the field of view of the guide, the programme brings it to the centre of the field through manipulation of the correcting drives of the telescope.

The latter procedure is performed only on the telescope Zeiss-600, since with manual setting of the telescope the accuracy of pointing is not better than $1.5' - 2'$. Driving the reference object to the centre of the guide field, we take up the errors of pointing and set the object at the specified point of the main CCD chip. After that, a short trial exposure is initiated to check the precision of pointing and to correct the position of the object under investigation in the field of view of the main CCD. This is needed to avoid hitting the object image to defect pixels of the detector. A series of exposures is specified by the command line of the BAT file as a list of filters, exposures and names of images. The sequence of operations for each exposure is as follows: the specified filter is set up, CCD exposure is triggered, the shutter opens and the process of guiding begins. Depending on the quality of the telescope guiding, the time between the corrections is chosen to be 3 to 10 s. If the centre of gravity of the reference star image is displaced from the initial point by more than 0.25″, the programme switches on for a calculated time the correcting drives of the telescope in right ascension and declination compensating thus for the image shift.

The process of guiding is displayed on the computer's monitor and recorded into the file. Besides the reference object image, graphs of variations of

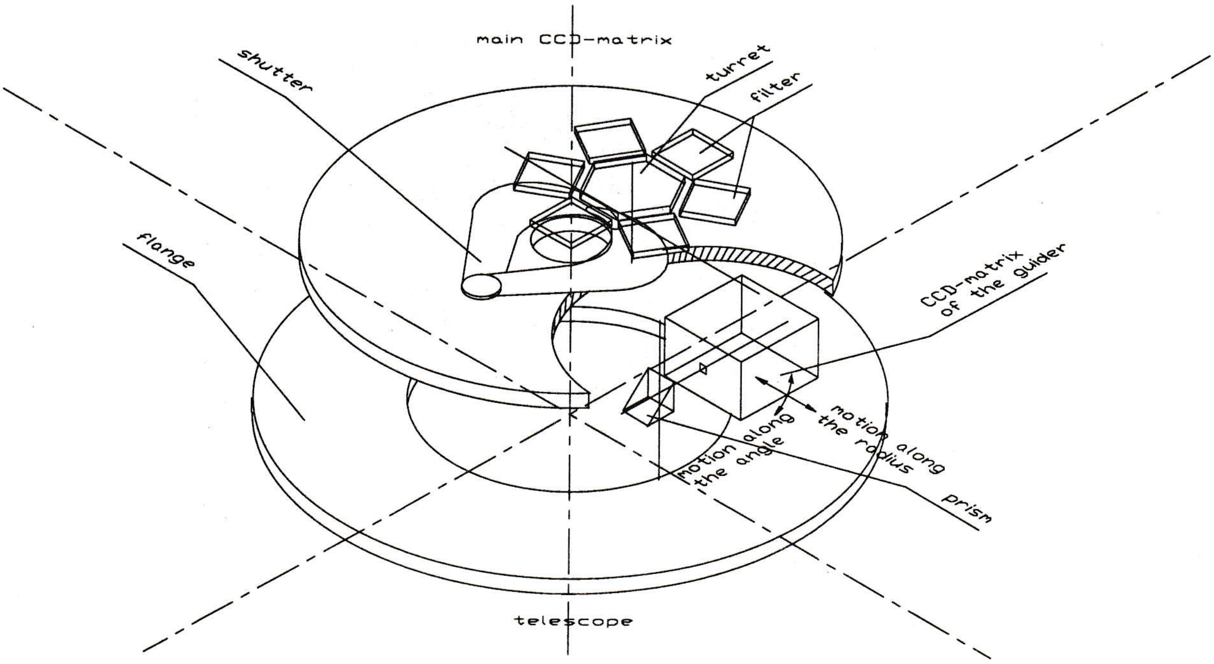

Figure 2: *Kinematic scheme of the photometer.*

its coordinates and signal are displayed. So, the observer has timely information about the quality of guiding and sky condition. For instance, considerable and rapid signal variations make it possible to register the appearance of clouds. On completion of the exposure, the shutter closes and the image is read from the CCD to the file with the indicated name. At an instrumental level the software enables summation over 4 or 16 CCD elements in an element of the image (binning 2 × 2 or 4 × 4). The obtained image is displayed on monitor for 10 s; after this the system switches over to the next exposure. If a pause between the exposures is specified, the process of guiding goes on not to lose both the reference star and the object of investigation because of the telescope driving errors. Programmes have been written which permit obtaining readout noises, dark noises and "flat fields" necessary for image reduction. If "flat fields" are obtained from morning or evening sky, when illumination changes rapidly, the programme uses the detector of the guide as the exposure meter. This allows automatic determination of the exposure of the main CCD matrix and obtaining a series of "flat fields" of one level in each filter.

2. Observations

Since 1997 the photometer has been in regular service on one of the minor telescopes of SAO RAS. In the process of observations the mechanical parts, control and software of the photometer were refined, and its principal parameters were investigated. The coefficients of the photometric system were determined from observations of some standard fields on photometric night using the following equations:

$$B_r = B_{inst} + K0_b + K1_b * (B_r - V_r) + K2_b * sec(Z)$$

$$V_r = V_{inst} + K0_v + K1_v * (V_r - R_r) + K2_v * sec(Z)$$

$$R_r = R_{inst} + K0_r + K1_r * (V_r - R_r) + K2_r * sec(Z)$$

$$I_r = I_{inst} + K0_i + K1_i * (R_r - I_r) + K2_i * sec(Z)$$

Here B_r, V_r, R_r, I_r are the stellar values of standards; $B_{inst}, V_{inst}, R_{inst}, I_{inst}$ are instrumental values of the standards;
Z is the zenith distance, the observations were conducted at;
K0, K1, K2 are the system coefficients.

Table 1 lists for each filter: N_{exp} — the number of observations, N_r — the number of standards used in the calculations and the system coefficients.

After the circuit of control of the telescope was closed by the guide, the detection threshold improved considerably owing to the improved image quality and lifting restrictions on the duration of exposure. In particular, this refers to Zeiss-600.

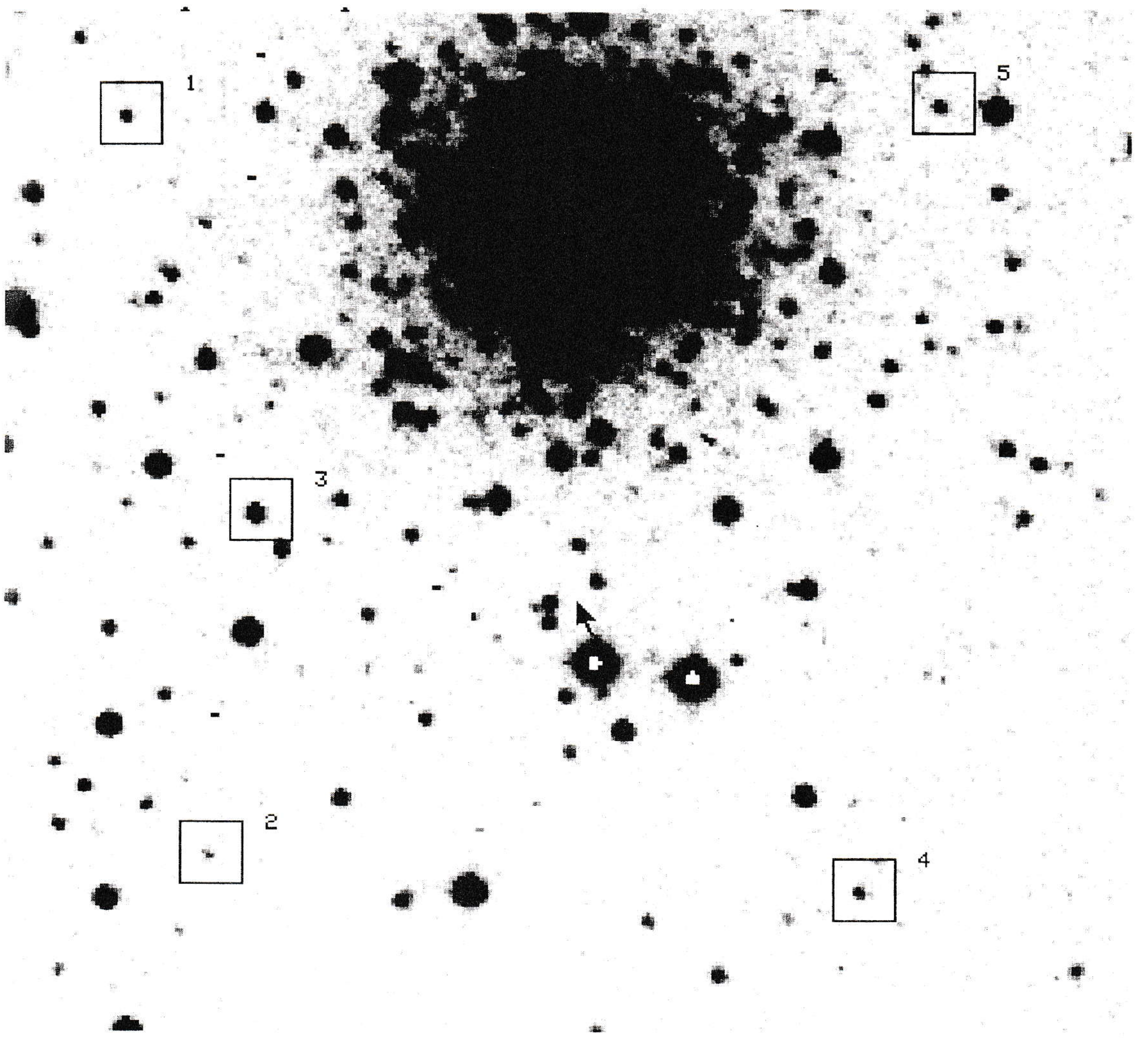

Figure 3: *The globular cluster NGC 7006 in R filtre, exposure — 15 min.*

Table 1:

F	N_{exp}	N_r	K0	K1	K2
B	6	186	25.37	-0.088	-0.23
V	8	194	25.66	-0.051	-0.20
R	8	170	25.68	0.044	-0.10
I	7	173	24.8	0.022	-0.10

Table 2:

No.	M_r	S/dsp	M_t
1	18.92	4508/38.2	22.35
2	19.29	2363/56.8	21.60
3	17.36	16078/36.0	22.23
4	18.81	4641/48.1	22.00
5	18.58	5699/36.6	22.30

As an illustration, Fig. 3 shows the image of the globular cluster NGC 7006 obtained on July 20/21, 1998 with the telescope Zeiss-600 in the R filter with an exposure of 15 min and a seeing of 1.6″. In Table 2 are given the parameters of five objects marked on the image: stellar magnitude (M_r), signal/noise (S/dsp) and detection threshold (M_t) at a level of 5×dsp.

The scatter of the detection threshold is determined not only by a random noise component but also by the residual inhomogeneity of the matrix sensitivity over the field. Near the object No.2, traces of a powerful "column" are visible, which were not managed to be removed completely since the necessary reduction is not ideal.

The design of the photometer makes it possible to readily change to polarization observations. This change-over does not require mounting of additional mechanical units and control elements. A linear polarization analyser is placed on the rotation platform in front of the CCD. The slewing of the platform ensures the necessary position angle of the analyser. We have worked with this technique since 1998 August and found it useful.

3. Conclusion

At the present time the complex is in permanent operation on one of the minor telescopes of SAO RAS.

Since November 1997, observations for three programmes have been conducted with it: monitoring of quasars and Lacertides, monitoring of Seyfert galaxies and investigation of morphology of Seyfert galaxies. A total of over 4000 observations have been carried out. Experience of operation of the photometric complex has shown that it has essentially improved the accuracy and recurrence of observations, diminished exertion of the observer, reduced the effect the errors introduced by the observer have on the final result.

The high performance reliability of the system permits the authors to argue that the complex can well be used in remote observations.

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