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Photoelectric photometry era at the Astronomical Institute of the Slovak Academy of Sciences I.

Instrumentation, colour system and extinction

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Abstract. We present a detailed description, including technical, optical and observational properties, of the photoelectric photometers used at the Astronomical Institute of the Slovak Academy of Sciences during last decades. The article contains long-term experience with the photoelectric photometer at the Skalnaté Pleso and Stará Lesná observatories. The authors hope that this description will lead to better knowledge of and correct work with the photoelectric photometer.

Key words: photoelectric photometry – photomultiplier – colour system

1. Introduction

Photoelectric photometry (hereafter PEP), or *photon counting*, is an observational technique used to obtain highly precise, calibrated observations of small amplitude stellar brightness changes in the sky. The PEP was formally established at the Skalnaté Pleso observatory (hereafter SP) (*longitude*: $20^\circ 14' 01''$E; *latitude*: $49^\circ 11' 22''$N; *altitude*: 1786m a.s.l., currently part of the Astronomical Institute of the Slovak Academy of Sciences, hereafter AISAS) in 1961 (Tremko, 1975). In 1987 we also started with PEP at the Stará Lesná observatory (hereafter SL) (*longitude*: $20^\circ 17' 25''$E; *latitude*: $49^\circ 09' 08''$N; *altitude*: 810m a.s.l., currently part of the AISAS) in the pavilon G2. Although the PEP passed through several technical adjustments, including later automatization based on the first pipelines, the observations at SP were running continuously till 2012 (at SL observatory the PEP was used till 2014). In 2012, the telescope at SP, together with the photometer, was uninstalled in order to be replaced by a new 1.3m Nasmyth-Cassegrain reflector. Therefore, that year can be considered as the end of the PEP era at SP observatory. Nevertheless, during the excellent 51 year history of PEP at SP observatory there were obtained over 20,000 PEP observations of over 300 different targets. All of these observations are archived at the servers of AISAS.

The main goal of the present paper is to describe the main properties of the last photoelectric photometers used at AISAS. The remainder of this paper is organized as follows. In Section 2, we describe basic parts of the photoelectric photometer (`OPTEC SSP/5A`) used at SP observatory in the period from 1996 to 2012. Section 3 presents a short description of technical limitations and problems discovered during first observations. In addition, this section also contains the solution of instrumental problems and some technical improvements which were carried out by the authors (R. Komžík and V. Kollár). The PEP at SL observatory is described in Section 4. Section 5 is devoted to optical properties based on the photometric system measurements. Finally, in Section 6 we summarize our description.

2. Photoelectric photometer `OPTEC SSP/5A`

The last upgrade of the photoelectric photometer at SP observatory was done on January 16, 1996. On that date, the instrument `OPTEC SSP/5A`[1] with a Hamamatsu R4457 photomultiplier tube[2] and standard $UBVR$ filters was installed at the 0.6m Cassegrain reflector ($f = 7.5$m). The photoelectric photometer used before was described already in the papers by Tremko (1975, 1976). With the R4457 photomultiplier tube (PMT) option, the SSP-5 can exhibit an S-5 response in higher quality in comparison to the original 1P21 photomultiplier tube. For researchers interested in better sensitivity and extended red response to 830 nm, the R4457 PMT option is available along with Johnson $UBVR$ filters. Each PMT is a 9-stage, side-on, low-noise photomultiplier housed in a small 1/2-inch diameter enclosure.

2.1. Photometer head

A cross-sectional view of the photometer head is shown in Figure 1. Light enters the photometer through the 1.25-inch telescope adapter and is directed either to the focusing eyepiece or the PMT by means of a flip-mirror. The focusing eyepiece (of Ramsden type) is of a 1-inch focal length and contains an illuminated reticle with a precisely scribed ring that defines the aperture field of view. After a star is centered in the ring, the flip-mirror is rotated to allow the light to pass through the aperture stop which separates the star from the background. A Fabry lens then projects a diaphragm image of the primary mirror onto the photocathode of the PMT.

2.2. Detector - PMT options

Our photomultiplier (the model R4457) was manufactured by the Hamamatsu Corporation and measured only 40 mm long by 14 mm in diameter. The model

[1] http://www.optecinc.com/astronomy/catalog/ssp/ssp5.htm
[2] http://www.hamamatsu.com/jp/en/index.html

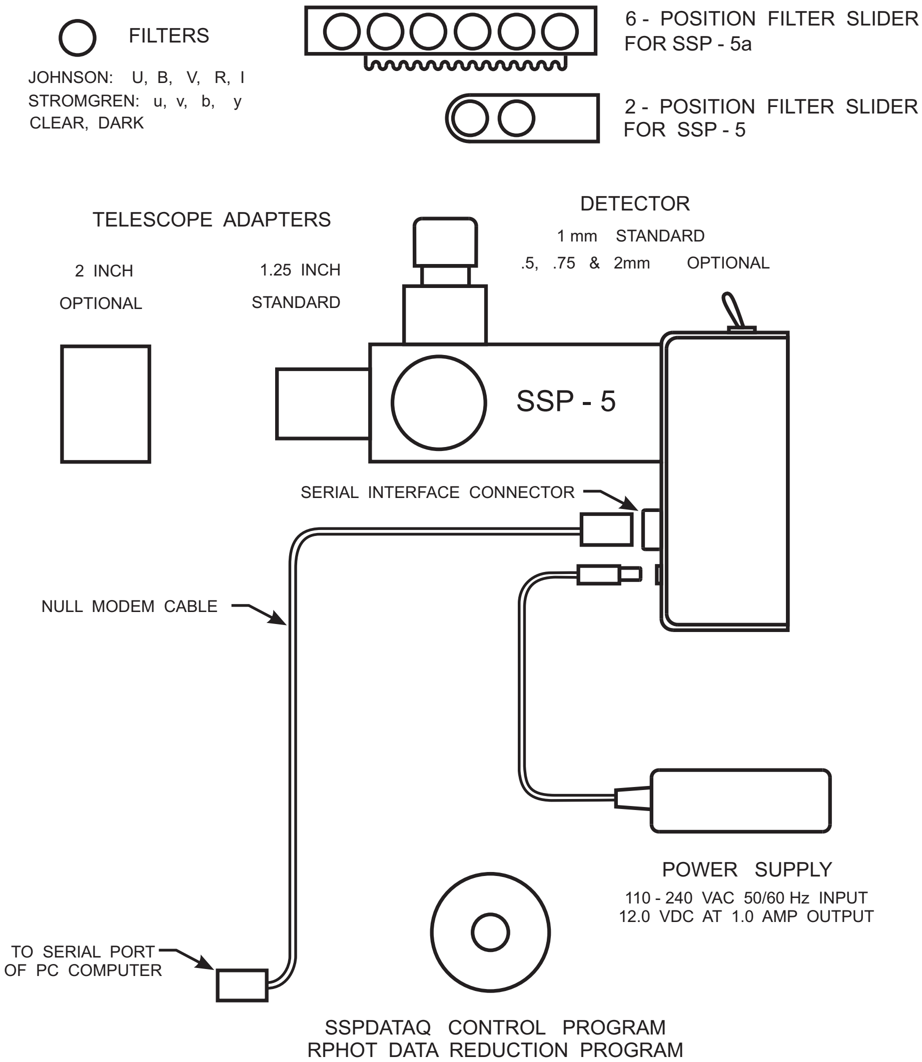

Figure 1. The SSP-5 photometer system and accessories (www.optecinc.com).

R4457 is an extended red response PMT which allows measurements into the Johnson R-band. The quantum efficiency (QE) of the R4457 is much better than in the previous case. The QE at the center of the Johnson V-band, 540 nm, is approximately 2% for the photomultiplier 1P21 and 16% for the R4457 (see Fig. 2). Because of this increased sensitivity, when the R4457 PMT is specified the operating supply voltage is set to -750 VDC rather than -850 VDC. At this voltage, the measured dark current is typically less than 2 pA at 70° F (21.1° C) ambient temperature.

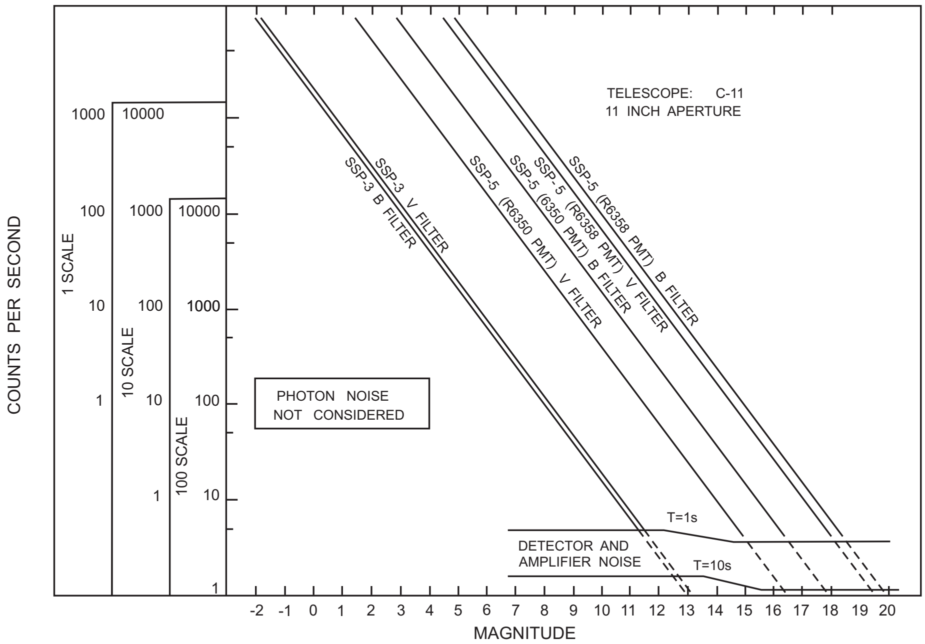

Figure 2. Performance of the SSP-5 compared with the SSP-3 (similar to 1P21) which use a silicon photodiode detector (www.optecinc.com).

2.3. Field aperture

A single field aperture of 2.0 mm diameter (55 arcsec) was placed at the focus of the telescope inside the photometer head. This aperture is not removable or changeable after assembly. Experience with the PEP before indicated that the need for adjustable field apertures is not great for a vast majority of applications which usually consist of stellar brightness measurements. The focusing eyepiece contains an illuminated reticle with a scribed ring which precisely coincides with the boundary of the field aperture. Normally, the star is centered within the ring of the focusing eyepiece and then a measurement is started by rotating the flip mirror to the measurement position - a turn of about 180°.

2.4. Fabry lens

Because the photomultiplier tube's cathode surface has very poor response uniformity, a Fabry lens is needed to fill a large area of the cathode uniformly regardless to where the star is positioned within the field aperture. Considering an f/10 cone of light as produced by a Celestron or Meade telescope, the Fabry lens used in the SSP-5 will image the telescope's entrance pupil slightly past the wire mesh screen in front of the photocathode with a spot having a diameter of 2.5 mm. Telescopes with f-ratios in the range from 7 to 20 should work with the 25.4 mm focal length Fabry lens without difficulty (the f-ratio of 0.6m Cassegrains at SP and SL is f/12.5). The Fabry lens has a plano-convex shape and a diameter of 9 mm.

2.5. Filters

The UBV filter system established by Johnson (Henden & Kaitchuck, 1982) is generally followed today for photoelectric systems using a 1P21 or equivalent photomultiplier tube. This system defines wide color bands in the spectrum interval from 300 to 720 nm. Using the red-sensitive R4457 PMT, SSP-5 owners can perform photometry into the Johnson R-band as well (up to 960 nm). The S-5 response of the R4040 PMT is nearly identical to the S-4 response of the original 1P21 photomultiplier tube, so the recommended filters for the R4040 most closely match Johnson's original filter specifications. However, by specifying some of the SSP-3 filters for use with the R4457 PMT, the response of this filter-detector combination can more closely match Johnson's standard $UBVRI$ response functions. Figure 3 shows the filter-detector responses (also referred to as the response functions) of the Johnson $UBVR$ system. Table 1 lists the physical specifications for the SSP-5 $UBVR$ filters.

Table 1. Physical specifications of the Optec filters.

Diameter	12.7±0.15 mm
Thickness	7.0±0.3 mm
Surface Quality	80-50
Flatness	2 waves within center 6 mm
Wedge	Not to exceed 5 arcmin

Filters are mounted in two-position sliders which are inserted through a side port. A spring plunger screw keeps a slight amount of pressure on the slider to keep it in place and to locate one position by a detent machined in the slider. The other position is found by pushing the filter slider in until it stops. Filters, or clear glass of identical thickness, have to be used in order to keep the focus in the same position as determined by the focusing eyepiece. Using no filter at all will move the focus up by about 3.5 mm. A black felt light seal is used on the filter slider port to prevent external light from being picked up by the PMT. Experience at Optec has shown that even bright office lights do not effect the output when a slider is in place and the flip mirror is in the viewing position.

The Model SSP-5A is supplied with a motorized filter slide which allows any of six (the case of SP and SL observatories) or ten filters to be selected by computer control. Coupled to the SSPCARD IBM interface, complete automatic control and data acquisition of the photometer is possible. Filter selection cannot be made manually since the filter covers and geared drive to the stepper motor prevent any other selection except by proper activation of the stepper motor.

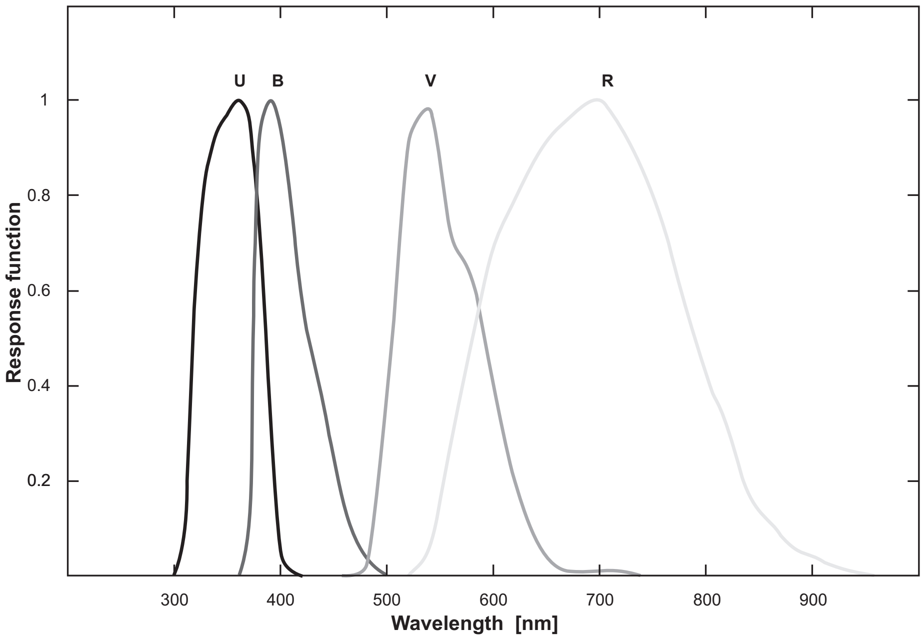

Figure 3. Standard $UBVR$ response functions used in the photoelectric photometer OPTEC SSP/5A at SP according to the Johnson (Henden & Kaitchuck, 1982).

3. Observations at Skalnaté Pleso observatory

In the previous section we described the model of the photoelectric photometer installed at SP observatory at the beginning of 1996. However, it was still needed to solve several problems remaining from the last decades:

– At the beginning of PEP, it was necessary to observe by two observers: one pointed the telescope in the dome manually and the other was responsible for data collection in the observing room. For data collection and measurement control, we used a PC for the first time in 1987 (a PP01-16 IBM compatible PC XT with the operating system DOS). In order to improve the precision of pointing, the stepper motors were used for controling fine movements. For the passage between the stars (*variable-standard-check*), the automatization of movements acceleration was implemented. The drivers of stepper motors were constructed by 8bit microcontrollers INTEL 8051. We established the system of drivers (e.g. right ascension, declination, dome, photometer) which received commands from the PC, or the hand control. The communication process was realized by a standard serial port. All equipments were galvanic separated from each other by optocouplers. Finally, using the TV Nightvision camera TV11-22/SIT, we were able to point objects directly from the observing room (observation by one person).

Concerning the photoelectric photometer OPTEC SSP/5A, after its installation we noticed and solved the following problems:

– The original Optec Voltage to frequency (hereafter V/f) converter was scaled to three positions (see Fig. 2). However, crossing between them was nonlinear and unstable. We solved this problem using our own V/f converter with original electronics and 10× higher count statistics in comparison with the original converter.

– Only one diaphragm with diameter of 2mm was installed in the original Optec photometer. In order to improve a signal-to-noise ratio, we installed the diaphragm with a diameter of 0.8 mm. The diaphragms were exchanged according to requirements of observers/observing conditions.

– Finally, we had mechanical problems with the two-material slider of filters (plastic parts would deform with the change of temperature, movement problems –brassy crest). All filters ($UBVRuvby$) were sealed up in their positions without any possibility to change them. In addition, no possibility to set up filter positions (with no electronic detection of the position in this model of the photometer). The position was found only based on the number of steps from the initial position of the slider.

4. Photoelectric photometer at Stará Lesná observatory

For the purpose of PEP we also used, like in the case of SP observatory, the 60cm Cassegrain reflector (f=750 cm, Carl Zeiss Jena, Germany) with a photoelectric photometer: an EMI 9789 Q photomultiplier and a UBV filter set, designed and made by Dr. Pavel Mayer (Charles University, Prague, Czech Republic). The detailed scheme of Mayer's photometer is presented in Fig. 4.

The light enters the photometer and is directed by means of a flip mirror to the focusing eyepiece or the PMT. The light passes through the aperture stop (diaphragm) which separates the object from the field of the telescope, and passes next through the filter. Then a Fabry lens projects the image of the aperture onto the photocathode of the PMT. Under the diaphragm there is a

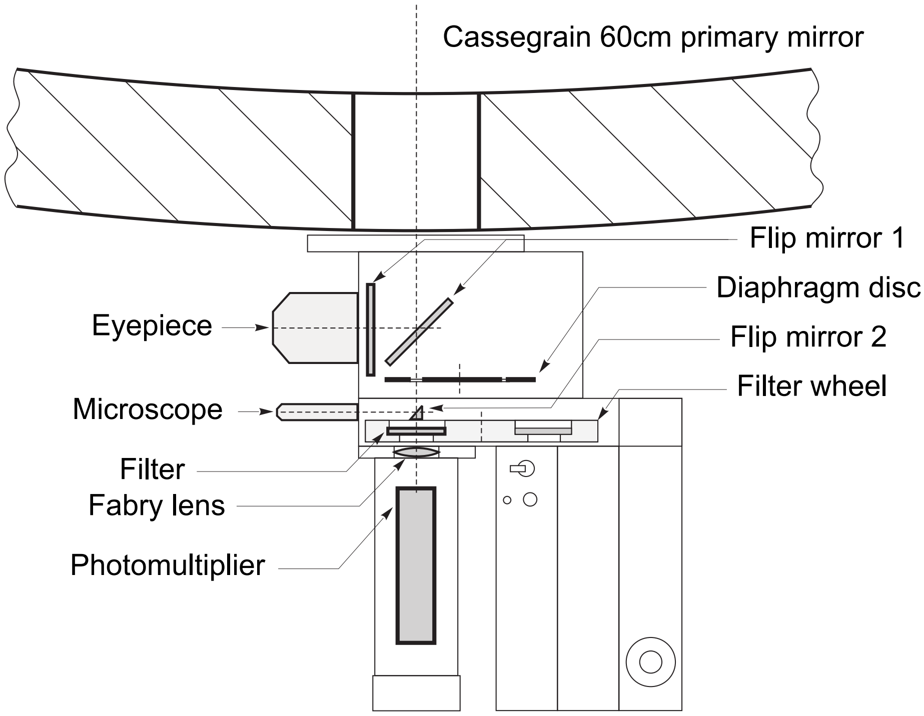

Figure 4. The schematic placement of the optical and mechanical parts in the head of the photometer at SL observatory.

second flip mirror for precise check of the star position in the diaphragm. The PMT has a mu-metal shield of high permeability to reduce the effect of external magnetic fields. There is a place for a re-chargeable silica gel canister under the PMT. The silica gel pellets are dark blue when activated and turn pale pink when their drying ability is diminished. The PMT box is humidity sealed. The photometer uses a high linearity voltage-to-frequency converter. The counter of impulses is placed in the photometer head as well. The disc of filters is turned with the aid of a stepper motor. The microcontroller evaluates the position of this disk by reading a position sensor. It performs all necessary functions in two work regimes: an autonomous or a slave one. The communication with a master computer is done via the standard serial port RS 232 without any special interface computer card.

4.1. Activity and specifications

The communication with the PC is controlled by the synchronization impulses from a synchronization unit. The synchronization unit is a precise clock producing short impulses on the RS 232 level (+12 V level of impulse). Basically, the generator of synchronization impulses is a master computer. By means of these impulses the information from counters is written into latches and the sending routine of a microcontroller is initialized. In sending routine the microcontroller reads the information from position sensors and information from latches of counters and then the routine sends the information into the serial port. The master computer receives the information via the serial port COM1 or COM2, and after processing this information by the resident program it is displayed on the screen. The application program reads the information from the screen as a character string from a specific place and saves it into an output file. The control instructions (e.g., for setting filters and beginning of a measurement) are sent via a specific place on the screen as well. The resident program reads it and sends it through the serial line into the microcontroller. The specifications of the used photometer are given in Table 2.

4.2. Software for photometer

The software consists of three basic components. The programs can run at the same time. After the proper configuration these programs can communicate and work together: (i) software in the photometer head: `KR.A51`, (ii) PC resident: FOT??.EXE and (iii) user software: UNIV (see paper II; Vaňko *et al.*, 2014b)

4.2.1. Photometer head software

The program is burned into the EPROM memory. It is written in the assembler language for microcontroller INTEL 8051. The program controls all functions and via the serial port RS 232 communicates with the master computer. After turning on the photometer power supply, initialization routine starts. It sets the speed of communication and the workmode for timer TIM-0; the priority of interrupts (the INT-0 has the highest priority and TIM-0 has the next priority). This initialization routine also sets available interrupts and program ends in a never-ending loop. The program is activated by the hardware interrupts.

The INT-0 interrupt is produced by the synchronization impulses coming from a master computer or from an external synchronization unit. **The highest priority level (INT-0)** activates a service routine which reads the actual filter position, status switches and sends the obtained information via the serial port in one byte. Following the information from level of counters is sequentially read and sent to the serial port as well. The receiving register contains the command sent by a master computer, this is also read by the routine. Such one-byte-long command contains the number of the requested filter. **The lower priority level (TIM-0)** activates a routine which controls the stepper motor movements. The frequency of these interrupts determines the speed of the stepper motor (for turning the filter wheel).

Table 2. The specification of the photometer used at Stará Lesná observatory.

Diaphragms	number of diaphragms	8	
	dimensions	[mm]	[arcsec]
		0.64	18
		0.95	26
		1.19	33
		1.63	45
		2.74	76
		4.34	119
		7.11	196
		10.99	302
Filters	number of filters	8	
	dimension	1 x 1 inch	
Photomultiplier	type	EMI 9789Q	
	photocathode	13VBCsSb	
		10 mm	
V/f converter	full scale frequency	1 MHz	
	linearity	$< 0.01\%$	
	offset	100 Hz	
Counter	synchronous binary		
	24 bits		
Microcontroller	Intel 8051		
Computer requirements	PC 286 or higher		
OS requirements	MS DOS 3.0 or higher		

4.2.2. PC resident

This resident program is activated by a defined hardware interrupt. The timer of a system clock can periodically start this resident. It uses IRQ8 interrupt; the period is 1 second. At first the resident sends a short 0.2 millisecond synchronization impulse, and then waits for four bytes from the serial port. After decoding the obtained information it displays it at a defined place of the screen communication box. The subsequent action of the program is reading the commands for photometer head from other defined place in video memory. These commands are sent to the serial port.

The information about installing this resident program (FOT??.EXE) in a PC computer can be found in Paper II.

```
SEND
   1. byte                 _ _ _ _  _ _ _ _
         comm-filt
                           | | | |  |_|_|_|_______ number of the filter
                           | | | |________________ mirror priority
                           | | |__________________ start measurement
                           |_|____________________ reserve
   2. byte                 _ _ _ _  _ _ _ _
         level off count. 1
   3. byte                 _ _ _ _  _ _ _ _
         level off count. 2
   4. byte                 _ _ _ _  _ _ _ _
         level off count. 3

RECEIVE
                           _ _ _ _  _ _ _ _
                           | | | |  |_|_|_|_______ number of
                           | | | |                 requested filter
                           |_|_|_|________________ reserve
```

Figure 5. The meaning of the bytes in communication.

4.3. Photometer errors

The errors of the detector found during data processing, and also their possible solutions, are divided into the following sections:

1. **NO DATA RECEIVED** on the computer screen
   (a) Check the power supply (change the fuse).

   (b) Check the connection between the computer and the photometer (the signal cable).

   (c) Check if the computer serial port you are using for the connection with the photometer is COM1 (it cannot be COM2, etc.). Check if other codes do not use this port (e.g. a mouse driver).

   (d) Check if this serial port COM1 is functional, e.g. by attaching a mouse into this port and loading a corresponding mouse driver (the mouse should work).

   (e) Try to change the filters manually (the button on the photometer head; the flip mirror must be in position in which the light goes into the upper eyepiece). If it is not possible to change the filters manually you must replace the microcontroller card.

   (f) Other errors must be corrected by an electronics engineer.

2. **Impossible to change the filters**, however the **data connection is OK**
   (a) Check the signal cable.
   (b) Check the black connector on the block of filters.
   (c) Replace the microcontroller card.
   (d) Other errors must be corrected by an electronics engineer.
3. **The filter indication** on the photometer head does not work
   (a) Try to change the filters manually (the button on the photometer head; the flip mirror must be in position in which the light goes into the upper eyepiece).
4. **The received pulses are equal 0 (zero)**
   (a) Check the connector from the power supply and the connector to the V/F converter.
5. **The pulses per second do not change**
   (a) If the number of pulses per second is more than $\sim 1\,235\,000$ and this number changes just at the last digits you must decrease the high voltage. This is the highest value for pulses per second.

5. Transformation to instrumental system

The variable stars were observed in U, B and V spectral ranges using the filters of the Johnson photometric system. In order to determine the transformation coefficients for conversion of the instrumental magnitudes to the standard UBV magnitudes, the standard stars in the open clusters Pleiades, Praesepe and IC 4665 were observed. At SP we have obtained 13 such observations from February 1, 1992, to May 1, 2012 (when the observations with the photoelectric photometer were stopped there) and 8 observations at SL observatory from October 1, 1991, until 2014. The transformation coefficients ϵ, μ and ψ, were simply calculated from the equations:

$$\Delta V - \Delta v = \epsilon \times (\Delta B - \Delta V), \tag{1}$$
$$\Delta B - \Delta V = \mu \times (\Delta b - \Delta v), \tag{2}$$
$$\Delta U - \Delta B = \psi \times (\Delta u - \Delta b), \tag{3}$$

where ΔU, ΔB, ΔV are differential magnitudes of the standard stars in the Johnson UBV system and Δu, Δb, Δv are instrumental differential magnitudes corrected for atmospheric extinction of first order, i.e. out-of-atmosphere magnitudes (the correction for second order extinction has been neglected). This procedure is described in Henden & Kaitchuck (1982).

The transformation coefficients for the period of 20 years at SP varied in the following ranges: ϵ [-0.007;-0.146], μ [0.916;1.061] and ψ [0.952;1.215] (see Fig. 6).

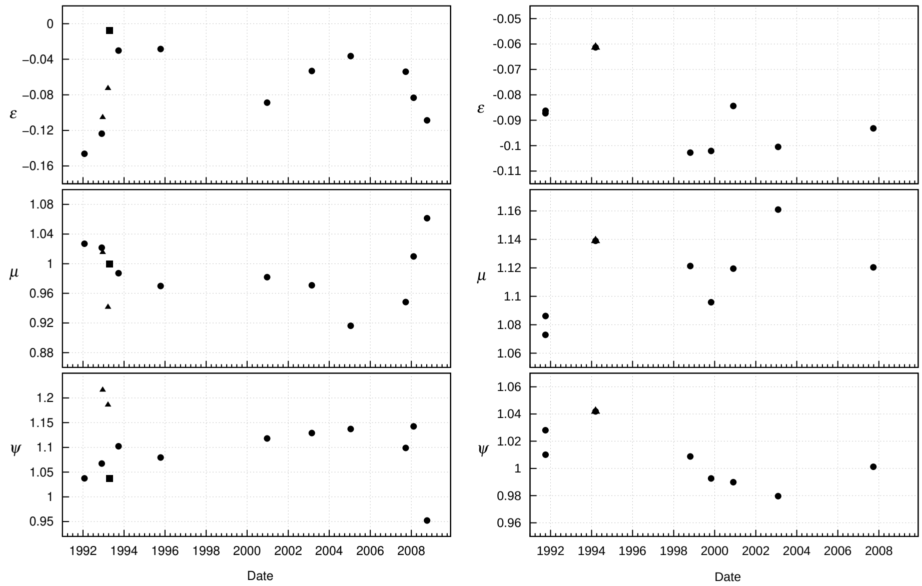

Figure 6. The variation of transformation coefficients for conversion of the instrumental to standard magnitudes of the Johnson UBV system, determined from the observations of standard stars in the Pleiades (circles), the Praesepe (triangles) and in the open cluster IC 4665 (square) for the observatory at SP (left panel) and in Stará Lesná (right panel).

The replacement of the photometer on January 6, 1993, and January 15, 2008, influenced mostly the value of a μ-coefficient. The poorer weather conditions during the observation of standard stars in the Pleiades on January 16, 2005, could to some extent cause the difference in determination of the μ-coefficient. Nevertheless, the most marked influence into the system were cleaning the mirror on April 16, 1993, and its coating after long time on October 7, 2008, which demonstrate the changes of all three coefficients.

At the SL observatory, the determined transformation coefficients are within the ranges: ϵ [-0.102;-0.061], μ [1.072;1.160] and ψ [0.979;1.041] (see Fig. 6). Because of short and rather poor observational conditions on March 11, 1994, the mean values of coefficients were calculated from the magnitudes of standard stars in the Pleiades and the Praesepe. On October 16, 1998, the mirror of the telescope was cleansed and in October 2007 it was coated.

6. Conclusion

This article describes the technical and optical properties of the photoelectric photometers `OPTEC SSP/5A` and `EMI 9789 Q` installed at SP and SL observatories, respectively. The main goal of the article is to show the flexibility and ability of such type of detectors in order to obtain valuable scientific results. This paper could also be used as a manual for future generations of observers using the data obtained with photoelectric photometry.

For the complete view and the description of how the whole system of photometric photometry works, see the next paper (II), where the software and data handling are discussed.

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URL: HAMAMATSU homepage, `http://www.hamamatsu.com/jp/en/index.html`

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