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A Multichannel Fiber Optic Photometer

Present Performance and Future Developments*

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Abstract

A three-channel photometer for simultaneous multicolour observations has been designed with the aim of highly efficient photometry of fast variable objects like cataclysmic variables. Experiences with this instrument over a period of three years are presented. Aspects of the special techniques applied are discussed concerning their applicability for high precision photometry. In particular the use of fiber optics is critically analysed. Finally the development of a new photometer concept and the ideas behind are outlined.

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Introduction

The photometric investigation of fast variable phenomena of objects like cataclysmic variables, pulsars and bursters raises a variety of problems that have to be taken into account while selecting adequate observing techniques and strategies.

The relative faintness and fast variability of such objects require their continous monitoring with sufficiently high time resolution in various wavelength regions. In order to obtain the intrinsic stellar variability, the influences of sky background radiation and atmospheric extinction have to be compensated.

These tasks can only be performed by simultaneous multicolour observations of the program star together with at least one nearby comparison star and the sky background. A photometer providing these facilities has been developed at the Universitäts-Sternwarte München. A detailed description has recently been published (Barwig, et al., 1987). The main characteristics of this instrument, designated by MCCP (Multi Channel Multi Colour Photometer), are explained by Fig. 1.: Light of three sources in the focal plane of a telescope (e.g. object, comparison, sky) is guided via optical fibers to three prism spectrographs. Each of them projects a small spectrum covering 3400-9000 Å onto a fiber array that selects 5 wavelength regions matching approximately the UBVRI filter bands. The fiber end faces of this array are connected to the detector unit consisting of 15 photomultipliers (PM). Thus each object channel is split simultaneously into 5 colour channels. The instrument provides data acquisition with a time resolution up to 10 ms, reduction facilities and monitoring of on line lightcurves.

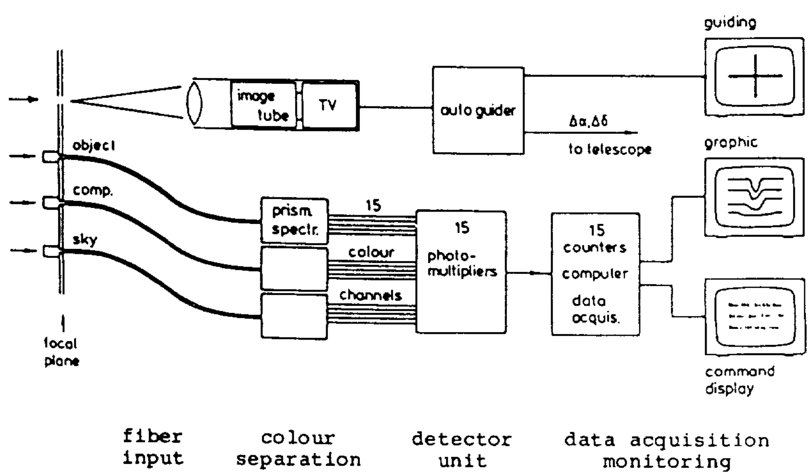


Fig. 1) Block diagram of the MCCP

Some features of the MCCP may be of interest for high precision photometry. Therefore some instrumental properties, their accuracy and the reduction techniques applied in this photometer shall be discussed in this context. Due to the hitherto lacking possibility to perform systematic, time consuming test runs using an own telescope we are confined to experiences gathered with the MCCP in the course of regular observing runs at ESO and Calar Alto Observatories.

1. Detector stability

Classical PM were found to be the most effective detectors for the spectral resolution chosen in the MCCP. They are encapsuled in a single housing which is cooled down to -18°C by regulated Peltier elements that guarantee a temperature stability of ±0.1°C, while the photon counting electronics operate at room temperature. The PMs are fed by optical fibers that are arranged between spectrograph and detector unit in a fixed configuration to keep the light transmission constant.

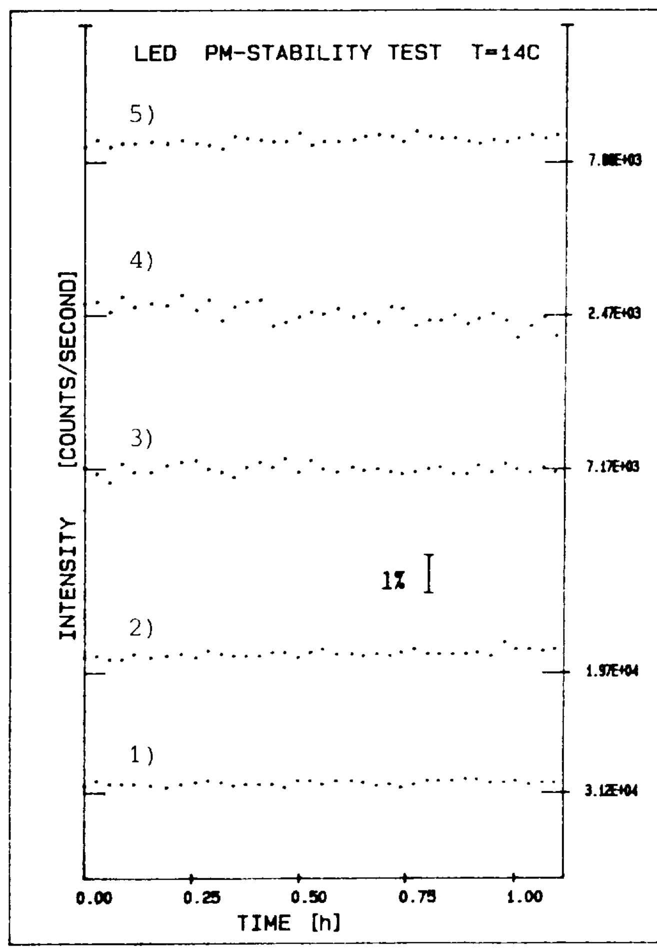


Fig. 2) Stability test of five different photomultipliers exposed to various LED radiations (1),2) Hamamatsu R647, 3),4),5) R1463)

In order to check the detectors (Hamamatsu R647 for U, B, R1463 for V, R, I) a stabilized LED source located in front of the fiber output array within each spectrograph can be switched on. Thus 5 PMs are fed by a single LED. Their individual count rates ($3x10^3$-$3x10^4$ cts/s) differ due to different fiber core diameters. The test allows to recognize differential gain variations caused by different fatigue effects. The dark current was measured in the beginning and at the end of each check sequence. A mean value of 4±1 cts/s was obtained. The results for the channels with the highest count rates show that a stability of 0.2% (Fig. 2) in timescales of hours is achieved, in contrast to results presented by Rosen and Chromey (1984). The tests were performed at a cathode temperature of 14°C. Identical measurements at a temperature of -17°C which is normally established during observations revealed a slight decrease in effective sensitivity very likely due to ice formation on the PM windows.

2. Fiber optic input channel

Each photometer channel has to meet the following specifications:

1) Unvignetted pick up of the signal of individual, sometimes quite close light sources through diaphragms in the telescope focal plane

2) Unvignetted and high efficient light transfer to the colour separation and detector unit

3) The total amount of light measured and its distribution on different spectral regions must not depend on the star's motion within the diaphragm. In particular, if simultaneous colour separation is achieved using a spectrograph, the cross section of the diaphragm has to be transferred to a uniformly illuminated entrance slit or a smaller circular aperture.

All these requirements suggest the application of optical fibers mainly due to their easy handling and their ability of light scrambling.

An input channel of the MCCP consists of a relatively large diaphragm (≤ 1 mm) that is coupled through a transfer optic to a quartz fiber of 400 μ core diameter. Its end face forms the entrance pupil of a small prism spectrograph and therefore defines the spectral resolution.

Of crucial importance is the uniform sensitivity (i.e. flat field) over the whole diaphragm area. Inhomogenities may be due to varying light loss within the transfer optics, at the fiber entrance surface and in the fiber itself. Further flat field distortions can arise within the spectrograph mainly due to vignetting effects caused by the transfer characteristic of the entrance optic. In the present photometer version the diaphragm is projected onto the quartz fiber by means of two ball lenses (Fig. 3). They are arranged to match a confocal system that makes the light beam enter the fiber nearly symmetrically with respect to the fiber axis. This in turn yields a constant light cone at the fiber exit end independently of the star's position in the diaphragm. The optical setup requires a very careful alignment of all optical components.

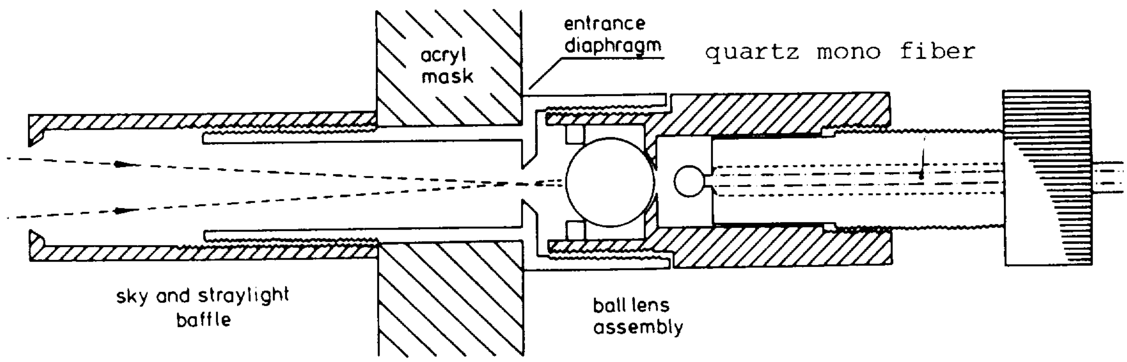
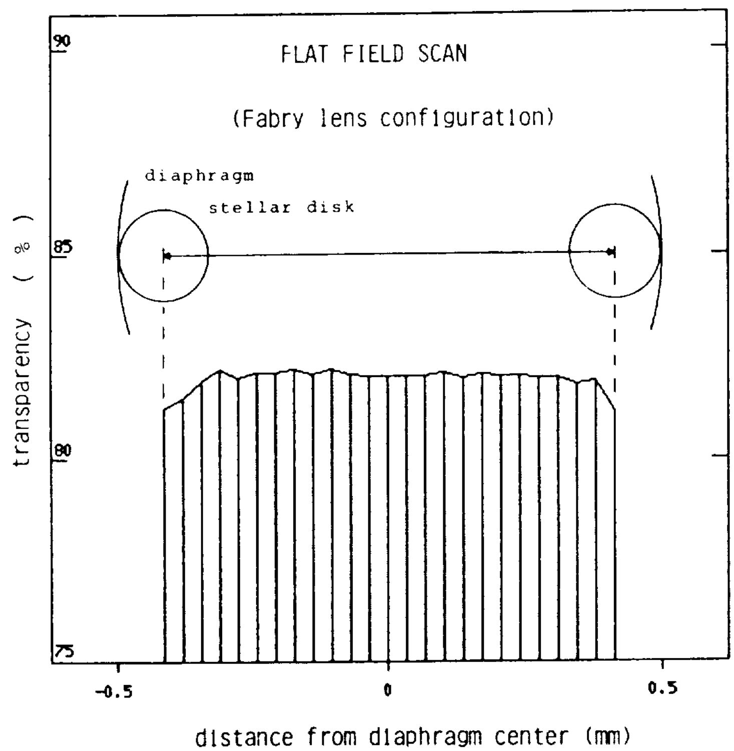


Fig. 3) Optical setup of the confocal lens system at the fiber entrance.

An alternative method of coupling the star signal to a fiber is currently under test and seems to be superior. A single Fabry lens of short focal length projects the telescope pupil onto the fiber face, thus transforming spatial motion to angular variations. Ray tracings have been calculated for both optical designs without involving the rather complicated light propagation through the fiber. However both optical configurations have been tested connected to a straight fiber of 40 cm length. For this purpose the f/8 light cone of a star in the focal field of a 1 m telescope has been simulated by a special optical setup. The artificial stellar disk of uniform brightness and of 0.2 mm (5") diameter can be radially moved across the diaphragm while the fiber output is imaged onto a PM cathode. Results are shown in Fig. 4.

The flat field obtained with the two lens system exhibits unsymmetric distortions due to small errors in the adjustment of the optical components and due to a defect on one side of the tested fiber. A better alignment with respect



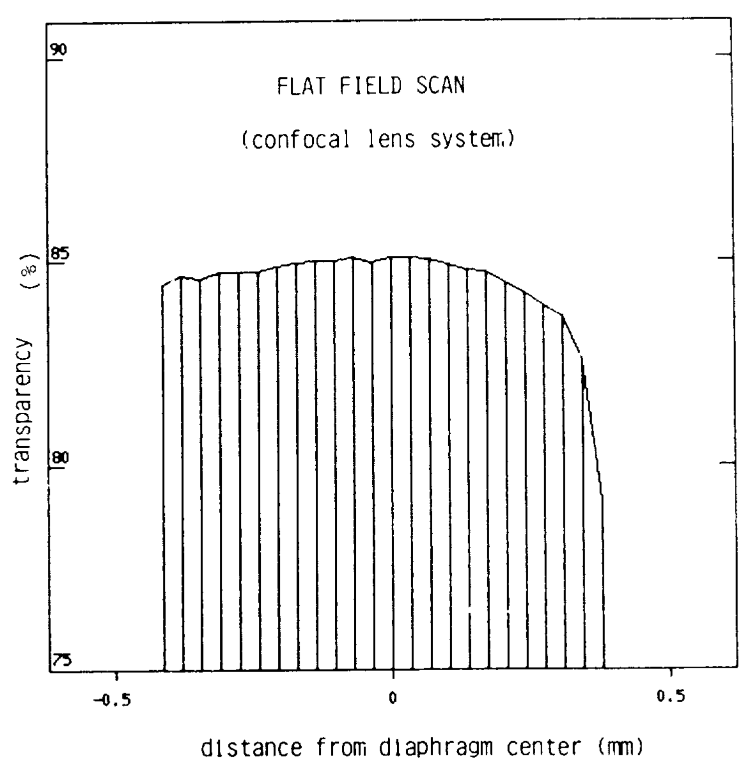


Fig. 4) Flat field scans for the two tested fiber input configurations

to the optical axis yields a flat field with symmetrical shoulders on each side not altering the main characteristics. The central part of the diaphragm (Ø = 0.3 mm) shows sensitivity variations on the order of the measuring accuracy (≈0.1%) while changes up to 0.5% occur over a field of 0.6 mm. If flat field distortions up to 1% are admitted then the useful area is extended to 0.8 mm. Theoretically the transmission of the two lens configuration decreases due to Fresnel reflection by 0.5% at the outer rim of the selected diaphragm.

The single lens configuration provides a much better flat field (≤ 0.2% over 0.7 mm) due to the uniform brightness distribution on the fiber entrance surface. The strongly variable f-number at fiber input (f/30 - f/2.7) is mostly smeared out by fiber degradation effects yielding variations of the spectrograph entrance cone between f/4.4 and f/2.5.

Bending variations of the fibers influence the values only marginally without affecting high spatial frequencies of the flatfield. A single bend of r=10mm applied to the fiber used with the single lens version stabilizes the f/number variations (f/3 - f/2.5) and scrambles the distributions of directions of the exit rays.

Of course both configurations suffer from high sensitivity to dust particles that may be released on the lens surface close behind the diaphragm. This problem may be solved by sealing the fiber input optic through an anti reflection coated quartz window that could be attached to the small sky baffles at a larger distance from the focal plane.

3 Measuring method and reduction procedures

3-1 Measuring method

The primary aim is the determination of intensities of the object relative to a comparison star (i.e. reduced to airmass X=0) in the instrumental filter system. The required data are obtained by positioning the fibers on object, comparison star and sky respectively in the focal plane of the telescope. During each integration the individual contributions of object, comparison, sky and dark current (O_x, C_x, S_x, D_x) to the signal in channel CH_x for a given colour are:

Object channel:	$CH_1 = O_1 + S_1 + D_1$
Comparison channel:	$CH_2 = C_2 + S_2 + D_2$
Sky channel:	$CH_3 = S_3 + D_3$

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3-2 Standard reduction

To obtain relative intensities (O_1/C_1) in a first approximation the signals of object and comparison channel are divided after subtraction of the respective contributions from sky and dark current and after some transformations of all quantities to allow for different channel sensitivities and diaphragm sizes. This so called standard reduction (SR) is given by

$$\text{SR:} \quad \frac{O_1}{C_1} = \frac{CH_1 - T_{3-1} \; S_2 - D_1}{T_{2-1} \; (CH_2 - T_{3-2} \; S_3 - D_2)}$$

where T_{x-y} indicates the channel transformation coefficients between CH_x and CH_y.

3-3 Channel transformation

The channel transformation coefficients (CTC) are derived from the photon counts of individual channels calibrated with sky and star sources respectively.

This can be achieved by measuring 1) a point light source (e.g. the comparison star itself or an artificial light that is attached to the fibers) in both star channels and 2) an extended source (e.g. sky background or an artificial light source) in all three channels. Both calibration methods have been applied. The accuracy of the derived CTC reflects different dependence on instrumental and atmospheric properties.

The scatter of calibrations performed with artificial light sources are influenced by time dependent variations of individual detectors and pulse counting electronics and by brightness changes of the test lights. Flat field distortion from fiber optic inhomogenities ($\leq$ 0.2 %) do not appear since the artificial point light source illuminates a fixed small area on the diaphragm.

From actual measurements performed at beginning and end of several observing nights the scatter of the CTC has been found not to exceed 0.5%.

Calibrations using comparison star and sky on the other hand yield considerably larger residuals ($\approx$1-2%), that must be explained in terms of the following effects:

a) atmospheric transparency fluctuations during the non simultaneous measurements of the comparison star in both channels

b) colour dependent extinction due to non identical filter characteristics of the three channels

c) influence of errors in the sky transformation coefficients on the star channel calibration

d) influence of seeing and guiding in combination with flat field distortions

Special problems arise if the sky background radiation itself is used for calibration. Dark skies require long integration times for photon noise reduction whereas bright sky measurements during moonlight or dawn result in incorrect coefficients due to spatial brightness gradients. Such effects yield systematic differences (up to 20%) in the derived sky transformation coefficients.

3-4 Accuracy of standard reduction

Application of the MCCP for high precision photometry requires a thorough consideration of the accuracy that can be achieved with the SR and of possible improvements as well.

Instrumental influences mainly refer to telescope aperture, diaphragm size, detector stability, flat field distortion and the derived transformation coefficients. The influence of telescope and diaphragm aperture with respect to diffraction and scintillation has already comprehensively discussed by Young (1974). Flat field distortions (≤ 0.2% in the center of the diaphragm, neglecting dust contamination) independently affect the signals from object and comparison star. They cannot be compensated by calibration. Differential gain instabilities of PMs have been found not to exceed 0.3%. Careful treatment of environmental conditions (e.g. humidity, temperature) of PM tubes and of photon counting electronics may lower the error limits. Frequent calibration measurements that allow linear interpolation might be a better solution, however. Finally the theoretically resulting scatter of transformation coefficients should be compared to that of real measurements in order to detect possible brightness variations of the (artificial) calibration sources.

Further instrumental effects on the SR accuracy like different filter characteristics of individual channels shall be considered in the context of atmospheric extinction.

Neutral absorption is eliminated by SR supposed that the influences on object and comparison are completely correlated. However selective extinction usually expressed by first and second order extinction coefficients affects both stars in a different way, depending on their individual flux distribution and on the filter bandwidth. The first order term is compensated by SR only in case of identical filter properties of both star channels. The systematic error of SR neglecting second order extinction effects raises up to a few percent depending on airmass and differences in spectral type. Compensation of this error requires the determination of second order extinction coefficients, that may be obtained by classical standard star observations.

A peculiarity of multichannel photometers concerns differences in the spectral sensitivity of individual channels. As a consequence the CTC obtained from comparison star calibration becomes sensitive to variations of its flux distribution e.g. caused by atmospheric extinction. It can be shown that systematic errors due to differential filter shifts are nearly independent of the spectral type of the comparison star but do depend linearly on the difference between airmass during calibration and actual observation (for example: for $X = 1$, systematic error in B = 1-2%).

3-5 Increasing the accuracy of SR

The effects of extinction and non ideal filter characteristic can be taken into account using a numerical simulation of the overall photometer throughput combined with wavelength dependent standard extinction coefficients. The effective instrumental spectral sensitivity could be obtained by folding the spectral transmission curves of fiber channel and spectrograph with the quantum efficiency of the respective PM.

At present we try to measure the relative overall transmission applying a scanning monochromator that produces light in the wavelength region 3400-9000A at a constant photon flux rate. For this purpose a photodiode with approximately unity quantum efficiency (Zalewski and Duda, 1983) regulates the scanner output brightness. The light signal can be connected to the individual photometer channels via a single quartz fiber. However variations of bending radii of this test fiber during channel interchange influences the signal transfer efficiency. Thus at present only relative filter curves can be derived.

By an alternative method that is going to be investigated at present, the test light is fed to the photometer diaphragms through the telescope optic itself: the monochromator signal, emerging from a spot in the focal plane passes through the telescope and is partly reflected back to the photometer by a plane mirror located near the secondary support ring. In this way the spectral reflectivity of the telescope mirrors could be included in the numerical simulation of the photometer equipment. It is expected that the calibration of all three channels using a scanner monochromator will provide the required information on i) the CTC by integrating over the respective wavelength regions, ii) the higher order extinction effects and iii) the colour transformation coefficients.

4. Future developments

The successful application of the MCCP for high efficient high speed multicolour photometry, that can be performed even under poor atmospheric conditions stimulated the design of an improved instrument with increased channel number, higher spectral and time resolution and improved accuracy. The basic properties of the projected photometer as well as the ideas behind shall be outlined in the following.

4-1 Input channels

The new photometer will be equiped with at least four fiber channels that allow to pick up light of a second comparison star or of the sky background at an additional test point. Measuring two comparison stars offer the possibility to check their differential brightness constancy and to improve the compensation of colour dependent extinction effects by selecting objects of different spectral distribution. From observations of the sky radiation at separate positions the intensity gradients can be calculated and compensated.

The input channels will not be fixed by a mask but dynamically positioned under computer control. During observation this allows a quick check or correction of decentering errors, e.g. due to differential refraction. The hitherto used mono fibers will be replaced by fiber bundles.

4-2 Colour separation and detector

The four photometer channels feed a single spectrograph that produces four spectra (one upon each other) with a resolution of about 20. In order to reach high efficiency the total wavelength region (3400 - 9000 A) is split by means of a dichroitic filter into two lightpasses that are dispersed by separate prisms. The resulting individual spectra then are projected onto the photocathode of a two-dimensional photoncounting resistive anode detector (MEPSI-CRON) that will be operated at integration times down to 1 ms. The increased spectral resolution offers the possibility of computer synthesis of different photometric systems and to improve the compensation of higher order extinction effects.

4-3 Software developments

The primary aim is to optimize the observing strategy for a given observing program. Parameters like integration time, calibration cycle, spectral type of available comparison stars, frequency of standard star observations have to be adjusted according to the required accuracy and to the actual instrumental and atmospheric conditions. Another investigation aims at the development of more sophisticated reduction algorithms and adequate methodes of data analysis.

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